AN3526

Dual Reference Noise and Stability Measurements with the 53100A Phase Noise Analyzer

INTRODUCTION

Measurement of the phase noise and short-term stability of high-performance signal sources has always imposed unusual demands on both the instrumentation and the reference sources involved. Should either fall short of the performance anticipated from the device under test—or if the expected performance levels are simply not known—the measurement will provide only an upper bound rather than an accurate indication of what the DUT can really do. Worse, when working near the state of the art, factors ranging from budgetary considerations to the fundamental limits of physics may conspire to place appropriate reference sources entirely out of reach.

In this application note, we'll look at a real-world test scenario in which "impossible" noise and short-term stability measurements are made easily with the help of the multichannel input capabilities offered by the 53100A. With full support for dual-reference measurements, the 53100A can help you make the best measurements possible with the reference sources available.

MEASUREMENT GOALS

We'll use the 53100A to characterize the device under test (DUT), a very high performance double- OCXO, without the need for an expensive reference input such as an atomic standard. The demanding DUT specification (Allan deviation: 8E-14 at t=3s and phase noise: –130 dBc/Hz at 1 Hz) will be verified by using the 53100A's dual reference input configuration. This configuration simplifies a task that has traditionally been challenging to accomplish outside of national standards laboratories

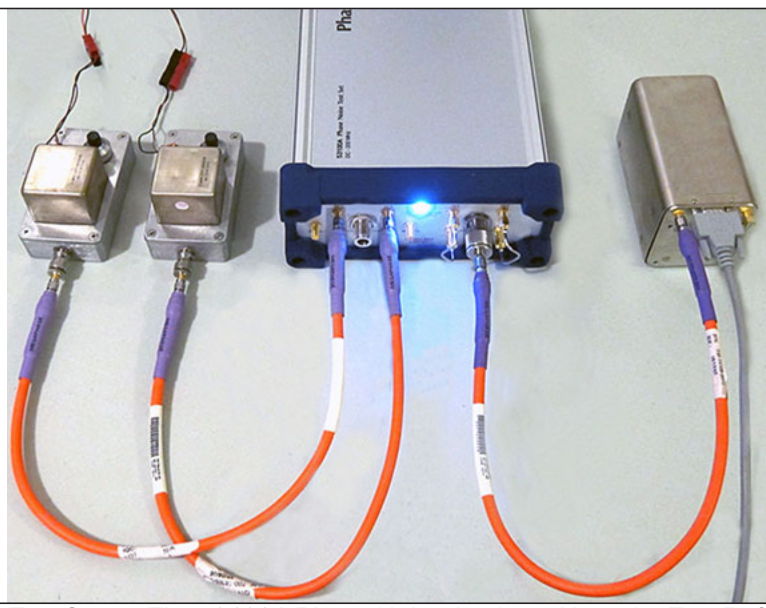

FIGURE 1: Test Setup: The 53100A Phase Noise Analyzer Uses the Two Reference Oscillators on the Left to Measure the Device under Test on the Right.

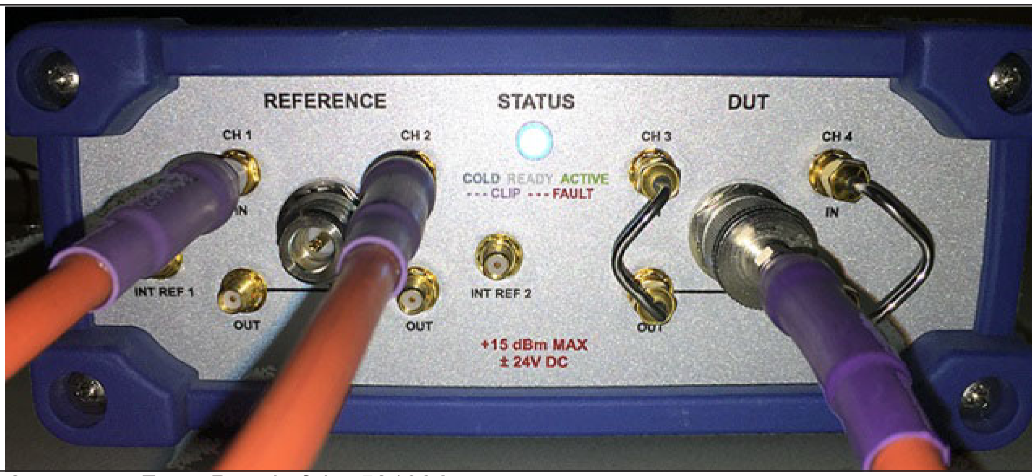

FIGURE 2: Front Panel of the 53100A.

SETTING UP THE HARDWARE

In Figure 1 (CH 1 and CH 2), the 53100A is connected to two reference oscillators instead of the default setup of one reference. The oscillators are double-oven OCXOs that provide the independent uncorrelated references needed to support two distinct types of advanced real-time measurements.

First, cancellation of uncorrelated noise by averaging the cross spectra from two independent acquisitions will allow one to measure phase noise and AM noise at levels well below those achievable with either reference by itself. At the same time, the “three-cornered hat” analysis technique will be employed to help isolate the DUT’s contribution to multiple Allan deviation plots. Used judiciously, the three-cornered hat method can provide good estimates of the frequency stability of signal sources that could not be measured with only a single reference OCXO.

Connection details at the 53100A’s front panel are shown in Figure 2. The SMA jumpers have been removed from the CH 1 and CH 3 jacks, permitting the two reference oscillators to be connected directly to the channel inputs. The internal splitter associated with the REFERENCE, CH 1 OUT, and CH 2 OUT jacks is unused in this application and remains unconnected, while the DUT is connected to the main DUT input jack. The DUT channel jumpers at channels 3 and 4 are left in place for this test. Note that only channels 1, 2, and 3 will participate in the three-cornered hat Allan deviation measurement, so in principle the channel 3 jumper could be removed and the DUT connected directly to its input. However, as noted above, we’d like to run a cross-correlation measurement of its phase noise and AM noise at the same time the stability measurement is running. The noise measurements will benefit greatly from the presence of the two independent references employed for the stability measurement, even though the underlying algorithms are very different. This strategy requires the oscillator under test to be connected to both DUT input channels via the internal splitter, rather than to channel 3 alone.

Note that the reference oscillators do not have to operate at the same frequency as the DUT, or at the same frequency as each other for that matter. These reference oscillators generate 10 MHz while the DUT is a 5 MHz part. Nevertheless, the 53100A’s input circuitry is designed to maintain a high degree of isolation between inputs as well as immunity to outside RF interference, and it’s worthwhile to maintain that standard when connecting external devices.

Consequently, the reference oscillators’ power connections are carefully decoupled with feed-through capacitors at the point of entry into each enclosure and fed from separate supplies. The RF cables are phase- and amplitude-stable parts with multiple shields. Cables with shielding effectiveness (SE) ratings below –90 dB should be employed when possible.

A final remark on the subject of isolation: for demonstration purposes, Figure 1 and Figure 8 show the DUT and reference oscillators lying next to each other on a table. This practice isn’t ideal unless you’re certain that temperature changes or other localized environmental fluctuations won’t cause correlated stability artifacts between the sources. This isn’t a major concern with the DOCXOs measured here, but it’s worth keeping in mind. Uncorrelated sources are a key assumption in three-cornered hat measurements.

WORKING WITH THE 53100A ACQUISITION DIALOG

The first step in the measurement process is to open the 53100A acquisition dialog with the *Acquire>Microchip 53100A* menu option. The dialog box that appears should resemble the image in Figure 3.

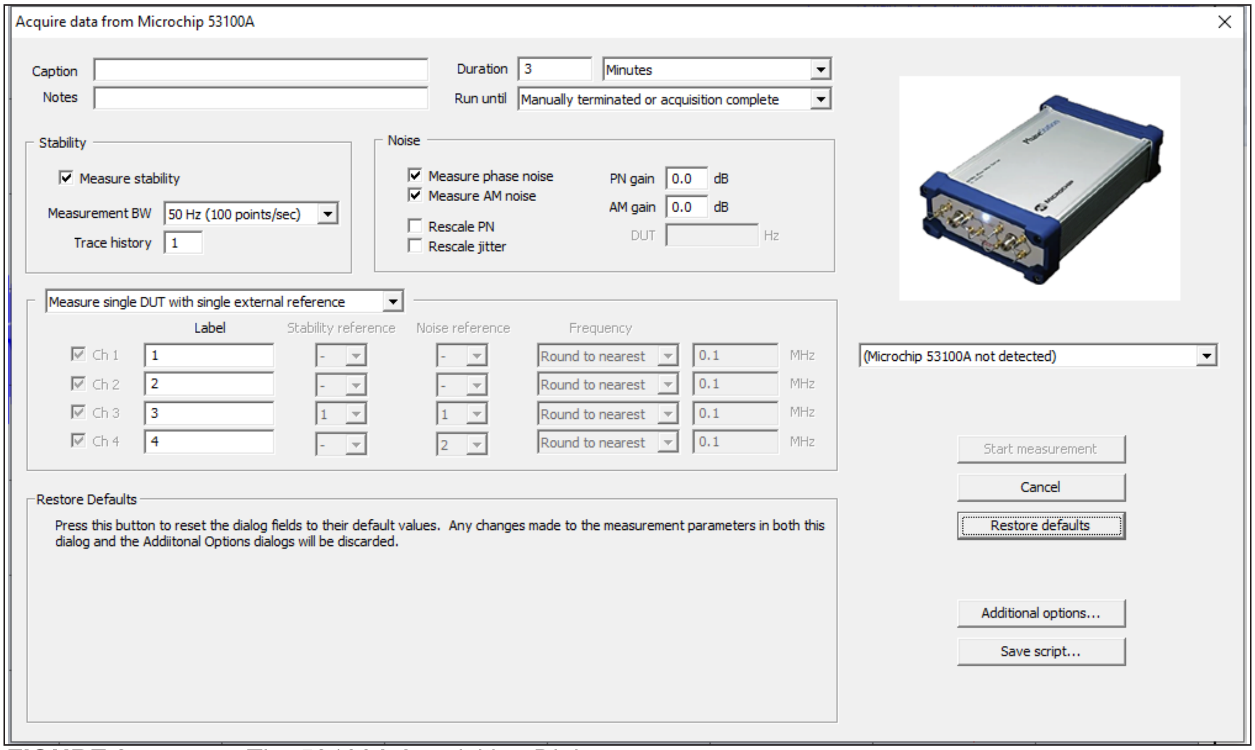

FIGURE 3: *The 53100A Acquisition Dialog.*

If you have previously run any 53100A measurements, any changes to dialog settings that you may have made will be retained. Consequently, you may wish to press the Restore Defaults button before continuing. This will restore the fields and controls in both the main dialog and the Additional Options dialog to their factory default values, establishing a starting point for subsequent changes. The following notes describe the specific changes shown in Figure 3 that were made to set up the demonstration.

- The default measurement duration of 3 minutes has been changed to 10 minutes. Because the reference oscillators are expected to be significantly less stable than the DUT, the extra time will improve the accuracy of both the stability and noise measurements. Later, we'll compare the results to a much longer measurement made with different references in order to obtain some feedback on the quality of our initial 10-minute run.
- The default measurement role—Measure Single DUT with Single External Reference—assigns ADC channels to the DUT and reference inputs that correspond to the factory default SMA jumper configuration. A previous application note, AN3502, illustrated the use of the 53100A's default measurement role in detail. For this demonstration, we've selected a different predefined role, Measure Three Independent DUTs (Three-Cornered Hat).
- Descriptive names for the devices participating in the measurement have been entered in three of the four Label fields beneath the measurement role selector. When the three-cornered hat display is enabled with *Trace>Show Separated xDEV Variances (N-Cornered Hat)* <Ctrl-h>, these labels will be used to report the estimated stability of each device on an individual basis. It will be difficult to keep all the results straight if the channels are not given meaningful labels corresponding to the devices connected to them. Because the stability traces use only the first three channels when the three-cornered hat role is selected, there's no need to assign a label to channel 4.

Selecting the three-cornered hat measurement role will cause the acquisition to yield three separate stability plots, each based on the unwrapped phase differences between two of the three channels. By default, these three stability measurements will be rendered with conventional Allan deviation traces and other statistical displays that are based on the phase differences between the participating channels. However, when the three-cornered hat display is enabled with *Trace>Show Separated xDEV Variances (N-Cornered Hat)* <Ctrl-h>, the three deviation traces will instead show the estimated stability of the channel input sources by themselves.

This is possible because the three-cornered hat measurement role configures each input channel to contribute to two separate measurements in a round-robin fashion. The first trace represents the stability of the device at channel 1 using the device at channel 2 as a reference, the second trace portrays channel 2 relative to channel 3, and the third trace is based on channel 3 relative to channel 1.

So, although we've been using the term "reference" to distinguish the two OCXOs at CH1 and CH2 from the device at the DUT input jack, the fact that each source is measured with respect to its two peers means that each of the three oscillators can be considered a "device under test" in the context of the three-cornered hat measurement. In fact, given the DUT's exceptional stability specifications, we anticipate that its contribution to the measurement will allow the stability of the "reference" OCXOs to be estimated with greater confidence than that of the DUT itself.

No other parameter changes are required in order to perform a three-cornered hat stability measurement with the 53100A. Having selected the appropriate measurement role and entered the necessary channel labels, it's time to press the **Start Measurement** button at the right to close the **Acquisition Dialog** box and begin collecting data.

VIEWING THE STABILITY MEASUREMENT IN PROGRESS

Upon starting the measurement, the resulting plots should begin to appear in TimeLab within 10 to 20 seconds.

Depending on the current Measurement menu selection, you may find yourself looking at the Allan deviation trace, the phase noise trace, or one of the other measurement views after the acquisition begins. Any of these views may be selected for observation during the test, but in this demonstration we'll focus on the Allan deviation measurement first. To observe the three-cornered hat measurement as it evolves in real time, first select *Measurement>Allan Deviation* (or simply press lowercase <a>). Three ADEV traces resembling the example shown in Figure 4 should appear, noting that only the leftmost portions of the traces will be visible at the beginning of the measurement.

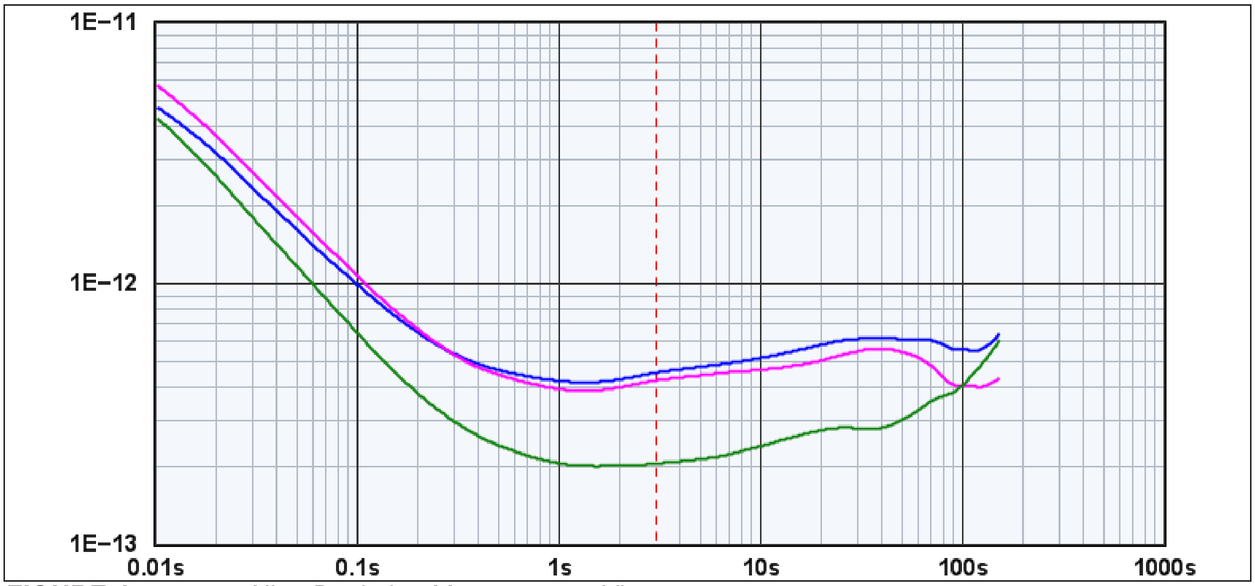

FIGURE 4: *Allan Deviation Measurement View.*

You can then toggle the three-cornered hat measurement view on and off by selecting *Trace>Show Separated xDEV Variances (N-Cornered Hat)* or by pressing <ctrl-h>. When the three-cornered hat view is enabled, the traces will be rendered using dashed lines. The solid traces that take their place will represent an estimate of the separate Allan deviation statistics for each individual channel, rather than the usual DUT-reference channel pairs. Figure 5 depicts the result obtained at the end of the 10-minute measurement conducted here.

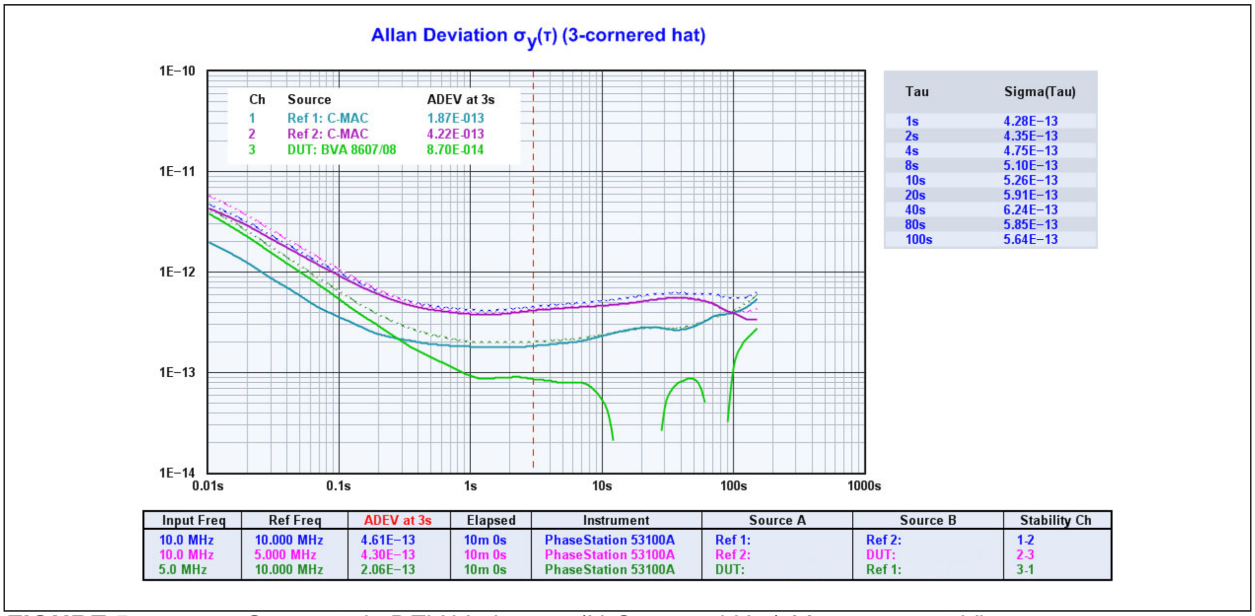

FIGURE 5: *Separated xDEV Variances (N-Cornered Hat) Measurement View.*

This is a good time to use *Legend>Select* <d> to enable appropriate columns for display in the table beneath the plot. The legend table columns are a matter of personal preference, but for three-cornered hat measurements like this one, Input (or DUT) Freq, Ref Freq, Spot Cursor, Elapsed, Source A, Source B, and Stability Ch may be particularly useful.

After using the *Legend>Select* <d> dialog to configure the legend table, you may wish to adjust the TimeLab window size by dragging the window borders. The font size can easily be adjusted as well using <Ctrl-mouse wheel> or the <( )> parentheses keys as shortcuts for *Display>Increase/Decrease Font Size*.

NOTES ON THE THREE-CORNERED HAT DISPLAY

Extensive literature has been published regarding the advantages and drawbacks of the three-cornered hat technique, so no attempt will be made to cover the subject in depth here. A good summary and bibliography appears in W. J. Riley's *Application of the 3-Cornered Hat Method to the Analysis of Frequency Stability*. Although geared towards the Stable32 application, this note is equally applicable to the calculations performed by TimeLab.

In particular, note that the three-cornered hat view in TimeLab is just that: an alternative way to view statistical traces. These traces should be regarded as estimates based on other estimates because they are derived from multiple deviation traces that have error bars of their own. In fact, portions of three-cornered hat traces often exhibit negative or degenerate variances. TimeLab will avoid rendering negative trace segments, but statistical quality will often be degraded in neighboring portions of the trace that remain visible. While three-cornered hat traces can be a valuable analysis tool, a large amount of discretion is required when interpreting them.

Bear in mind that the entries in the legend table beneath the graph still correspond to the underlying phase-difference measurements that contribute to the three-cornered hat solution, as indicated by the Source A, Source B, and Stability Ch columns (Figure 6).

Input Freq	Ref Freq	ENBW	ADEV at 0.03s	Elapsed	Instrument	Source A	Source B	Stability Ch
10.0 MHz	10.000 MHz	50 Hz	2.32E−12	10m 0s	PhaseStation 53100A	Ref 1:	Ref 2:	1-2
10.0 MHz	5.000 MHz	50 Hz	2.66E−12	10m 0s	PhaseStation 53100A	Ref 2:	DUT:	2-3
5.0 MHz	10.000 MHz	50 Hz	1.79E−12	10m 0s	PhaseStation 53100A	DUT:	Ref 1:	3-1

FIGURE 6: *Legend Table for Three-Cornered Hat Measurement.*

Because three-cornered hat traces are only an alternative way to view existing data from multiple plots, their bin contents are not exported or saved. However, the traces can be recreated at any time by reloading the original plots into TimeLab. After pressing the <Home> key to clear any existing plots, simply load the applicable files with *File>Load .TIM File* <l>, select *Measurement>Allan deviation* <a> or another statistical measurement, and use *Trace>Show Separated xDEV Variances (N-Cornered Hat)* <Ctrl-h> to enable the three-cornered hat view as described above.

Likewise, the numeric sigma(tau) chart accessed with *Display>Numeric Table* <Ctrl-n> will continue to display the deviation statistics at various taus for the entry in the legend table that's currently selected with the up/down arrow keys. If you export the deviation data for the selected trace with *File>Export ASCII xDEV Trace*, or use the mask-test feature in TimeLab, the results will also be based on the underlying DUT-reference statistics rather than the separated variances.

Important: Please note that a number of conditions must be satisfied before *Trace>Show Separated xDEV Variances (N-Cornered Hat)* <Ctrl-h> will have any effect at all. These conditions are as follows:

- One of the statistical deviation measurements (<a>, <h>, <m>, or <t>) must be selected in the Measurement menu.
- Overlay mode must be turned on with *Display>Overlay All Loaded Plots* <o>.
- The plots contributing to the separated-variance solution must all be enabled for display with *Display>Toggle Visibility of Selected Plot* <v>.
- All of the participating plots must have valid phase data records with the same sample interval (tau zero).
- The trace history must be set to 1 for all plots.
- All plots must share the same bin density value.
- Each measurement channel must contribute to at least two plots. Conversely, both the DUT and reference channel in each visible plot must appear in at least one other visible plot.

Beyond these prerequisites, here are some further guidelines for three-cornered hat plots and multichannel measurements in general:

- A key assumption behind variance separation is that the measurements must have been made concurrently. You can render three-cornered hat stability traces in TimeLab with any set of three measurements that meet the qualifications outlined above, but the results will be questionable unless they were originally captured with synchronized counters or a true multichannel instrument such as the 53100A.
- The variance separation code in TimeLab implements the generalized M-clock solution described by W. J. Riley in the note above. However, solutions for M > 3 are considered experimental and untested at the time of writing. When displaying a three-cornered hat solution, it is strongly recommended that only the three participating plots be loaded into TimeLab or enabled for visibility. Before loading or acquiring plots for display with the three-cornered hat feature, consider using *File>Close All Visible Plots* <Home> to avoid confusion.
- Particularly during the first few seconds of the measurement, TimeLab's Y-axis adjustment algorithm will attempt to accommodate the rapid appearance and disappearance of negative trace segments in three-cornered hat displays. This may result in a visually distracting effect. When this occurs, it may be helpful to left-click and drag to establish fixed graph limits with the zoom function, as no automatic axis adjustment is performed when the zoom mode is active. Keep in mind that you can left-drag slightly outside the graticule area in a desired direction to expand the graph.
- The broken traces visible in Figure 5 are the contributing ADEV traces that would be rendered with *Trace>Show Separated xDEV Variances (N-Cornered Hat)* <Ctrl-h> turned off. You can use *Trace>Toggle Trace Thickness for Current Measurement* <T> to make these traces less conspicuous in the three-cornered hat plot, or use *Trace>Show Original Traces in N-Cornered Hat Display* <F6> to toggle them on and off.
- Load-pulling effects can cause unexpected frequency excursions or drift during the first few seconds or minutes of measurements involving unbuffered crystal oscillators and other sensitive test sources. This phenomenon typically occurs when the instrument adjusts its input filters and attenuators based on the frequency and amplitude of the signal present at each input jack. To avoid this issue, the 53100A provides a high degree of load isolation at the DUT and REFERENCE active splitter inputs at the two 'N' input jacks, where the DUT and reference sources are connected during conventional two-channel measurements. However, no additional isolation is provided at the four individual SMA input jacks. One solution is to select deferred-acquisition mode with the *Acquire>Configure/Enable Deferred Acquisition* commands, allowing the measurement to run for a specified settling time before data collection begins. External isolation amplifiers and/or fixed attenuators may also be helpful.

INTERPRETING THE RESULTS

Looking back at Figure 5, the DUT's estimated Allan deviation at t=3 seconds is close to its specified value of 8E-14. The observed estimate of 8.7E-14 is within a reasonable margin of error for three-cornered hat traces in general, especially ones as short as these.

As suggested earlier, the two reference oscillators have also been nicely characterized by the three-cornered hat algorithm, thanks to the influence of the ultra-stable DUT oscillator on the solution. The reference traces can be interpreted with somewhat more confidence than the DUT's own estimate because they adhere closely to the source ADEV traces (shown with dashed lines) and do not exhibit degenerate behavior at any tau intervals.

By the end of the 10-minute measurement, the phase noise trace has converged at offsets beyond 10 Hz and looks plausible at offsets close to the carrier as well (Figure 7). It can be inspected by pressing the up-arrow key if necessary to select the first of the three plots, then selecting *Measurement>Phase Noise* <P>. The noise-floor estimate is depicted as the shaded area beneath the heavier of the two traces if the *Trace>Show Estimated Instrument Noise* <F2> option is in effect, while the thinner AM noise trace can be displayed on the same plot with the *Trace>Show AM Noise in PM View* <F8> option.

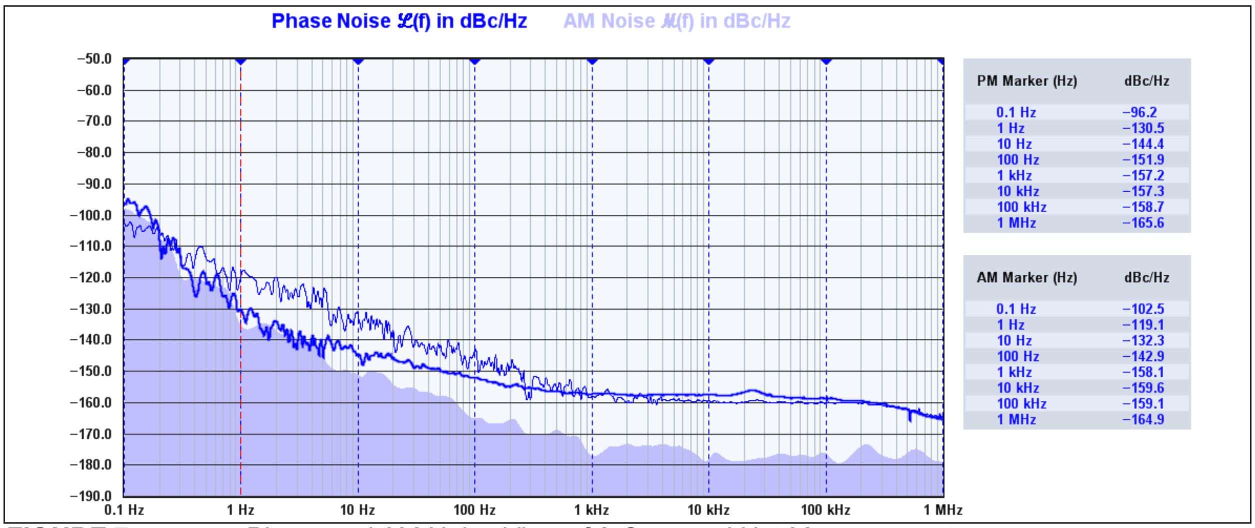

FIGURE 7: *Phase and AM Noise View of 3-Cornered Hat Measurement.*

For comparison, the DUT's phase noise specifications from the manufacturer are detailed in Table 1. Checking these values against the noise markers obtained from the measurement, we see that the DUT oscillator outperforms its specification of –130 dBc/Hz at 1 Hz while falling short by 0.6 dB at 10 Hz and 1.1 dB at 100 Hz.

TABLE 1: DUT PHASE NOISE SPECIFICATION (BW = 1 HZ)

Offset	Phase Noise (5 MHz Version)
1 Hz	–130 dBc
10 Hz	–145 dBc
100 Hz	–153 dBc
1,000 Hz	–156 dBc
10,000 Hz	–156 dBc

Once again, the discrepancies might be assumed to fall within a reasonable margin of error, particularly at 10 Hz where the phase noise trace still shows some obvious variance. To determine how much confidence is warranted in our 10-minute demonstration run, some additional data is called for.

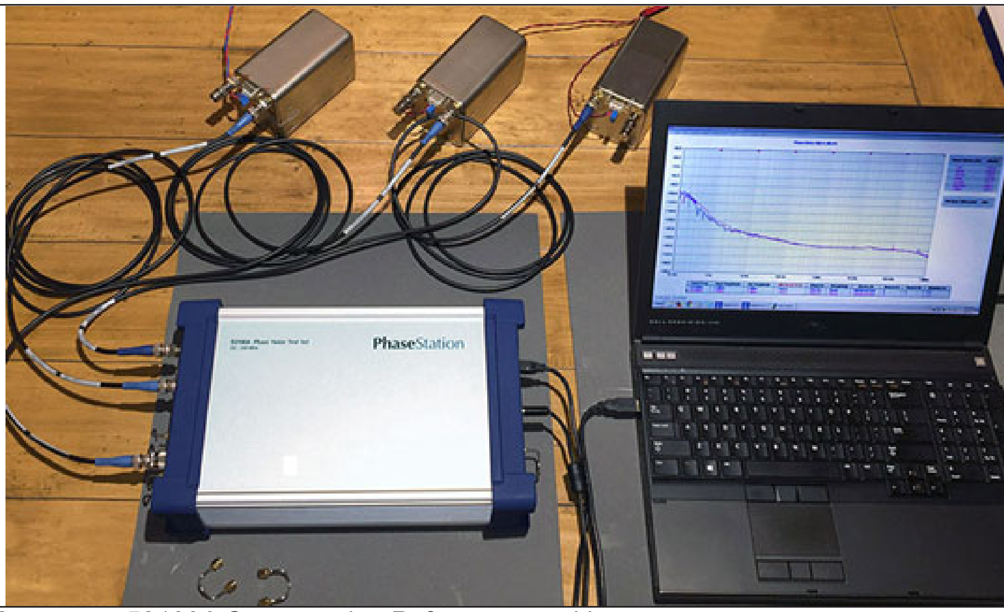

FIGURE 8: 53100A Connected to References and Laptop.

A SECOND OPINION

In Figure 8, we've set up a multichannel measurement similar to the previous one, but with two improvements geared toward increasing the confidence level. First, the reference oscillators have been replaced by two very high performance oscillators. Each oscillator is powered from its own supply as before, and all RF connections are made with double-shielded RG-223/U coaxial cable.

Additionally, the new measurement was configured to run for 8 hours rather than for only 10 minutes. The results appear below (Figure 9 and Figure 10).

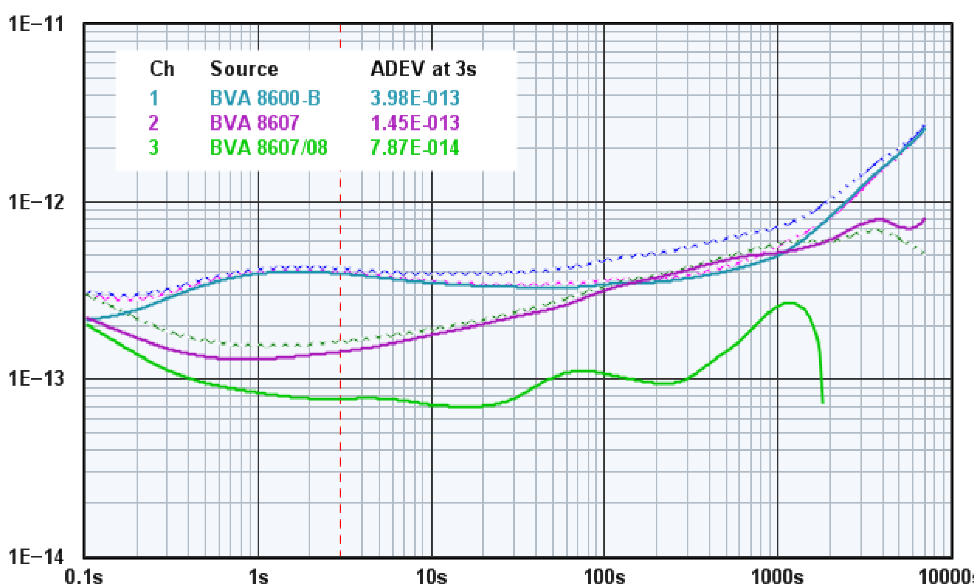

FIGURE 9: ADEV from Eight Hour, 3-Cornered Hat Test Featuring Higher Performance Reference Oscillators.

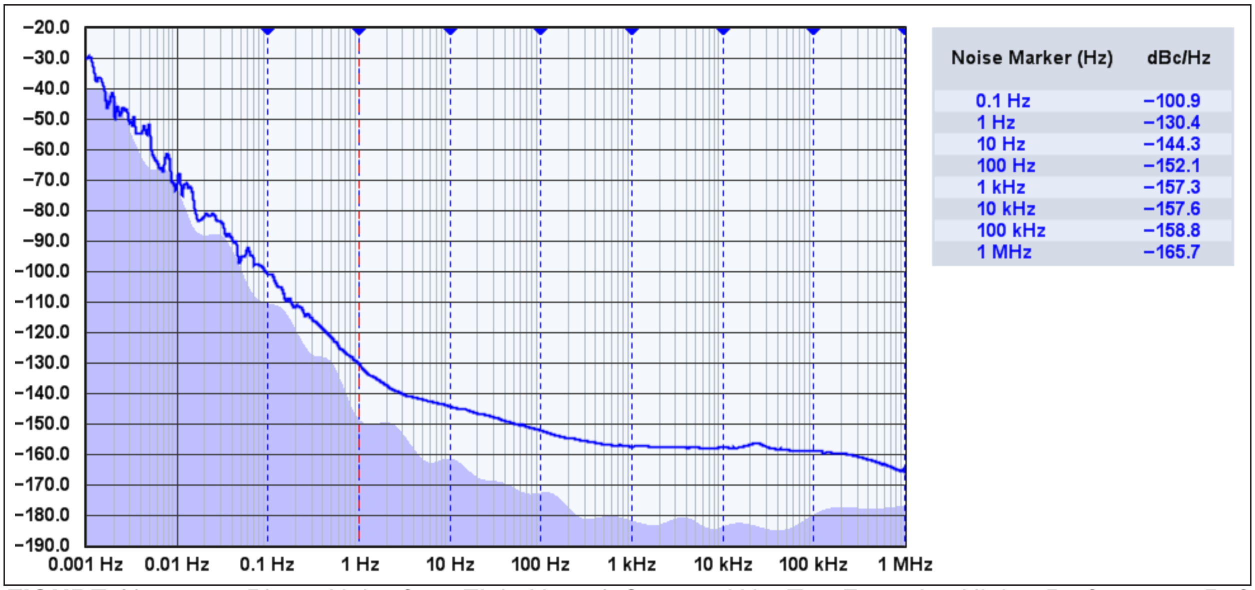

FIGURE 10: *Phase Noise from Eight Hour, 3-Cornered Hat Test Featuring Higher Performance Reference Oscillators.*

These are essentially the best measurements of the DUT that one can expect to achieve in an 8-hour test run, and they speak well of the results obtained in just 10 minutes with less exotic reference oscillators. In particular, the phase noise values at offsets of 1 Hz and above are within 0.3 dB of the earlier measurement. The agreement between this plot and the one obtained with the inferior reference oscillators shown in Figure 7 is striking.[1] Perhaps this DUT is technically out of spec at 10 Hz and 100 Hz offsets, but an extra 0.9 dB at 100 Hz on an OCXO that can reach –130 dBc/Hz at 1 Hz and 7.87E-14 at t=3s is not of much concern.

One final note of interest is that the noise floor estimate in dual-reference measurements tends to be dominated by the contribution of the reference oscillators rather than the ADCs. The shaded area in the graph above isn't just an idealized instrument floor, but a reasonably accurate indication of what can be measured with this particular pair of reference oscillators.

CONCLUSION AND ACKNOWLEDGMENTS

Following the earlier example in AN3502 in which conventional single-reference measurements were beginning to run out of headroom, we've used the 53100A to test a very high-performance double-oven oscillator at the limits of its specifications. Phase noise and frequency stability of the DUT were characterized in two separate measurements, first with a pair of good-quality DOCXOs in a 10-minute run, and once again for 8 hours, using two oscillators with specifications approaching the best parts commercially available. The results in both cases confirm the exceptional time- and frequency-domain performance of the DUT as well as the instrumentation.

Microchip Technology gratefully acknowledges Jackson Labs Technologies, Inc. and the assistance of Tom Van Baak of www.leapsecond.com in the creation of this application note.

Note 1: Enrico Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge University Press, 2009, ISBN 9780521886772, p. 160

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