

## Oscillator Measurement and Calibration with the 53100A Phase Noise Analyzer

### INTRODUCTION

Some of the most common applications for precision time and frequency instrumentation include measuring the output frequency, phase noise, and frequency stability of crystal oscillators, atomic frequency standards, and other high-performance signal sources. This application note demonstrates how to use the 53100A Phase Noise Analyzer to perform these fundamental tasks with unprecedented ease and economy, doing the work of several instruments with only one.

### MEASUREMENT GOALS

The device under test (DUT) chosen for our measurement exercise is a commercial 10 MHz double-oven crystal oscillator specified for applications that require low aging and very high temperature stability.

The typical phase noise performance numbers are shown in [Table 1](#) for the device, along with several other key specifications.

We'd like to perform the following operations on the DUT:

- Verify Phase Noise Performance ([Table 1](#))
- Verify Short-Term Allan Deviation ( $2E-12$  @  $t=1s$ )
- Verify Frequency Tuning Range ( $> \pm 2.5E-7$ )
- Calibrate Oscillator Frequency Against GPS
- Verify Warm-Up Time ( $\pm 5E-8$  within 15 minutes)



**FIGURE 1:** The Device Under Test.

**TABLE 1: PHASE NOISE PERFORMANCE**

Phase Noise, Typical (for 5 MHz)	
1 Hz	-105 dBc/Hz
10 Hz	-130 dBc/Hz
100 Hz	-145 dBc/Hz
1,000 Hz	-150 dBc/Hz
10,000 Hz	-155 dBc/Hz

### INSTRUMENT SETUP

For measurements of a single device under test (DUT) against a single user-supplied reference source, the SMA jumpers on the front of the 53100A should be connected in their factory default configuration as shown in [Figure 2](#).



**FIGURE 2:** Front Panel of the 53100A.

## CONNECTING THE DUT

The N-F jack labeled DUT on the 53100A's front panel is connected to the oscillator under test.

Because the DUT uses solder pins for both power input and 10 MHz output, some additional care is required to avoid crosstalk from incidental 10 MHz sources in the environment. Given the sensitive nature of the measurements we'll be performing, the quality of the test fixture and interconnects can be as important as that of the device itself. For example, additional RF decoupling at OCXO power input pins is sometimes needed even on devices with coaxial RF outputs.

This particular oscillator is housed in a well-shielded metal enclosure. A 10-turn potentiometer is connected to its electronic frequency control (EFC) input pin for calibration purposes. The connection to the 53100A's DUT input jack is made with double-shielded RG-400 coax.

## CONNECTING THE REFERENCE

The jack labeled REFERENCE will need to be connected to a suitable reference source, as described in the Choosing Reference Sources section of the user manual.

In this exercise, we'll use a low noise version of the Microchip GPS-3500 as a 10 MHz reference (Figure 3). The GPS-3500 is an especially good choice because both its phase noise and Allan deviation specifications are better than the performance expected from the DUT. Being GNSS-disciplined, it will also serve as a frequency standard for calibration at a level of uncertainty well below the DUT's specified aging rate.



**FIGURE 3:** Microchip GPS-3500.

As mentioned in Choosing Reference Sources, both the reference and DUT should be sinewave sources in the 1 MHz to 200 MHz range, operating at power levels between +5 dBm and +15 dBm for best results. Power levels towards the upper end of this range are preferred for high-performance noise measurements, as they will lead to faster averaging times and lower ultimate noise floors. The DUT's output level is only +7 dBm, but because the expected phase noise levels aren't close to the 53100A's performance floor, this won't be an issue. Likewise, the GPS-3500's output level of approximately +10 dBm is fine for this application.

Just like with the DUT connection, cables with good RF isolation and phase stability properties should be used to connect the reference source. Double-shielded coax, conformable or handflex cable, or other cable types with high shielding effectiveness are recommended. Crosstalk between the reference and DUT is likely to manifest itself as an unexpected low-frequency spur in the phase noise plot, while in the Allan deviation plot it may cause a periodic ripple artifact with nulls at intervals corresponding to the beat frequency. Isolation in excess of 120 dB is often needed to keep these symptoms from appearing.

## DEFINING THE TEST MASK

No specific changes to the default settings in TimeLab are necessary in this example, but you may find it helpful to define one or more limit lines for the DUT when your test requirements include pass/fail evaluation. For our example scenario, we'll define a phase noise mask for the DUT by copying the offsets and values from Table 1 into `masks.txt`. The table entries are specified for a 5 MHz part, but the DUT is a 10 MHz version with an internal doubler, so it's necessary to add 6 dB to the limits shown.

The resulting entry in `masks.txt` looks like this:

```
mask Commercial DUT phase noise (typical)
P (1, -99) (10, -124) (100, -139) (1000, -144) (10000, -149)
```

Refer to the Masks menu description in the 53100A manual for more information on using the `masks.txt` file to create and edit limit line definitions.

## WORKING WITH THE 53100A'S ACQUISITION DIALOG

After launching TimeLab, open the 53100A acquisition dialog ([Acquire>Microchip 53100A](#)). The dialog box that appears should resemble the image below (Figure 4).

**FIGURE 4:** 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.

For the initial phase noise and stability measurements in our exercise, it's unnecessary to change any of the default control settings in the acquisition dialog. Some brief observations:

- In TimeLab, the primary documentation for the Controls and Input fields in instrument acquisition dialogs is the mouseover help facility in the dialogs themselves. The help text has the advantage of being up to date with the software and driver versions that you're currently running, so it should be your first resort when encountering unfamiliar controls and features.
- It's a good idea to enter the name of the DUT and/or reference sources in the freeform Caption and Notes fields at upper left, along with any other pertinent details about the measurement. These fields can be displayed in the legend table beneath the graph by checking their corresponding boxes in the [Legend>Select](#) dialog.
- The default measurement duration of 3 minutes is a good fit for this scenario, because extremely low noise levels or long tau intervals are not involved.
- At the default measurement bandwidth setting of 50 Hz/100 points per second, the phase record will be 18,000 points in size, requiring a negligible (by modern standards) 144 KB of RAM for storage at double precision. Measurement durations up to a week or more are practical given sufficient memory, but most measurement tasks with the 53100A can be accomplished in only a few minutes.
- 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 shown earlier. Other measurement roles are discussed in additional application notes.
- The AM Noise checkbox is selected by default. Because our application example doesn't include AM noise measurement, this measurement can be unchecked if desired. Disabling measurement types that are not required can be helpful if you find that acquisitions terminate prematurely due to insufficient CPU performance.
- Along the same lines, consider unchecking Overlapped Acquisition in the Additional Options dialog if you encoun-

ter performance issues. This will have no effect on stability measurements, but it will increase the time needed to reach a given measurement floor in AM and phase noise measurements, particularly at close-in offsets. Because we don't anticipate extremely low noise levels in this example, Overlapped Acquisition can be safely unchecked if necessary with little effect on the measurement time.

- **Note:** Overlapped Acquisition provides much more efficient utilization of incoming data by the FFT routines, but requires significantly more CPU time, ultimately resulting in smoother phase noise and AM noise traces. It is turned off by default.

MEASURING PHASE NOISE

Once the desired acquisition options have been selected and configured, simply press the Start Measurement button at right to close the Acquisition dialog box and begin acquiring data. 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. The first task on our list is to verify the DUT's phase noise performance, so the following steps are recommended as a starting point.

- Select *Measurement>Phase Noise* (or simply press uppercase P).
- Optionally, select a test mask—*Masks>Commercial DUT* in this case—to display the desired phase noise limit line. You may also wish to left-click on the phase noise plot with the Shift key down to toggle noise markers at desired offsets.
- Use *Legend>Select* (d) to enable the desired columns for display in the table beneath the plot. The Legend table columns are a matter of personal preference, but Trace, Notes, DUT Freq, Ref Freq, Input Amplitude, Elapsed, and Spot Cursor are among the more common choices. If your measurement involves a test mask, you may wish to select the Mask Result and/or Mask Margin columns as well.
- After using the *Legend>Select* 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*.

In less than one minute after beginning data acquisition, the phase noise trace will have reached the 1 Hz minimum offset required to verify the performance of the DUT. Data acquisition will continue for the rest of the specified 3 minute measurement time, yielding further noise floor improvement through the cross-spectrum averaging process. The result will be a clean, low-variance plot with adequate measurement headroom at all offsets of interest (Figure 6).

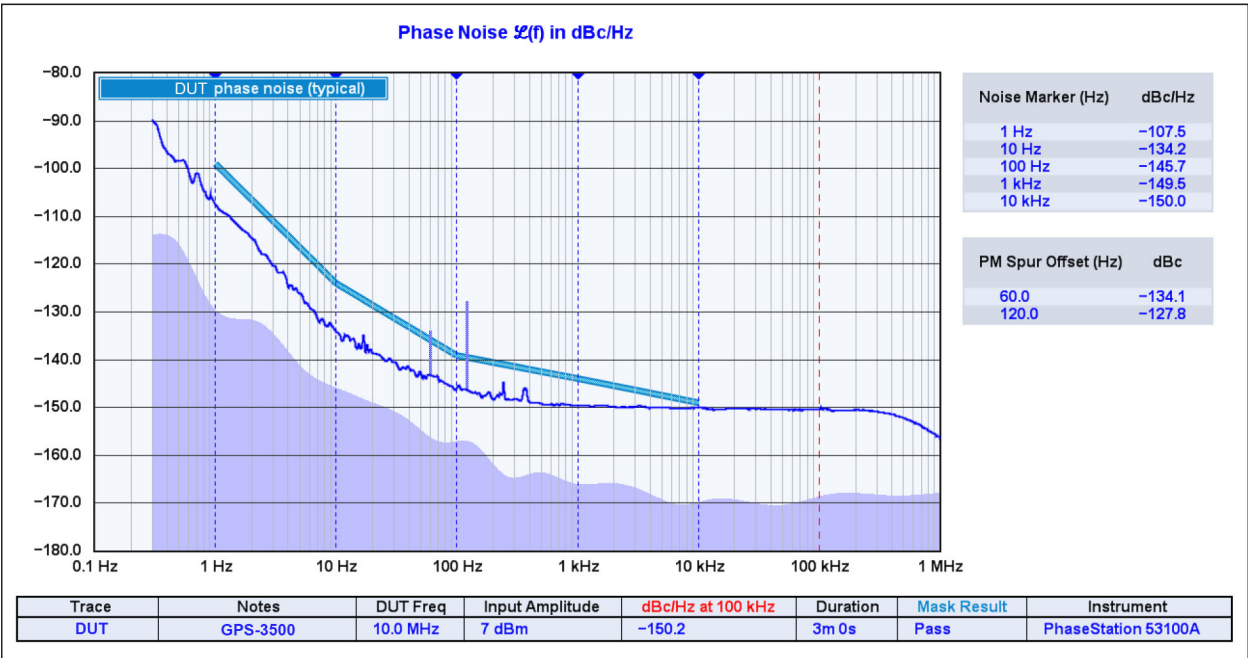


FIGURE 5: Phase Noise Trace.

Looking at the trace—and the Mask Result column in the Legend table beneath the graph area—we can see that the DUT has passed this part of the test successfully. The oscillator's white noise floor meets its specifications. No spurs except for typical low-level AC line harmonics are apparent. Because the 60 Hz and 120 Hz spurs are recognized correctly by the software, they do not result in a noise mask violation.

Interestingly, the close-in noise from this particular example is better than the specifications require. In fact, if the noise observed at 1 Hz were much lower, even the GPS-3500 with its typical noise level near  $-114$  dBc/Hz wouldn't be clean enough to characterize the DUT accurately. A dual-reference configuration may be necessary in such instances.

The 53100A's measurement floor estimate is visible in the shaded area below the trace, revealing well over 10 dB of margin at most offsets. The floor estimate can be turned off with *Trace>Show Estimated Instrument Noise* (F2) to reduce display clutter, such as when multiple saved plots are loaded into TimeLab for comparison with each other. Note that the shaded area portrays only the 53100A's own floor estimate, not the limitations of the single reference source. With dual independent reference sources, the estimate would reflect the reference-imposed floor limit as well.

In the case where DUT phase noise measurements are less than 10 dB above the reference noise level, a correction factor can be subtracted from the phase noise measurement to provide a best estimate of the phase noise of the signals.

Table 2 lists the suggested correction factors:

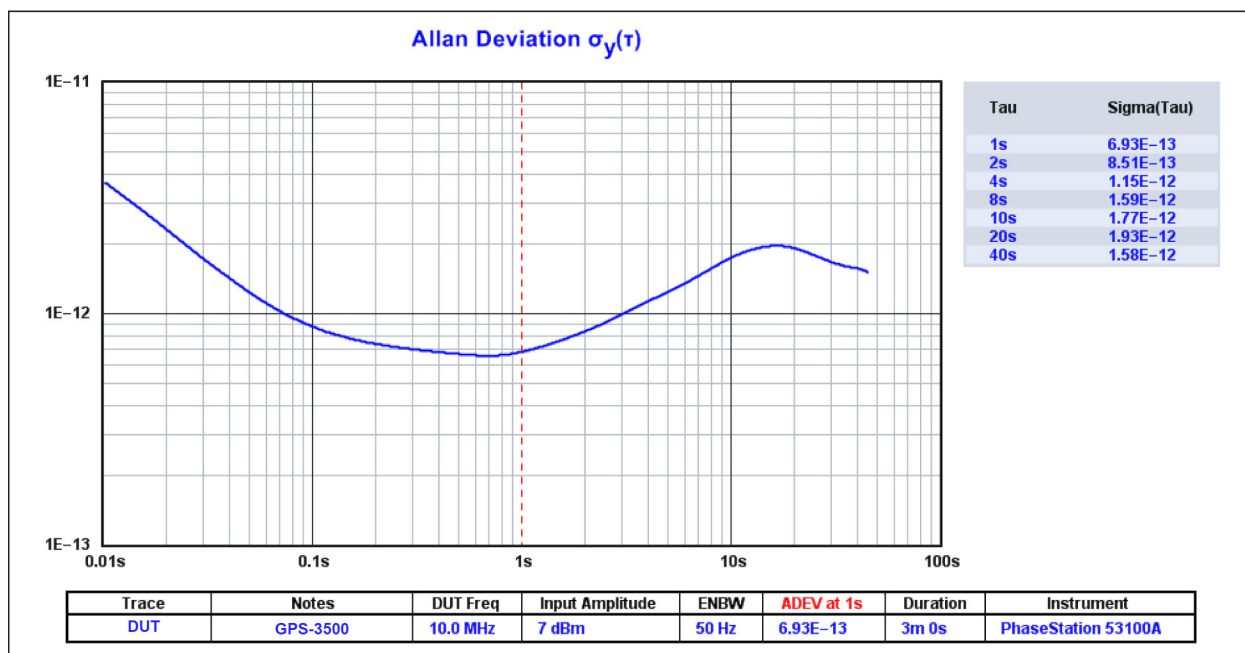
**TABLE 2: MAGNITUDE DIFFERENCE AND NOISE CORRECTION FACTOR**

Magnitude Difference (dB)	16	10	6	3	2	1	0
Noise Correction Factor (dB)	0.1	0.4	1.2	1.8	2.1	2.5	3

See the Choosing Reference Sources section of the 53100A User Guide for more details.

## MEASURING ALLAN DEVIATION

No test mask is needed for the Allan deviation plot, because the manufacturer's data sheet specifies the frequency stability at only a single tau interval ( $t=1$  second). The ADEV measurement was running behind the scenes while we were watching the phase noise display, so we'll switch over to it with a shortcut key (*Measurement>Allan Deviation*). Given the DUT's phase noise performance near 1 Hz, it's not surprising that it also meets the factory's ADEV specification of  $2E-12$  @  $t=1s$  with significant margin to spare (Figure 6).



**FIGURE 6:** Allan Deviation Measurement.

Note that the red "spot cursor" was positioned in the graph by left-clicking near the  $t=1s$  column. The corresponding ADEV value is shown in the Legend table beneath the graph. In fact, the spot cursor will be visible only if it is selected for display in the Legend table with *Legend>Select*. We could also have simply referred to the 1s entry in the chart at right.

As with the phase noise plot, the DUT's true Allan deviation at  $t=1s$  is difficult to characterize with a single reference, even a best-in-class rubidium standard such as the one employed here. In fact, looking closely at the ADEV trace, we can spot what appears to be the transition between the GPS-3500's internal loop bandwidth and the likely true performance of the DUT near  $t=0.7$  seconds.

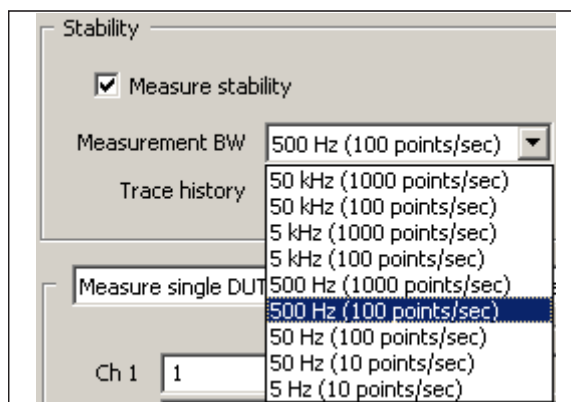
A maser would be up to the challenge—but so would a pair of GPS-3500's or other high-quality oscillators at a small fraction of the cost, thanks to the 53100A's ability to conduct separated-variance measurements with multiple references. This approach will be discussed in detail in a subsequent application note. See the User Guide for more details.

## MEASURING FREQUENCY TUNING RANGE

The tuning range of a varactor-controlled crystal oscillator or other electronically tunable source is defined as the frequency deviation achieved by varying the electronic frequency control (EFC) voltage across its specified range. For the DUT in our example, the control voltage range is 0V to +5V, corresponding to a specified frequency tuning range of  $\pm 2.5E-7$ . Converting from fractional frequency deviation to absolute terms, the expected tuning range is 10 MHz  $\pm 2.5$  Hz.

Because we've equipped the DUT with a 10-turn potentiometer connected to its electronic frequency control (EFC) input, it's easy to verify the tuning range by starting a measurement with the 53100A and switching to the Measurement>Frequency Difference (f) view, watching the plot while spinning the knob.

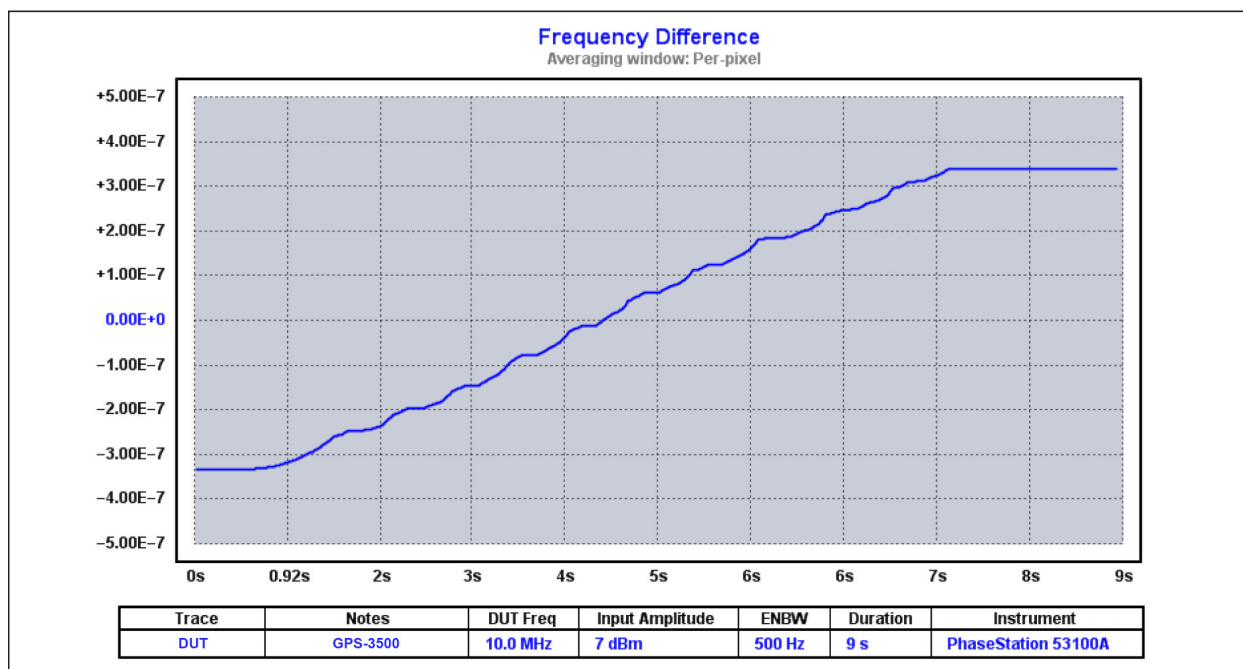
Returning to the acquisition dialog from the earlier phase noise/ADEV measurement with Acquire>Microchip 53100A, we need to widen the measurement bandwidth to support this measurement. One possible setting is shown in Figure 7. Because the 53100A is designed to measure stable sources, TimeLab reports drift warnings if either the DUT or the reference frequency varies by more than a small fraction of the measurement bandwidth, typically 10%, during the course of a measurement. By switching from the default measurement bandwidth of 50 Hz to a bandwidth of 500 Hz or higher, we'll be able to avoid these warnings even if the DUT's tuning range proves somewhat wider than specified, which is common enough in practice.



**FIGURE 7:** Measurement Bandwidth Selection.

After changing the measurement bandwidth, we can press Start Measurement to begin the measurement as before, this time followed by the f shortcut key to access the Measurement>Frequency Difference display. Once the measurement is running, adjusting the 10-turn potentiometer from its minimum setting to its maximum setting reveals that the tuning range meets the  $\pm 2.5$  Hz requirement with adequate linearity and headroom (Figure 8).





**FIGURE 8:** Frequency Difference Measurement.

Some additional points regarding this measurement:

- Rather than allowing the measurement to run for its specified 3-minute duration, the space bar (*Acquire>Stop/Repeat Acquisition*) was pressed to end the measurement early after the entire control range was swept.
- There's not much useful information to be gained from the noise and Allan deviation displays during a test of this nature. In principle, linear drift by itself appears as a slope of  $1/f^6$  on the phase noise plot, but the brief, random transients that accompany manual adjustment of the 10-turn potentiometer are likely to wreak havoc with the PM and AM noise displays. It would be reasonable to uncheck the AM Noise and Phase Noise Measurements before running the test, but it's not necessary to do so.
- Notes on correctly displaying the data correctly: The center (zero) baseline of the frequency difference trace corresponds to the frequency that's displayed in the DUT frequency field in the Legend table beneath the graph. This figure will simply be 10 MHz in this example because the frequency rounding mode associated with the Measure Single DUT with Single External Reference role is Round to nearest 0.1 MHz.
- If the oscillator frequency happens to be very close to its 10 MHz zero-error baseline when the measurement begins, it will not matter if the "z" mode is selected when viewing the frequency difference plot (*Trace>Phase/Frequency Traces Begin at Zero*). However, we can't make that assumption here. Because we're specifically checking for symmetrical tuning response around the nominal 10 MHz frequency, the "z" mode should be turned off.
- The same is true of the "r" mode (*Trace>Show Linear Phase/Frequency Residual*). We need to see the actual frequency difference plot for this test without subtracting its trend line, so the "r" mode needs to be turned off.
- It's easy to determine the absolute frequency at any given point in time along the frequency difference trace. If the frequency count chart isn't visible, press Ctrl-n (*Display>Numeric Table*) to show it. Left-click and drag to select a vertical or rectangular portion of the frequency difference trace that ends near the desired time, then hold the middle mouse button down to pan along the X axis. The frequency count chart will now show the absolute frequency at various trailing averaging times relative to the right edge of the selected region, rather than the last data point in the overall plot.
- To inspect the frequency count chart at a given time without zooming in, hold the Shift key while dragging with the left mouse button to define the selection area. The area will remain highlighted after dragging as illustrated in Figure 9.

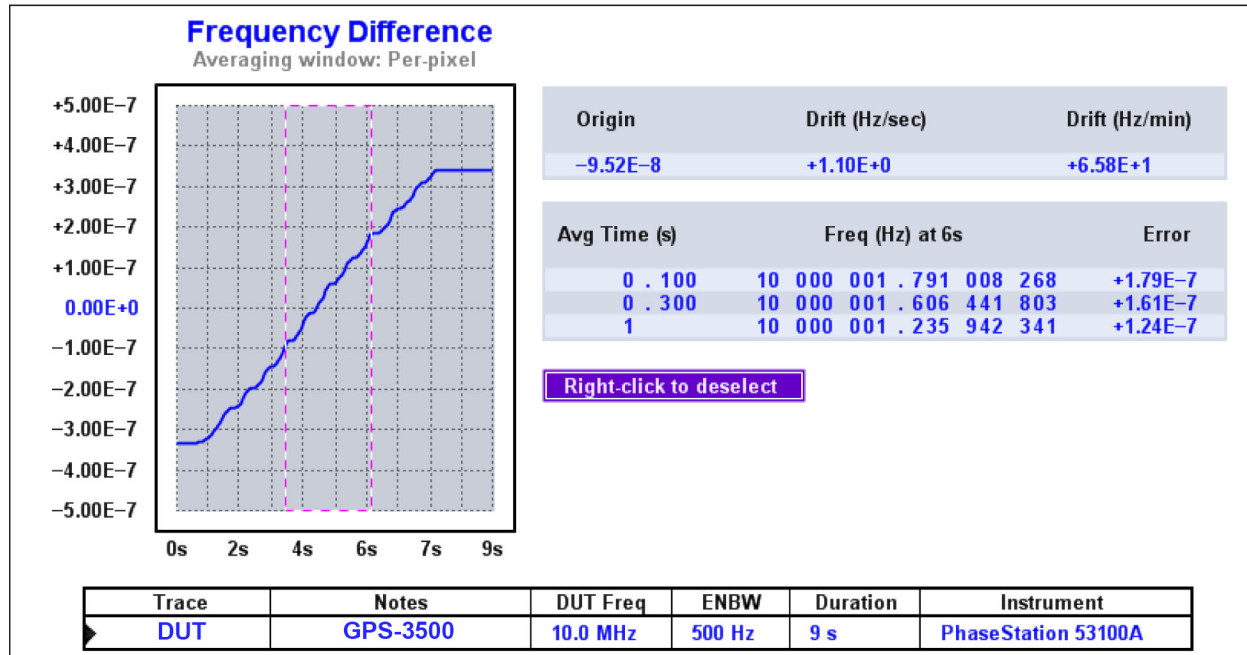


FIGURE 9: Frequency Difference Plot.

## CALIBRATING THE OUTPUT FREQUENCY

It's important to understand that the frequency measurement accuracy of the 53100A is inherited from its reference source, noting that a GNSS-disciplined reference like the GPS-3500 can be characterized and certified as a traceable calibration standard in its own right. When deployed in a calibration role, the 53100A serves as a digital phase comparator whose inherent uncertainty is superior to that of virtually any available reference source including all GNSS-disciplined standards. Equally important, the 53100A requires no adjustments to maintain its specified performance.

This step is particularly straightforward. Simply restart the previous measurement from the [Acquire>Microchip 53100A Acquisition](#) dialog and adjust the 10-turn potentiometer to bring the output frequency as close to 10 MHz as possible as shown in the [Measurement>Frequency Difference](#) display.

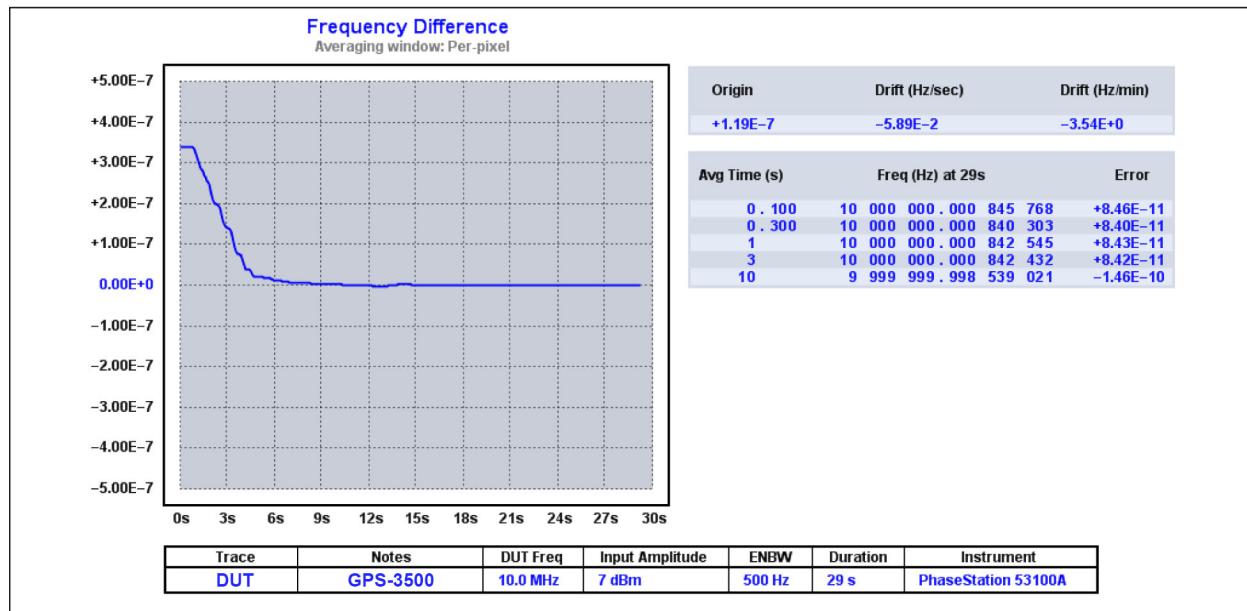


FIGURE 10: Frequency Difference Plot.



In [Figure 10](#), the DUT's output frequency has been adjusted to within approximately  $\pm 1\text{E-}10$  relative to the reference oscillator.

Note that it's often easier to adjust crystal oscillators by referring to the shorter-term averages in the frequency count chart instead of the frequency difference plot, because large tuning excursions can expand the Y axis scale to an extent that renders smaller changes hard to distinguish. If the count chart isn't visible in the Frequency Difference Measurement view, press Ctrl-n (*Display>Numeric Table*) to display it, as seen above.

As noted earlier, it's usually necessary to turn off the residual and zero-baseline modes with r and z when performing calibration adjustments with the aid of the frequency difference plot.

## OBSERVING WARMUP BEHAVIOR

After calibrating the DUT, we'll wrap up the exercise by assessing its fractional frequency deviation after 15 minutes following a cold start. At the end of this 15-minute warmup period, the frequency must be within  $\pm 5\text{E-}8$  of its calibrated value, corresponding to 0.5 Hz at 10 MHz.

With the 53100A, we can not only measure the frequency as accurately as needed at the 15-minute mark, but we can capture the oscillator's behavior during almost the entire warmup period. This measurement will tell us how long the oscillator actually took to warm up, how far off frequency it was after the first few seconds of power-on time, and how well behaved it was in general during the warmup period. Any unexpected jumps or dropouts will be easy to spot in the frequency difference trace.

**FIGURE 11:** The *Acquire>Microchip 53100A* Dialog.

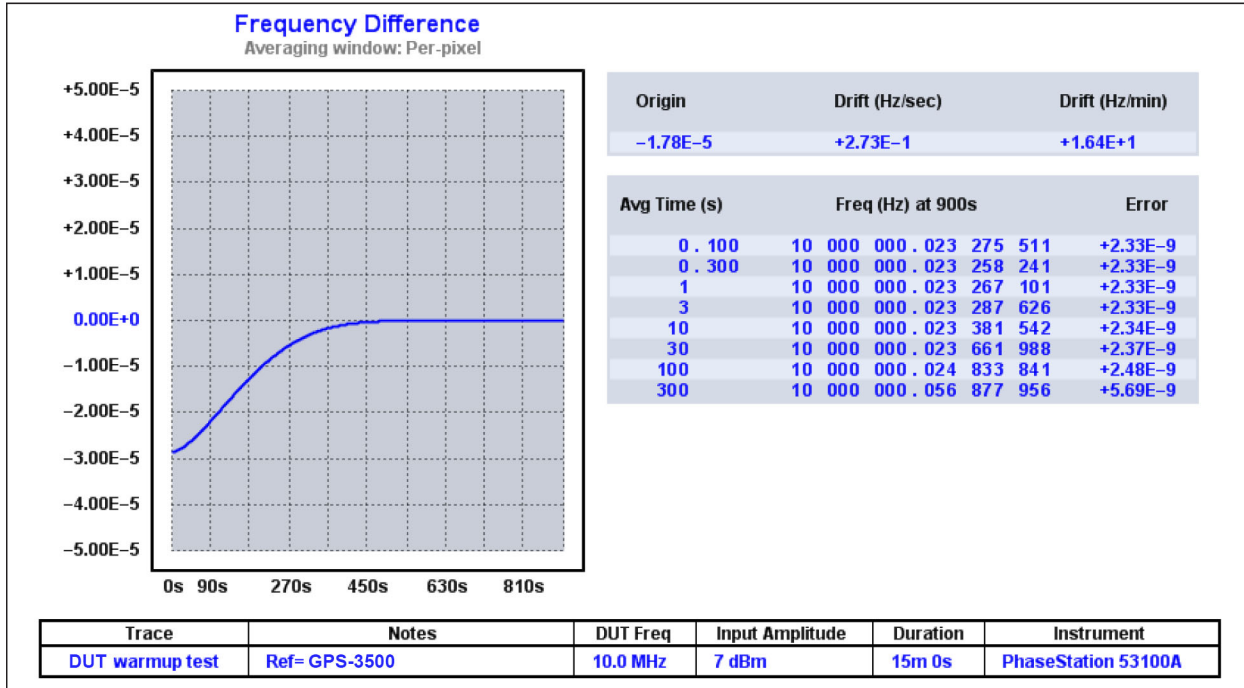
Opening up the *Acquire>Microchip 53100A* dialog once again ([Figure 11](#)), the measurement duration will need to be increased from the 3-minute default to 15 minutes as shown above. Additionally, because an OCXO's warmup drift can span hundreds of hertz, we need to select the widest available measurement bandwidth (50 kHz).

Note that increasing the measurement bandwidth to 50 kHz has some side effects. One is that the size of the phase data record would rapidly become unmanageable at the associated data rate of 100,000 points per second, so TimeLab decimates the phase data to more reasonable intervals of 100 points per second or 1000 points per second when measurement bandwidths above 500 Hz are selected. Another side effect is an increase in the noise floor for Allan deviation and other stability measurements. These properties can't be meaningfully measured during warmup or other periods of rapid nonlinear drift in any event, so this isn't a concern here. Likewise, we don't need to bother measuring the phase noise or AM noise under these conditions.

The 53100A cannot begin a measurement in the absence of a signal, so we'll need to press the Start Measurement button in the Acquisition dialog as quickly as possible after applying power to the oscillator. The resulting plot shows a fractional frequency error of less than  $+3\text{E-}9$  at the end of the 15-minute period ([Figure 12](#)).

As an aside, if the selection region appears as a box rather than two vertical columns, you may wish to press the y key (*Trace>Phase/Frequency Y Axis Unlocked in Zoom* mode) to limit the selected region to the X axis only.

The Y axis lock can be toggled before, during, or after the dragging operation. Unlocking the Y axis is often helpful when inspecting trace data in detail, but the vertical scale labels will take on arbitrary values that may be more difficult to follow as we look for the  $-5\text{E-}8$  crossing point



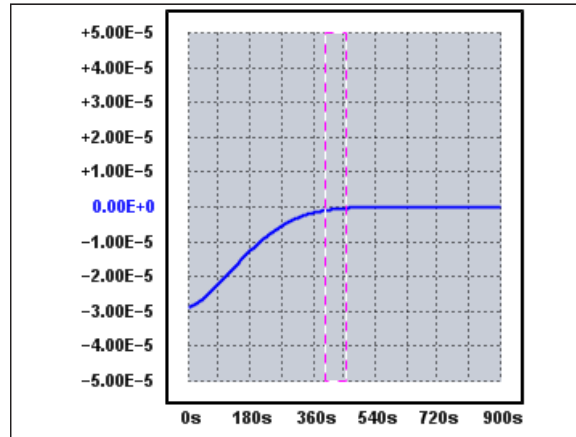
**FIGURE 12:** Warmup Period.

Once again, the *Trace>Show Linear Phase/Frequency Residual* and *Trace>Phase/Frequency Traces Begin at Zero* modes should be turned off with r and z when viewing this frequency difference plot.

## ZOOMING IN FOR A CLOSER LOOK

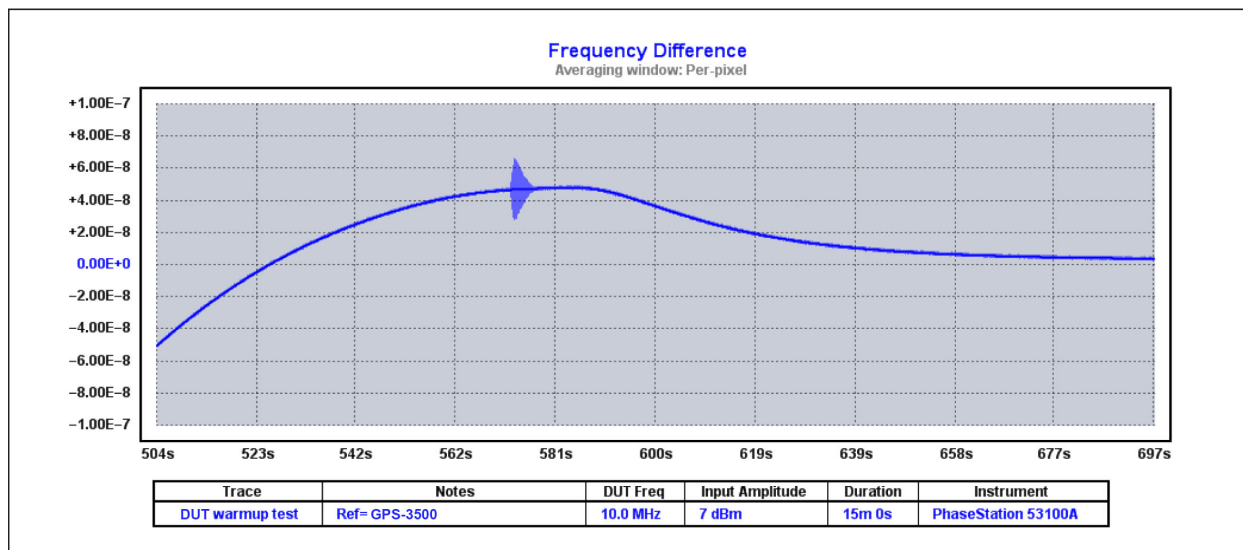
It's worthwhile to examine the DUT's behavior near the time when it first meets its warmup accuracy specification. We're looking for the point where the trace crosses -5E-8 on a plot whose Y-axis limits are 1000 times wider, so we'll need to zoom in by left-clicking and dragging to select a portion of the trace where it approaches the zero-error baseline, as shown in Figure 13.

After releasing the left mouse button, the view will zoom to the specified region between the vertical cursors shown above. It will now be possible to pan the zoomed region horizontally by dragging with the middle button, as well as to expand and contract it with the scroll wheel. Tip: you'll find that the Y axis scale is continually adjusted to accommodate the visible portion of the trace. If this behavior is undesired, you can toggle the y axis lock on and off as you manipulate the zoomed area with the middle button and wheel.



**FIGURE 13:** Zoom Selection.

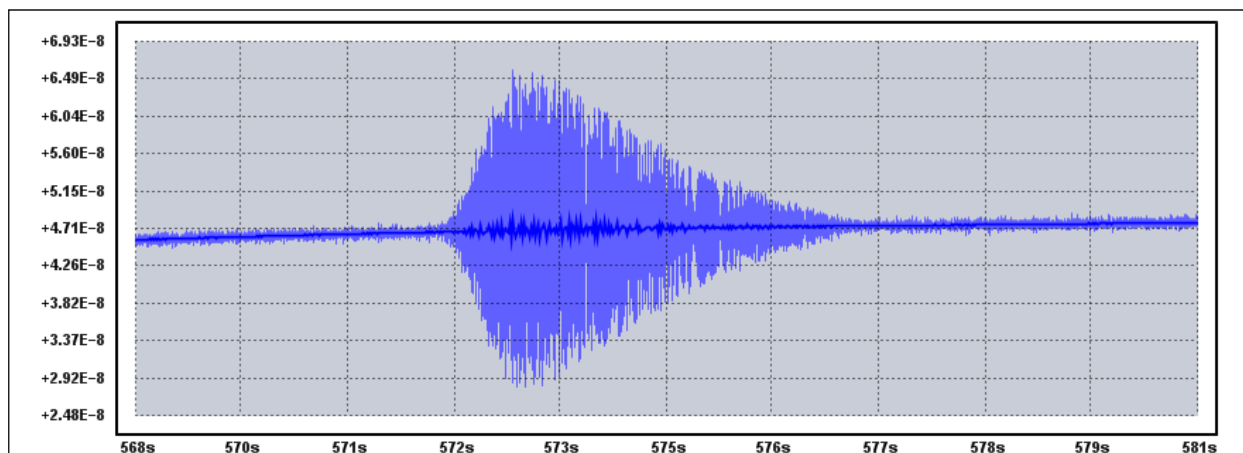
In this case, we find that the trace crosses the -5E-8 threshold about eight minutes into the 15-minute warmup period (Figure 14).



**FIGURE 14:** *Unusual Transient Noise Burst.*

Not long afterward, just before  $t+10$  minutes, the oscillator's oven controller cuts back and begins settling toward its steady-state temperature.

Also visible in Figure 14 above is an unusual burst of transient noise or instability that lasts for several seconds. The glitch occurs just before the oven temperature reaches its peak, possibly as a consequence of thermal stress. We can expand and recenter the view for a closer look with the middle button and wheel. Unlocking the Y axis with the y keyboard shortcut expands the artifact vertically as well, as shown in Figure 15.



**FIGURE 15:** *Zoomed Noise Burst.*

Although this transient causes the DUT to temporarily exceed its  $\pm 5E-8$  warmup error threshold, the oscillator quickly returns to its expected behavior. Careful inspection of the rest of the 15-minute trace shows that the phenomenon does not recur.

## CONCLUSION

Using the 53100A, we've tested a high-performance double-oven oscillator at the limits of its specifications and beyond. Phase noise, frequency stability, tuning range, warmup time, and transient behavior have been characterized accurately and precisely, while minimizing the investment in setup time, additional equipment, and operator training traditionally associated with these measurements. The 53100A's role in precision frequency calibration has also been demonstrated.

In addition to introducing the 53100A's hardware capabilities, this application note has also served as a brief introduction to the TimeLab software application. If you've followed this tutorial before looking over the chapter in the manual entitled Making Your First Measurements, that chapter is recommended as a next step.

NOTES:

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