

Vibration-induced PM Noise in Oscillators and Measurements of Correlation with Vibration Sensors¹

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Abstract - We present data that show correlations between phase fluctuations in a low g-sensitive 10 MHz oven-controlled quartz oscillator (OCXO) and acceleration/vibration sensors. We describe the equipment setup and measurement procedure. Data are in the form of scatter plots, which we find to be highly informative compared to usual $L(f)$ plots when the oscillator is subjected to vibration.

I. INTRODUCTION

Electronic oscillators often can provide sufficiently low intrinsic phase modulation (PM) noise to satisfy particular system requirements when in a benign environment. However, mechanical vibrations and accelerations can introduce mechanical deformations that degrade the oscillator's otherwise low PM noise. This degrades the performance of an electronic system that depends on this oscillator's low phase noise.

This sensitivity originates most commonly from phase fluctuations within the oscillator's positive-feedback loop, usually the physical deformations in the frequency determining element (resonator). Factors that lead to high resonator vibration sensitivity include nonlinear mechanical coupling effects and lack of mechanical symmetry that serve to cancel frequency changes in the resonator [1]. Vibrations also cause mechanical deformations in non-frequency-determining electronic components that then cause phase fluctuations [2]. Because these fluctuations are inside the oscillator feedback loop and are integrated by Leeson's model [3], they can become particularly excessive at Fourier, or offset, frequencies close to the carrier frequency. The primary degradation to the performance of electronic systems and synthesizers in field environments is often due to the vibration-PM noise induced into the system's reference oscillator.

NIST has projects aimed at characterizing induced PM noise at an oscillator's output signal, which noise is caused by vibration. Section II describes the usual characterization in which vibration sensitivity of oscillators is summarized by a "g" or gravitational sensitivity, and typically produces frequency shifts in oscillators of the order of $1 \times 10^{-9} / g$

where g is the acceleration of gravity near the earth's surface, approximately 9.8 m/sec^2 . One goal of the studies in this paper is to set up and develop more informative test methods of assessing whether electronic feedback techniques can cancel out or compensate for the effect of these vibrations in the oscillating signal via vibration sensors. Section III examines the use of correlation or "scatter" plots of the magnitude and phase of random vibration vs. PM noise, as opposed to characterization of oscillator g-sensitivity based simply on $L(f)$ under vibration. Section IV describes the measurement setup and procedure for obtaining such plots, and the benefit of choosing a setup that allows programming realistic vehicle, transport, or other field vibration situations. Section V presents data in the form just mentioned for a low g-sensitive 10 MHz oven-controlled quartz oscillator (OCXO).

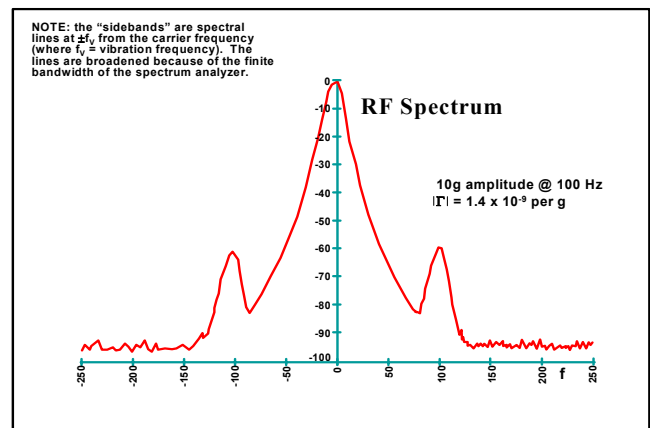


Figure 1. Power spectrum of an oscillator that is subjected to 10 g vibration at $f_v = 100 \text{ Hz}$. Figure is shown, courtesy of John Vig [1].

II. CHARACTERIZATION

If the vibration frequency is f_v from mechanical shock or other external processes, vibration-induced phase fluctuations cause carrier-frequency fluctuations characterized by $\Delta v_{rms} / v_0$ at f_v , where v_0 is a carrier frequency. Spurious sidebands will appear at $v_0 \pm f_v$, as shown in the oscillator's power spectrum. Fig. 1 shows the spectrum of a typical oscillator that is subjected to 100 Hz

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vibration along one axis [1]. Note that the intrinsic random electronic noise (shown as the noise pedestal on both sides of an ideal carrier signal) is significantly degraded by additional noise due to this vibration and the resulting upper and lower sidebands at $f_i = 100$ Hz that it produces [4].

Vibration sensitivity is expressed as notation $|\Gamma| = \mathbf{y}_{\text{rms}}/\mathbf{g}$, where “ \mathbf{y}_{rms} ” is fractional frequency fluctuation $\Delta\nu_{\text{rms}}/\nu_0$ of carrier frequency ν_0 . The measurement technique typically uses a 3-axis accelerometer mounted on or near the oscillator’s resonator or other vibration-sensitive components. The spectrum of the mechanical vibration along each axis determines the acceleration level and this is measured against $L(f)$, the resulting PM noise of the oscillating signal while the device is vibrated [5,6].

Noteworthy to this discussion, the spurious sidebands generated by oscillators under vibration is a more serious issue as the signal frequency increases. Systems are in place which require ultra-low PM noise from reference oscillators operating at X-band, in the range of 6 – 18 GHz. Given a nominal g-sensitivity of $|\Gamma| \sim 1 \times 10^{-9} / \text{g}$, the level of vibration spurs in phase-noise plots of $L(f)$ becomes excessively large at X-band and higher ranges, often seriously affecting, or even prohibiting, the use of microwave systems [7].

III. MEASUREMENTS ON A LOW G-SENSITIVE QUARTZ OSCILLATOR

Passive vibration isolation systems consist of springs and dampers (dash-pots). Springs soften vibrations and perturbations, and dampers act to terminate oscillations [8]. Active systems use accelerometers and compensating electromagnetic drivers. Hybrid active-passive systems allow higher degrees of vibration isolation to be achieved, but such systems are not easily miniaturized, somewhat complex, and power-consuming [9]. In principal, atom-based frequency-determining elements such as are used in atomic frequency standards have extremely low acceleration sensitivity, thus low vibration sensitivity [10]. However, the large volume of these standards make them more vulnerable to mechanical deformation under vibration, so some method of suppressing induced frequency shifts is often required [11]. More compact atomic standards allow for simpler mechanical vibration isolation to be incorporated [12].

Strategies for electronically reducing vibration sensitivity have traditionally relied on accurately detecting this vibration with sensors [13] and even using the resonator itself as a vibration sensor [14]. Suppression at one vibration frequency along one axis in quartz oscillators by electronic means have been explored with good success [15]. More recently, significant advances have been made in which this electronic vibration suppression is effective over a wide range of vibration frequencies from a few hertz to 200 Hz. This is accomplished by fabricating high-Q quartz resonators

in which the “cross” g-sensitivity of the three orthogonal axes are decoupled to a high degree [16].

While vibration-induced noise modulation on a resonator is proportional to g-sensitivity, the proportionality as a function of f_i can be complicated in the range of audio frequencies of concern here (from a few hertz to 5 kHz). Resonator deformations that affect the resonator’s center frequency depend on issues of mounting, elastic properties of materials, acoustic resonances, sound and vibration isolation, orientation, etc. Low acceleration or g-sensitivity does not necessarily mean that phase noise due to acoustic and structure-born vibration is suppressed under all conditions. Therefore, suppression of only “dc” g-sensitivity has limitations and is insufficient to solve the larger problem of “ac” vibration sensitivity. The important property of an oscillator’s frequency determining element is that there is minimal coupling of mechanical vibration along a given axis to the other two axes [17]. The measurement technique described in this paper involves analyzing the coherence of PM fluctuations to accelerometer signals from each of the three axes.

IV. MEASUREMENT PROCEDURE

Fig. 2 shows the setup used to measure correlation of the phase noise vs. vibration noise of a low g-sensitivity FEI 10 MHz OCXO.

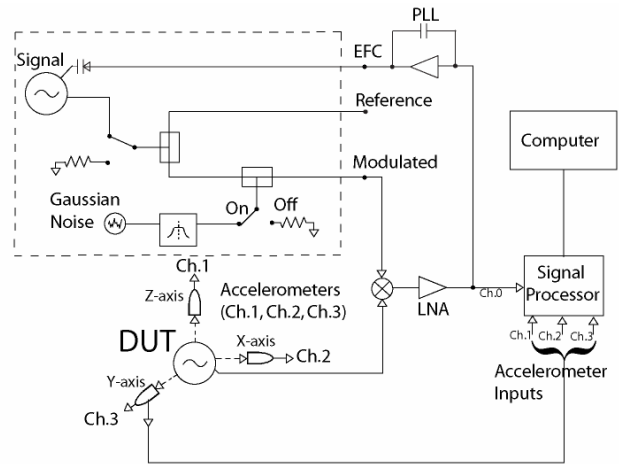


Figure 2. Setup consisting of a single-channel PM noise detector using the loose PLL technique [18] to measure PM noise between a reference signal and a device under test (DUT). The DUT, which is a low g-sensitivity 10 MHz OCXO, is mounted to a shake table, with the output of the phase detector going to the first channel and a 3-axis accelerometer whose three channels go to the remaining channels of a data acquisition system.

The main portion of this vibration setup is the vibration equipment. The equipment needed to vibrate a device consists of a vibration table or “shaker,” table driver or

power amplifier, mains power isolator and transformer, and vibration controller with associated accelerometer mounted on the shaker. A separate computer is used to control the amplifier, which in turn controls the vibration of the table. The computer contains a vibration controller card and specialized controller software from Data Physics Corporation. The controller card is part of a control loop that relies on an accelerometer mounted to the vibration table. This accelerometer provides the feedback data that the computer uses to calculate the ideal output signal and amplitude for the amplifier to drive the table to the specified software parameters set by the operator.



Figure 3. On the left is the vibration table (shaker), amplifier for driving shaker (the vertical rack-mount system), and controller, signal generator, and data-acquisition system in front of operator. On the right is the 10 MHz OCXO device under test (DUT) mounted to the shaker platform.

To measure the phase noise of the OCXO, a phase locked loop was obtained with a NIST Noise Calibration Standard at 10 MHz [18,19]. The Calibration Standard serves as the unvibrated, low-noise reference and is locked to the OCXO under test. A phase locked loop (PLL) is used to maintain phase quadrature of the reference to test oscillators for times longer than a few seconds. Short-term phase fluctuations at a frequency greater than 1 Hz thus represent the actual relative phase perturbations of the test device while subjected to vibration. The output of the PLL was measured with a FFT signal analyzer and also channel four of a data acquisition card, Model NI 4474.

The OCXO was mounted to the table using a custom mount designed for this purpose. The mounting hardware allowed for the OCXO to be mounted and vibrated along each axis.

The test was performed and the data were taken on four channels. These channels can be described as phase noise and acceleration. In this setup, one channel was used to measure phase noise, while the other three channels were the acceleration on the X, Y, and Z-axes. The program enables the user to enter specific channel data, such as serial numbers, various operating conditions, and several parameters related to the DUT, as well as accelerometer sensitivity.

The table has the capability to vibrate in a random vibration pattern, or various sine patterns, including dwell (single frequency) and sweep. For this test, sine dwelling and random vibration testing were chosen. For each axis of the OCXO, sine dwelling was done for verification, followed by random vibration. The frequencies chosen for a sine dwell were 20, 40, 80, 100, 200, 500, 1000, and 2000 Hz. In what follows, the DUT is subjected to a constant-acceleration spectral density of approximately $0.01 \text{ g}^2 / \text{Hz}$, random white-noise vibration profile with frequencies between 10 and 200 Hz.

The data are then processed by Matlab in order to compute the power spectral densities and the cross spectral densities of the different channels. The raw data was also exported in Microsoft Excel to produce scatter plots to be shown.

V. MEASUREMENT RESULTS

The signals from a 3-axis accelerometer feed three channels of a four-channel signal analyzer. The fourth channel input is connected to the output of a phase-sensitive detector that senses phase fluctuations of the oscillator being vibrated vs. a clean (unvibrated) reference oscillating signal, as shown in Fig. 2.

Fig. 4 shows calibrated accelerometer readings in units of dB relative to 1 g^2 (left axis and bottom plot) and level of the PM-noise discrete spur in units of dBc (right axis and top plot) for sine-dwell vibration frequencies between 20 and 2000 Hz.

From these results, the DUT met its vibration-sensitivity specification of $|\Gamma| < 5 \times 10^{-11} / \text{g}$ at the test dwell frequencies and all three axes. Remarkably, this sensitivity often dropped to an order of magnitude lower ($< 5 \times 10^{-12} / \text{g}$) on some axes and over some ranges of vibration frequencies.

From this setup, we can not only determine the g-sensitivity of the test device, but we can also view correlation by means of scatter plots, which are the primary results of interest when developing strategies for lowering vibration sensitivity further. Fig. 5 shows plots of DUT phase fluctuation vs. accelerometer-signal phase with a peak magnitude that exceeds several g's. The X-axis scatter plot (top) shows very small DUT phase perturbations and virtually no correlation between these perturbations and the random mechanical vibration to which the DUT is subjected. This indicates that active compensation schemes cannot suppress the phase fluctuations any lower.

The Y-axis scatter plot (middle of Fig. 5) shows that phase deviations are over ten times larger on average with noticeable correlation with the phase of vibration. Additional active suppression applied to this axis is possible given these data.

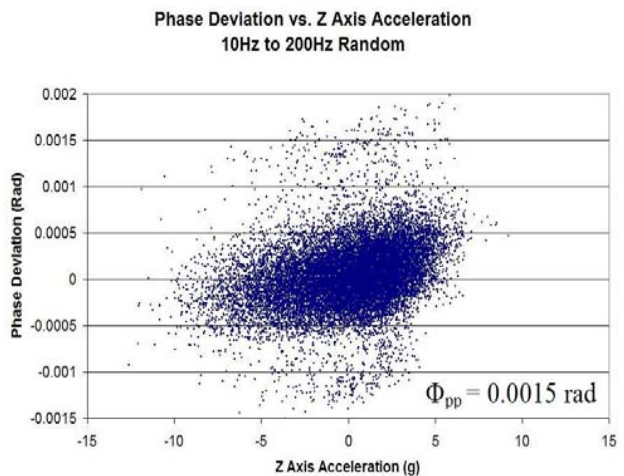
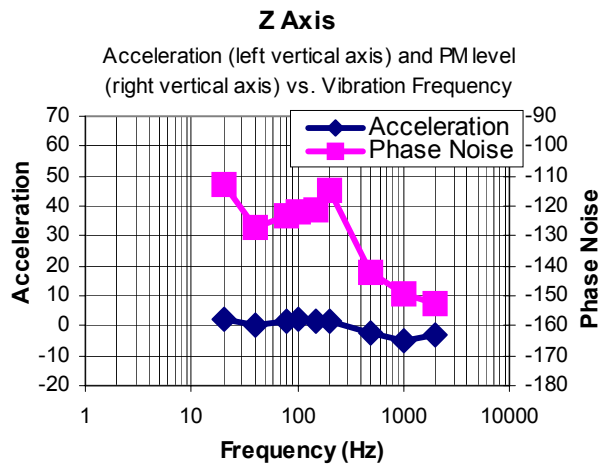
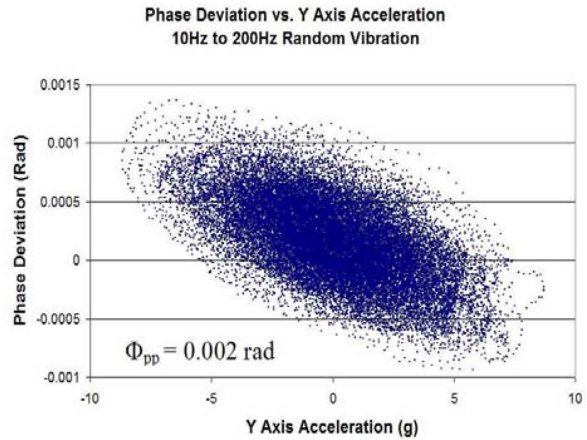
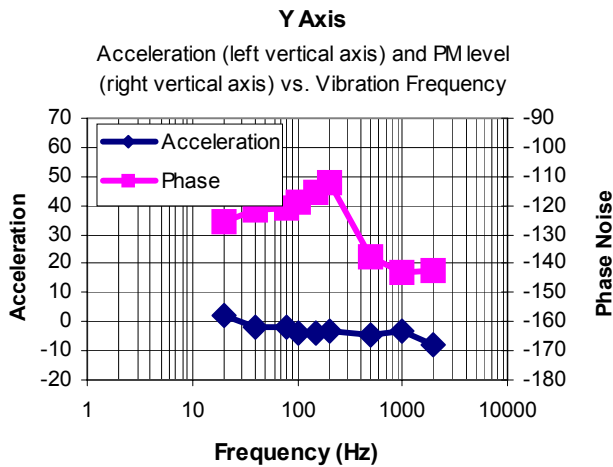
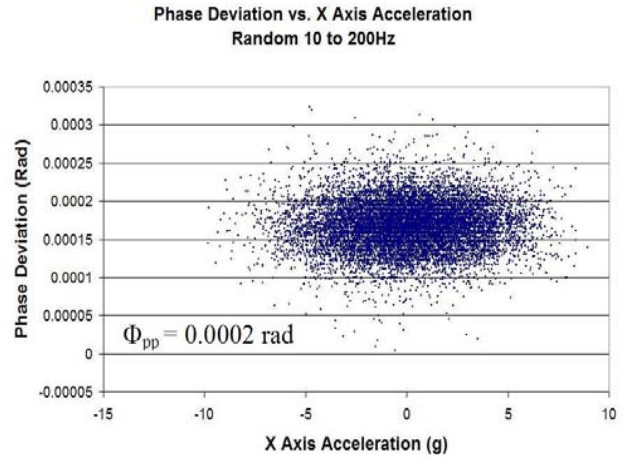
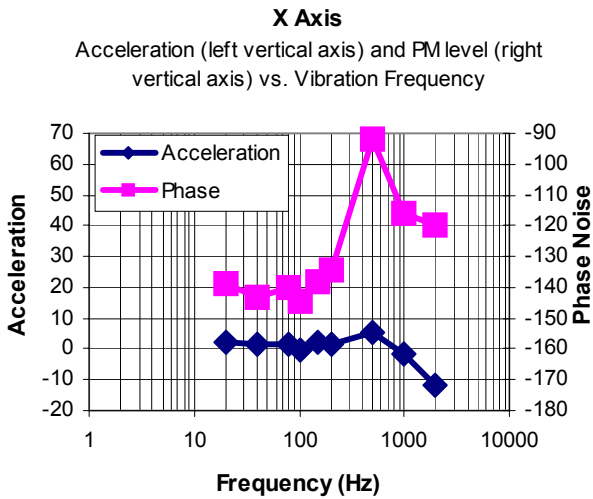


Figure 4. Accelerometer readings in units of dB relative to 1 g^2 (left vertical scale and bottom plot on each axis of vibration) and level of the PM-noise discrete spur in units of dBc (right vertical scale and top plot on each axis of vibration) for sine-vibration frequencies of 20 Hz – 2kHz.

Figure 5. X, Y, and Z-axis scatter plots showing correlation (coherence effects) between the phase fluctuations of the DUT and the phase of mechanical vibration to which the DUT is subjected. A random white-noise vibration profile was used with a spectral density of approximately $0.01 \text{ g}^2 / \text{Hz}$, $10 < f < 200 \text{ Hz}$.

The Z-axis scatter plot indicates some correlation effects, however, the rather vague nature of the correlation suggests dispersion effects that may be difficult to characterize. Also, except for some outlying points, the magnitude of the DUT phase deviations are relatively small. Indications are that additional active compensation is not easily attained.

As an added capability of the NIST setup, any two channels can be connected to separate phase-sensitive detectors and a cross-spectrum obtained to reduce uncorrelated noise from each detector, should the single-detector noise floor be too high. While this capability is not used in this paper, this setup has the potential to perform state-of-art PM noise measurements [20].

VI. SUMMARY

Vibrations are undesirable to precision, low-noise oscillators. This paper outlines a method of characterizing the correlation between the phase of the noise of an oscillating signal vs. the phase of mechanical vibration of the oscillator. We describe the measurement apparatus and test a low g-sensitivity OCXO to illustrate the procedure and show the corresponding measurement results.

REFERENCES

- [1] Vig, J., "An overview of effects of vibration on phase noise," 1st DARPA APROPOS Planning Meeting, Boulder, CO, January, 2003.
- [2] D. Steinberg, *Vibration Analysis for Electronic Equipment*, John Wiley & Sons, 1988.
- [3] D. B. Leeson, "A simple model of feed back oscillator noise spectrum," Proc. IEEE, vol. 54, pp. 329-330, 1966.
- [4] T. E. Parker, "Characteristics and sources of phase noise in stable oscillators," Proc. 41st Ann. Freq. Control Symp., 1987, pp. 99-110.
- [5] R. L. Filler, "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 35, No. 3, pp. 297-305, May 1988.
- [6] J.R. Vig, C. Audoin, L.S. Cutler, M.M. Driscoll, E.P. EerNisse, R.L. Filler, R.M. Garvey, W.L. Riley, R.C. Smythe, R.D. Weglein, "Acceleration, Vibration and Shock Effects-IEEE Standards Project P1193" Proc. Of the 46th Ann. Symp. On Frequency Control, pp. 763-781, 1992
- [7] T. Wallin, L. Josefsson, B. Lofter, "Phase noise performance of sapphire microwave oscillators in airborne radar systems," GigaHertz 2003, Proceedings from the Seventh Symposium, November 4-5, 2003, Linköping, Sweden, Linköping ISSN 1650-3740 (www) , Issue: No. 8, URL: <http://www.ep.liu.se/ecp/008/>.
- [8] P. Renoult, E. Girardet, L. Bidart, "Mechanical and Acoustic Effects in Low Phase Noise Piezoelectric Oscillators," Proc. Of the 43rd Ann. Symp. On Frequency Control, pp. 439-446, 1989, IEEE Catalog No. 89CH2690-6.
- [9] R.D. Weglein, "The Vibration-Induced Phase Noise of a Visco-Elastically Supported Crystal Resonator," Proc. Of the 43rd Ann. Symp. On Frequency Control, pp. 433-438, 1989. IEEE Catalog No. 89CH2690-6.
- [10] B. Thieme, D. Zoschg, and G. Baister, "Space worthy electronics package for the 35kg space active hydrogen maser on ACES," *18th European Frequency and Time Forum*, April 2004.
- [11] T.M. Kwon, T. Hahn, "Improved Vibration Performance in Passive Atomic Frequency Standards by Servo-Loop Control," Proc. Of the 37th Ann. Symp. On Frequency Control, pp.28-20, 1983, AD-A136673.
- [12] W. Riley, "The Physics of the Environmental Sensitivity of Rubidium Gas Cell Atomic Frequency Standards," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, vol. 39, pp. 232-240, 1992.
- [13] D.J. Healy, H. Hahn, S. Powell, "A Measurement Technique for Determination of Frequency vs. Acceleration Characteristics of Quartz Crystal Units," Proc. Of the 37th Ann. Symp. On Frequency Control, pp. 284-289, 1983, AD-A136673.
- [14] M.H. Watts, E.P. EerNisse, R.W. Ward, R.B. Wiggins, "Technique for Measuring the Acceleration Sensitivity of SC-cut Quartz Resonators," Proc. Of the 42nd Ann. Symp. On Frequency Control, pp. 442-446, 1988, AD-A217275.
- [15] V. J. Rosati and R. L. Filler, "Reduction of the Effects of Vibration on SC-Cut Quartz Crystal Oscillators," Proc. 35th Annual Symposium on Frequency Control, pp. 117-121, 1981
- [16] Frequency Electronics, Inc., 55 Charles Lindbergh Boulevard, Mitchel Field, NY 11553. For completeness, commercial products are mentioned in this document. No endorsement is implied. Products are available from other manufacturers.
- [17] Charles Stone, private communications.
- [18] D. B. Sullivan, D. W. Allan, D. A. Howe, and F. L. Walls (Editors), "Characterization of clocks and oscillators", National Institute of Standards and Technology Technical Note 1337, Section A-6, March 1990.
- [19] F.L. Walls, A. J. Clements, C. M. Felton, M. A. Lombardi, and M.D. Vanek, "Extending the range and accuracy of phase noise measurement," Proc. 42nd Annual Freq. Control Symp., pp. 432-441, 1988.
- [20] Warren F. Walls, "Cross-correlation phase noise measurement system," Proc. IEEE Freq. Contr. Symp., 1992, pp. 257-261.