

## Errata

**Document Title:** Analyzing Phase-Locked Loop Capture and Tracking Range  
(AN 358-13)

**Part Number:** 5952-8007

**Revision Date:** October 1990

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### HP References in this Application Note

This application note may contain references to HP or Hewlett-Packard. Please note that Hewlett-Packard's former test and measurement, semiconductor products and chemical analysis businesses are now part of Agilent Technologies. We have made no changes to this application note copy. The HP XXXX referred to in this document is now the Agilent XXXX. For example, model number HP8648A is now model number Agilent 8648A.

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## Application Note 358-13

# Analyzing Phase-Locked Loop Capture and Tracking Range

### Description

Phase-Locked Loops (PLL) are common yet essential circuits in many electronic applications. They may be used as narrowband filters to recover signals embedded in noise, or for synchronizing digital transmissions in communication applications. Other traditional uses include frequency synthesizers, demodulators, multipliers and dividers.

A typical loop consists of a phase detector, low-pass filter, voltage controlled oscillator (VCO) and frequency divider (see Figure 1).

### Problem

The analysis of PLLs is challenging. Components can be analyzed individually, but closed loop characterization is often difficult to obtain.

Both transient response and dynamic frequency response are of interest to the analog designer. Ideally, PLL behavior should be characterized under normal operating conditions.

This application note will address methods for analyzing the capture and tracking range of a PLL using the HP 5372A Frequency and Time Interval Analyzer.

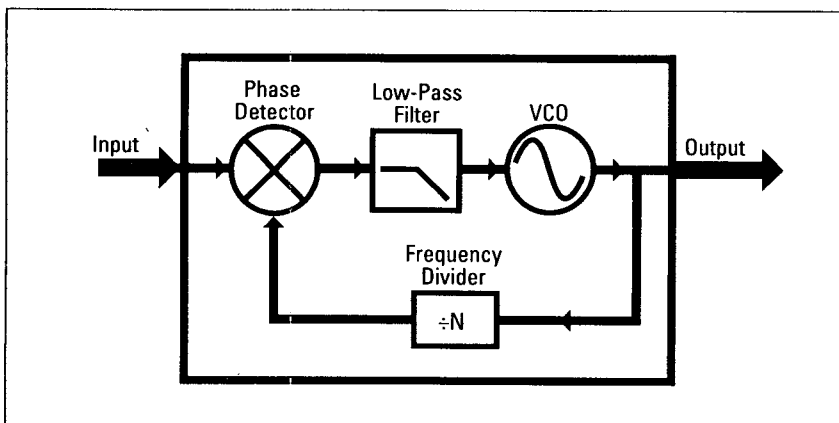
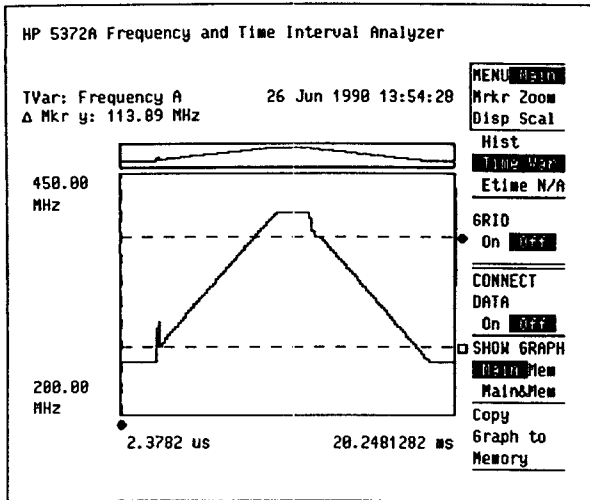


Figure 1. Typical phase-locked loop block diagram.



*Figure 2.  
This HP 5372A  
plot of frequency  
vs. time shows  
the capture and  
tracking range  
measurement  
of a PLL.*

## Solution

The HP 5372A Frequency and Time Interval Analyzer makes back-to-back frequency or phase measurements as often as every 75 ns. Up to 8191 continuous measurements can be stored in internal memory and shown on the display. Using the HP 5372A's built-in analysis features and flexible measurement arming, it is easy to capture and analyze the transient characteristics of a PLL.

Figure 2 shows a typical plot of a frequency vs. time display showing the capture range of a PLL.

This note describes how to set up and measure the following PLL characteristics:

**Capture Range** - The frequency range over which the PLL can acquire lock.

**Tracking Range** - The frequency range over which the PLL can maintain lock. Usually greater than or equal to the capture range.

- *View Phase-Locked Loop capture and tracking range*
- *Analyze capture transients*
- *Make high resolution time and phase measurements (200 ps or < 1 degree @ 10 MHz)*
- *Make measurements without a coherent reference*

## Measurement Considerations

The PLL used in this note is part of a frequency synthesizer. The synthesizer can be set in 100 kHz increments from 250 MHz to 410 MHz. The output frequency is fed back through programmable dividers to one input of the phase detector. The other input is a 100 kHz reference (obtained by dividing an accurate 10 MHz crystal reference by 100). The amplified and filtered output of the phase detector provides a signal that changes the frequency of the VCO, forming a feedback system. The feedback forces the VCO frequency to change such that the frequency out of the dividers is phase locked to the 100 kHz reference. See figure 3.

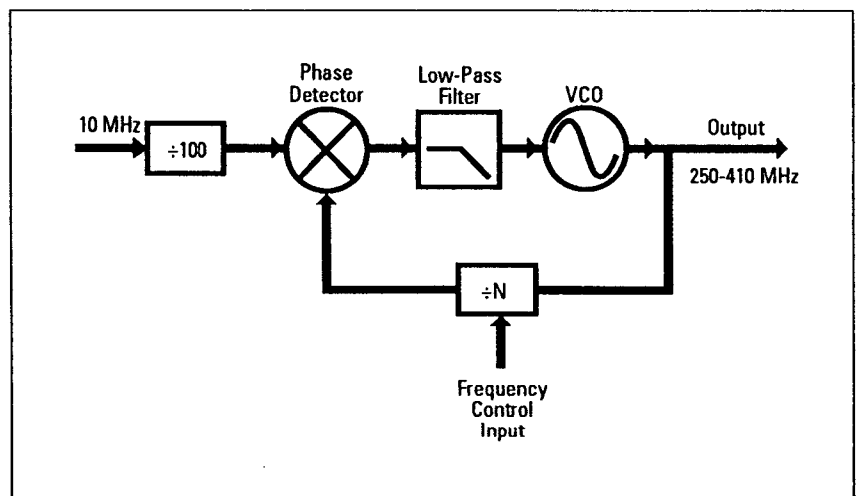


Figure 3. Synthesizer Block Diagram.

To make capture and tracking measurements, the PLL must be forced in and out of lock. This can be accomplished in a variety of ways. In this particular PLL, varying the 10 MHz reference is the easiest way to force the PLL in or out of lock. Performing the tests this way is as valid as changing the VCO frequency and holding the reference constant.

An equipment setup for measuring PLL capture and tracking parameters is shown in Figure 4. The measurements shown here are made by programming the synthesizer to 300 MHz and sweeping the reference frequency linearly from 7 MHz to 14 MHz and back to 7 MHz (sweeping from 7 to 14 MHz forces the loop out of lock). The period of the sweep is 20 ms. It is very important to use a sweep time that is slow enough to eliminate capture transient effects.

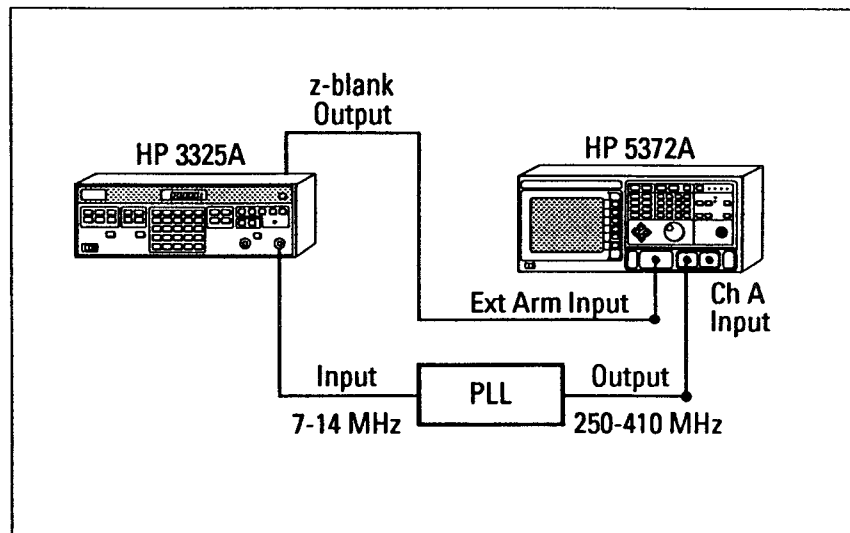


Figure 4. Block diagram of example PLL setup.

The HP 3325A Synthesizer is used as the frequency reference and is connected to the input of the PLL. The output of the PLL is connected to the Channel A input of the HP 5372A. A 1 M $\Omega$  input pod (HP 54003A) is used to minimize the effects of loading the circuit. In order to synchronize the start of the measurement with the start of the HP 3325A sweep, a trigger signal must be available. For the HP 3325A the Z-blank output from its rear panel coincides with the start of the sweep. It is connected to the External Arm input of the HP 5372A. This will be discussed in more detail in the **Measurement Setup** part of this note.

### Measuring PLL Capture and Lock Range

To measure the capture and tracking range of this particular PLL, the output frequency will be programmed to 300 MHz. As the input reference is varied from 7 to 14 MHz, the output frequency, due to the nature of the PLL response, will change in an attempt to stay in phase with the reference. The frequency vs. time plot in Figure 5 illustrates the PLL response.

Starting from the left of Figure 5, you can see that the PLL is not following the input signal, so is out of lock. The input frequency here is less than 7 MHz. As the HP 3325A frequency increases from 7 MHz, the PLL acquires lock at 270 MHz and starts to track the changing input frequency. Where the PLL acquires lock is called the lower capture frequency. As the frequency increases further, the PLL tracks, and then finally loses lock, at 410 MHz. This is at the flat spot on the graph. Where the PLL loses lock is the upper frequency of the tracking range. The HP 3325A frequency will finally start to decrease and the PLL will lock again, at 400 MHz. This point represents the upper frequency of the capture range. As the input frequency continues to decrease, the PLL tracks, and then finally loses lock, at 260 MHz. Where it loses lock again represents the lower limit of the tracking range. Note that from a single display, you can easily determine the PLL capture and tracking range.

Figure 5 shows where the HP 5372A markers must be placed to measure the capture range.

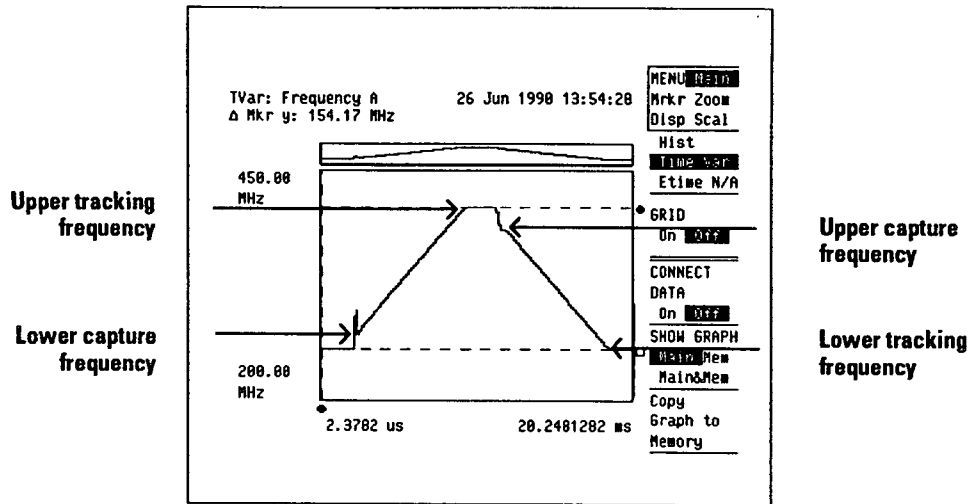


Figure 5. Measuring the PLL capture range.

Figure 6 shows where the HP 5372A markers must be placed to measure the tracking range.

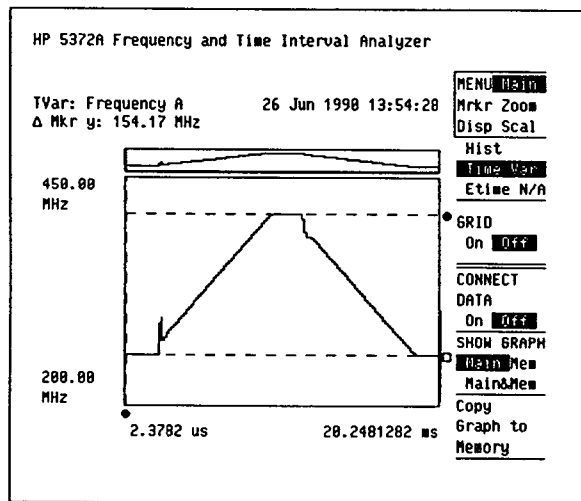


Figure 6. Measuring the PLL tracking range.

Before setting up the measurement, a few things must be considered

**1) What is the total measurement time?**

For this type of measurement, the measurement time is set by the period of the sweep of the reference frequency. For this example, the total measurement time was about 20 ms.

**Total Measurement Time = Period of Reference Sweep**

## 2) How many measurements and at what sample interval?

The total measurement time is a function of the number of measurements and the length or sample interval of each measurement. The HP 5372A can make up to 8191 measurements with a sample interval as short as 100 ns per measurement.

**Total Measurement Time = Number of Measurements x Sample Interval**

To obtain the best horizontal (or time) resolution, you would set the sample interval to 100 ns. To get the best frequency resolution (see below), you would increase the sample interval. The maximum interval is 8 seconds. After selecting an appropriate sample interval, and knowing the total measurement time, you can calculate the number of measurements. If the number is greater than 8191, then the sample interval must be increased.

## 3) What frequency resolution is required?

The frequency resolution is defined by the following formula:

**Resolution (Hz) =  $\pm$  ((150 ps) + (1.4 x Trigger Error))/Sample Interval x Frequency**

For the synthesizer used here, we know it steps in 100 kHz increments. Using the rule of thumb that the resolution of the measurement should be 10 times the desired result, you can solve this equation for the sample interval. Unless your signal is very noisy, or has a low slew rate, you can ignore the trigger error. Remember, the frequency being measured in this example is 300 MHz. For more information on resolution, refer to the HP 5372A Technical Data sheet (Publication number 5952-7997) page 16.

**Sample Interval =  $150 \times 10^{-12} \times 300 \times 10^6 / 10,000 = 4.5 \mu\text{s}$**

Plugging in 4.5 us into the total time equation, you can determine the number of measurements:

**Num of Meas = 20 ms / 4.5  $\mu\text{s}$  = 4444 meas.**

To make sure you capture all of the data, round the number of measurements up to 4500.

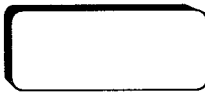
Now you are ready to set up the HP 5372A.

# Measurement Setup

## 1. Preset

Start the setup process by pressing the green **Preset** hardkey. Preset puts the HP 5372A into its default state and brings up the **FUNCTION** menu. It is good practice to preset the HP 5372A when beginning a new measurement setup. Next, put the instrument into the single measurement mode. In single measurement mode the HP 5372A acquires one block of data and then stops the acquisition process. Enable the single mode by pressing the **Single/Repet** key. The LED next to this key should be illuminated. Now, whenever you want to start a new measurement, just press the **Restart** key.

## Function Menu



## 2. Select the Measurement Function

To move around in any of the menus, you will move a highlighted cursor using the arrow keys. The arrow keys are located to the right of the CRT in the area labelled **CURSOR/SCROLL**. To change the value of a field, move the cursor and highlight the desired field. The choices for that field will then be visible in the softkey menu at the right edge of the CRT. For this PLL measurement, you will be measuring the frequency on channel A. Use the arrow keys to move the cursor to the **Measurement** field. At the right of the CRT you will see a list of measurements. Press the softkey next to **Frequency**. Move the cursor to the **Channel** field and select **A**. Figure 7 shows the Function menu at this point.

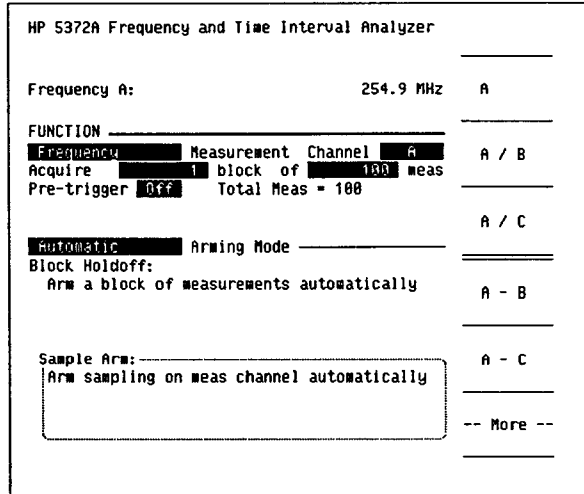


Figure 7. Function Menu.

## 3. Select the Number of Measurements and Arming Mode

From the discussion on page 6, you know that 4500 measurements are required to measure the PLL. Move the cursor to the **meas** field and enter 4500. Do this by typing **4500** from the numeric keypad and then pressing the **Enter** hardkey. Whenever a numeric value is changed using the keypad, make sure you press the **Enter** key or the softkey unit terminators.



The HP 5372A provides a number of arming modes which allow you to control how and when the HP 5372A starts and stops taking data. You can specify when a block of measurements begins as a holdoff condition, and how often measurements are acquired within a block by sampling.

In this note, Edge/Interval arming is used. This means that the HP 5372A will begin to gather data at the first edge following an edge on the External Arm input. It will use a specified interval for each measurement. The measurement process stops when the specified number of samples (in this case 4500) are collected.

For this measurement, the HP 5372A will wait until the HP 3325A starts a sweep, which is indicated by a negative edge from the Z-blank output of the HP 3325A. The Z-blank output is connected to the HP 5372A External Arm input. Once the sweep starts, the HP 5372A will make a frequency measurement every 4.5  $\mu$ s.

Move the cursor to the Arming Mode field. Press the topmost softkey until **Hld/Samp** is highlighted. Next, you will set up the condition for the External Arm signal. Press the softkey labelled **Edge/Interval**. This means holdoff (Hld) using a specified signal **Edge** and sample (Samp) on specific **Intervals**. Move the cursor to the edge field and select the **Neg** edge. Move the cursor to the next field and select **Ext Arm**.

Select the sample interval by moving the cursor to the sample arm field and enter 4.5  $\mu$ s. Do this by entering 4.5 from the keypad and pressing the  $\mu$ s softkey. This sets the HP 5372A to make a frequency measurement every 4.5  $\mu$ s. It is analogous to the gate time found in conventional frequency counters, except that the measurements are back-to-back and continuous.

This completes the setup for the FUNCTION menu. No other fields in this menu need to be modified. See Figure 8 for the completed menu.

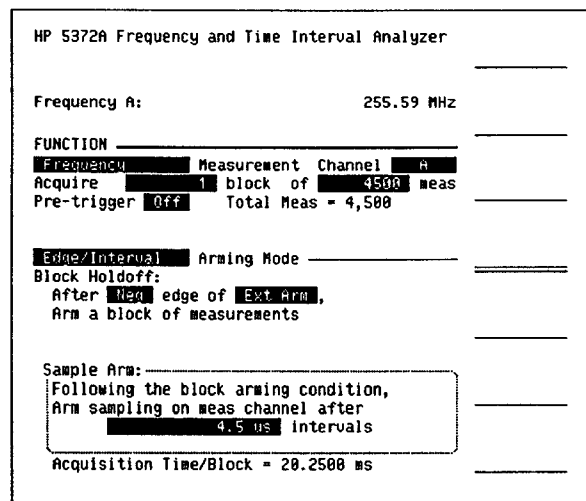


Figure 8. The completed Function Menu.

## Input Menu



The HP 5372A records the time of “threshold level crossings” on the input channel. For example a threshold level may be 0.0 volts on a rising edge. The threshold level is set up in the INPUT menu. Press the **Input** hardkey. Move the cursor to the Input Channels field and select **Separate** input channels to keep the input channels independent. For this measurement, only channel A and the External Arm input must be modified. Move the cursor to the Chan A field and enter respectively, **Pos**, **Manual**, and **30 mV**. Pos slope sets the channel to measure a positive (rising) edge. Manual mode instructs the HP 5372A to use a trigger level voltage entered by the user, in this case 30 mV. 30 mV was used here because the signal had some noise around 0 volts. The HP 5372A also has the ability to automatically determine the trigger level. However, the input frequency must be between 1 kHz and 200 MHz. In this example, the frequency is above 200 MHz.

The External Arm signal conditions must also be set. Move the cursor to the Ext Arm Level input. The signal from the HP 3325A is a TTL level. Press the softkey labelled **TTL Preset**.

Nothing else in this menu needs to be changed. However, if the input signal were very noisy, the Hysteresis on channel A could be changed from **Min** to **Max**. Figure 9 shows the input menu.

HP 5372A Frequency and Time Interval Analyzer			
Frequency A:	255.60 MHz	0 V	
<b>INPUT</b>			
<b>Separate</b>	Input Channels		TTL Preset
Trigger Event:			[ 1.4 V ]
	Slope	Mode	Level
Chan A:	Pos	Manual	30 mV
Chan B:	Pos	Auto	50 % = 0 V
Chan C:	POS	MANUAL	0 V
Ext Arm Level			1.40 V
	Channel A	Channel B	Channel C
Input Pod	HP 54003A	HP 54002A	----
Impedance	1 M $\Omega$	50 $\Omega$	50 $\Omega$
Bias Level	GND	GND	GND
Attenuation	1:1	1:1	0 %
Hysteresis	Min	Min	----
Max Input	2 V peak	2 V peak	+20 dBm

Figure 9. The Input Menu.

## Instrument State

This completes the setup for a PLL capture and tracking range measurement. To save this setup in the HP 5372A non-volatile storage memory, press the **Save** hardkey and then **1**. If the HP 5372A CRT displays a message indicating that the register is write protected, press the **Inst State** hardkey and either select a register that is not protected or turn off the protection and press **Save** and then **1** again. To recall this setup at a later time, press **Recall** and then **1**.

## Measurement Results

### Graphic Results



Press the **Restart** hardkey to acquire a new block of measurements.

To see the PLL results, press the **Graphic** hardkey. The first time you enter graphics, the HP 5372A may display a histogram. A histogram is not particularly useful for this measurement. For PLL measurements, use the frequency vs. time graph to examine the data. Press the top softkey until **Main** is highlighted. Press the second softkey from the top until **Time Var** is highlighted. You should now see a frequency vs. time display. From this display, you will be able to determine the capture and tracking range of the PLL. Figure 10 shows the display.

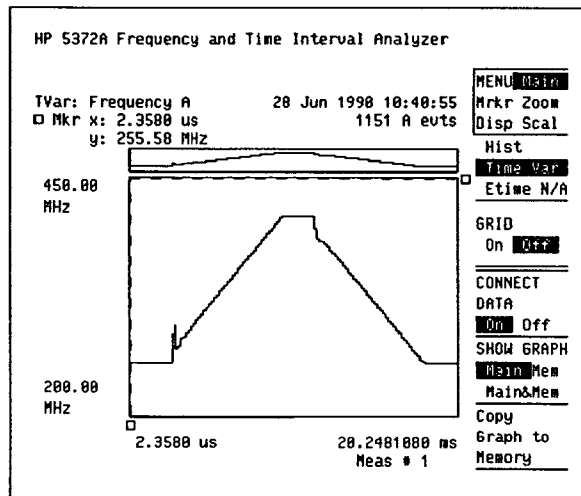


Figure 10. PLL capture and tracking range measurement.

Notice that the display has two graphs. The smaller rectangle above the main graph is the panorama display. It always displays all of the data collected. When the main graph is zoomed in, a thick underline will appear beneath the panorama, indicating which part of the data is being viewed.

The topmost softkey controls the selection of the graphics menus. There are five different choices. Press this softkey five times to review the menu options.

You may find the display is easier to interpret when the data is connected. Press the **CONNECT DATA** softkey until **On** is highlighted. This simply draws a line between adjacent data points.

#### 1. Using the HP 5372A Markers

Capture and tracking range can be determined using the display markers. The HP 5372A has four markers. There are two markers that move along the time axis. They are indicated as  $\leftrightarrow \square$  and  $\leftrightarrow \bullet$ .

The other two markers move along the frequency axis and are indicated by  $\uparrow\square$  and  $\uparrow\bullet$ . Note that the arrows indicate the direction the markers move on the display. Only one of the markers can be moved at a time, but all four are visible on the display. The markers are moved by turning the knob.

To get to the marker menu, press the **MENU** softkey until **Mrkr** is highlighted. The softkeys now show the marker options. By pressing the key labelled **More**, additional marker options are displayed.

To measure the capture range, you will use the  $\uparrow$  markers. Press the **MARKER ORIENT** softkey to activate the  $\uparrow$  markers. Turn the knob to move the  $\uparrow\square$  marker to where the PLL attains lock as the frequency increases. As you turn the knob, the marker value is displayed in the upper left corner of the main display. Figure 11 shows the marker positioned at the lower PLL capture frequency, in this case 279.17 MHz.

$\uparrow\square$  marker shows lower capture frequency

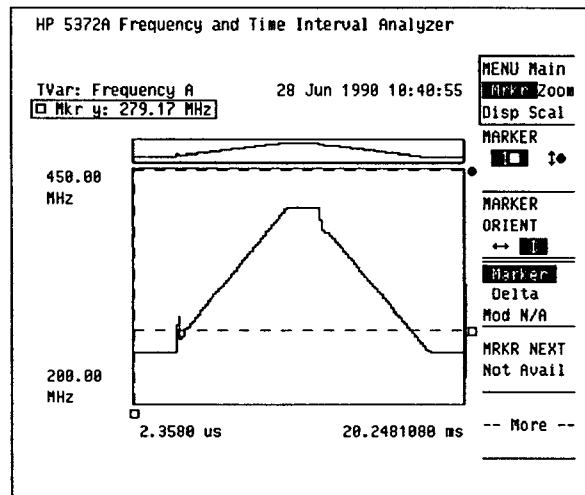


Figure 11. Lower capture frequency.

You will use the other horizontal marker to determine the upper capture frequency. Press the **MARKER** softkey to activate the  $\uparrow\bullet$  marker. Move it to where the PLL attains lock when moving from a higher to lower frequency. Figure 12 shows the marker placed at the higher capture frequency, in this case, 383.33 MHz. Notice that the value displayed in the upper left corner has the appropriate symbol to identify the marker that is currently active.

● y marker shows upper capture frequency

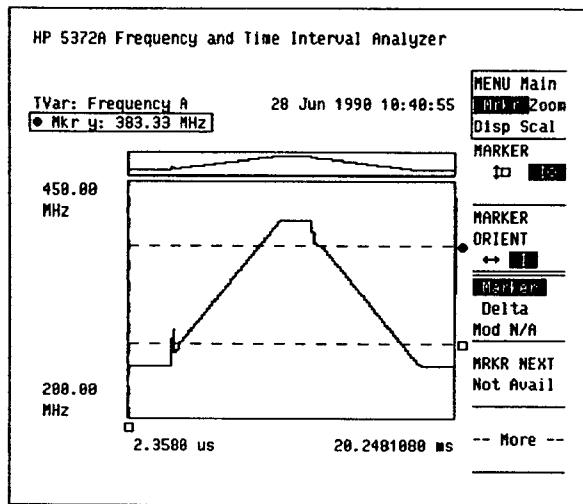


Figure 12. Upper capture frequency.

To determine the capture range, find the difference between the two markers. This is done by using the delta marker feature. Press the fourth softkey from the top until **Delta** is highlighted. The delta frequency is displayed in the upper left corner of the main display. Figure 13 shows the delta frequency measurement. For this PLL, the capture range is 104.17 MHz.

Delta marker shows capture range

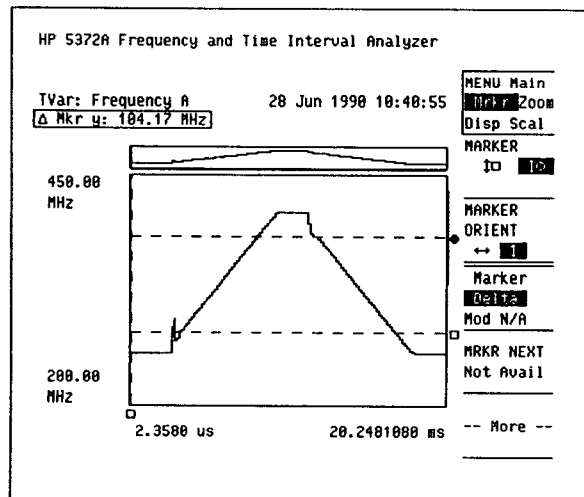


Figure 13. PLL capture range.

To determine the tracking range, the markers need to be repositioned. Press the fourth key from the top until **Marker** is highlighted. Now the value in the upper left of the display shows the marker value, and not delta marker value. Turn the knob to move the **●** marker to where the PLL loses lock due to an increase in frequency. Figure 14 shows the upper tracking frequency of 409.72 MHz.

● y marker  
shows upper  
tracking frequency

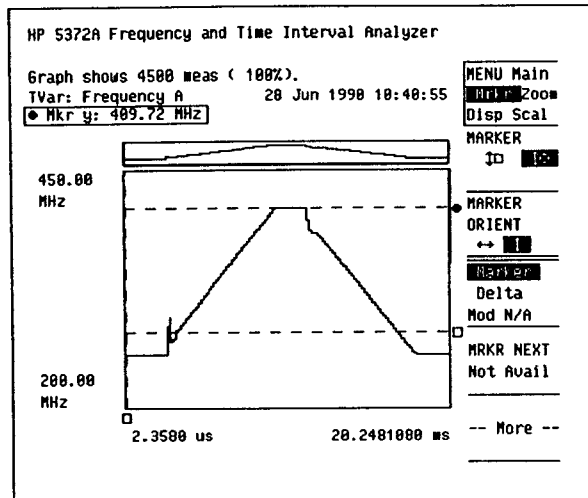


Figure 14. Upper tracking frequency.

Use the other marker to find the lower tracking frequency. Press the **MARKER** softkey to select the  $\square$  marker. Move it to where the PLL loses lock due to a decrease in frequency. Figure 15 shows the marker positioned at the lower lock limit of 255.56 MHz.

Another way to position the markers at the limits of a waveform is to use the **Move [●] Marker to Maximum** and **Move [●] Marker to Minimum** features. Press the **More** softkey to see the menu containing these softkeys. Press the **More** softkey to return to the original marker menu.

□ y marker  
shows lower  
tracking frequency

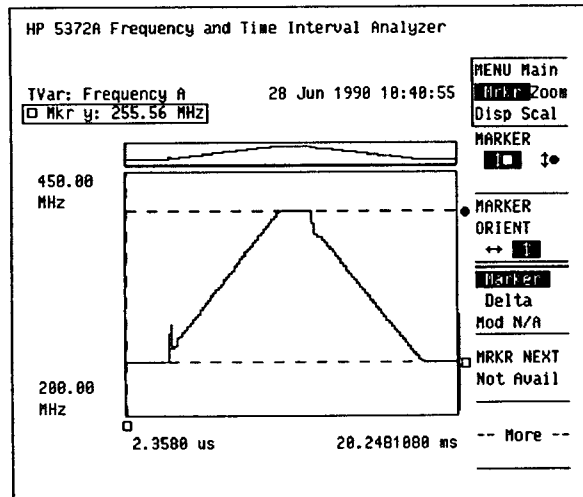


Figure 15. Lower tracking frequency.

To determine the tracking range, find the difference between the two markers. This is done by using the delta marker feature. Press the fourth softkey from the top until **Delta** is highlighted. Figure 16 shows the delta frequency measurement. For this PLL, the tracking range is 154.17 MHz.

Delta marker shows PLL tracking range

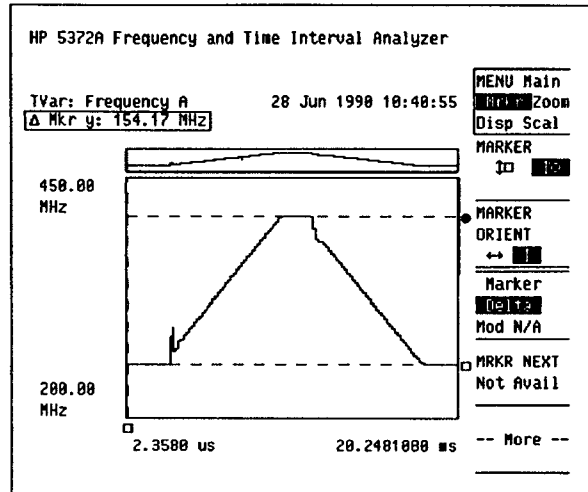


Figure 16. PLL tracking range.

### 3. Zooming in on the Display

By zooming in on the display, more detail about PLL transients can be observed. Before going to the zoom display, press the fourth softkey from the top until **Marker** is highlighted. This way, you will see the value of the marker, not the delta between markers. Press the **MENU** softkey until **Zoom** is highlighted. The softkeys show the options in the zoom menu.

Notice that when the PLL locks at the lower frequency there is a step and some overshoot. Use the zoom feature to examine it more closely.

Press the **MARKER ORIENT** softkey until the ↔ marker is highlighted. Press the **MARKER** softkey until the ↔ □ marker is highlighted. Use the knob to move the marker over by the transient. Figure 17 shows the marker placed for zooming.

Graph will zoom around this marker

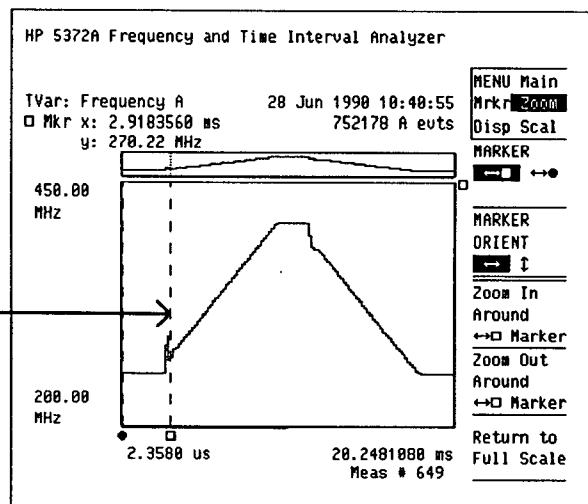


Figure 17. Ready to zoom around marker.

Press the **Zoom in around**  $\leftrightarrow$   $\square$  **Marker** softkey a few times, until sufficient detail is revealed. Figure 18 shows the zoomed in display.

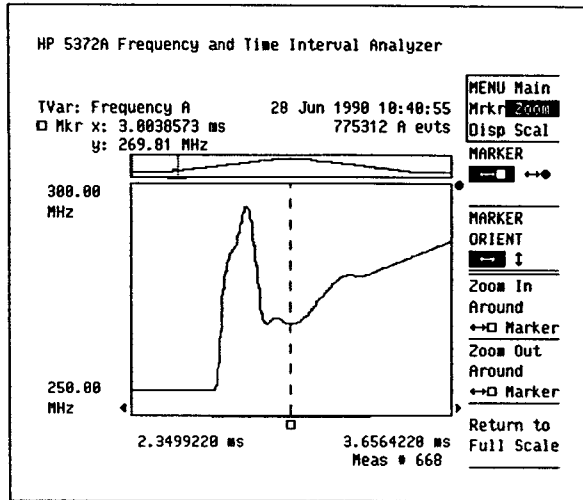


Figure 18. Zooming reveals more of the capture transient.

Using the delta marker feature, you can find out how long the capture transient lasts. Press the **MENU** softkey until **Mrkr** is highlighted. Press the **More** softkey until a softkey labelled **Move**  $\leftrightarrow$   $\bullet$  to  $\leftrightarrow$   $\square$  **Location** is highlighted. Press this softkey. This brings the other marker to the zoomed-in part of the display. You may not see both markers, because one is on top of the other. Turn the knob to see them both. Turn the knob to move the  $\leftrightarrow$   $\square$  to the start of the transient. Select the other marker and move it to where the display starts to move smoothly upward. Press the **More** softkey. Press the fourth softkey from the top until **Delta** is highlighted. At the top left of the display the length of this locking transient is shown. Figure 19 shows the markers and the delta time measurement, 647.9998  $\mu$ s.

Delta marker shows delta time and delta frequency of transient

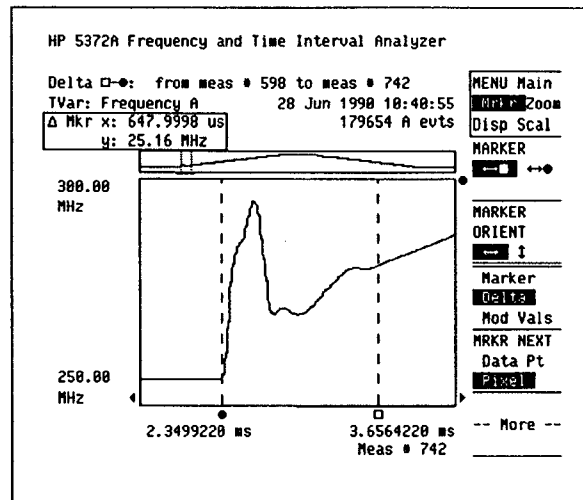


Figure 19. Capture transient time.



## **HP 5372A Advantages**

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The HP 5372A offers many features that make PLL capture and tracking range measurements possible. Features that most influence the success of a PLL measurement are:

- Measure PLL capture and tracking range in a single shot using the continuous measurement capability of the HP 5372A.
- 8k Measurement Memory allows you the most flexibility when determining measurement tradeoffs of resolution, timing and transient effects.
- Time Variation Graph shows all of the PLL measurement directly. Zooming lets you see fine detail anywhere in the measurement.

## **For Further Information**

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For more information on the HP 5372A Frequency and Time Interval Analyzer and the techniques described in this note, please refer to the following publications:

HP 5372A Data Sheet (5952-7997)

HP 5372A Condensed Reference and Specification Guide (5952-8012)

HP 5372A Operating Manual (05372-90001)

HP 5372A Getting Started Guide (5952-8009)

Application Note 358-7 "Analyzing Phase-Locked Loop Transients in the Modulation Domain" (5952-8001)

Application Note 358-8 "Single-shot BPSK Signal Characterization" (5952-8004)

The following application notes are excellent technical references for PLL design and testing:

Signetics Application Note 177 "An Overview of the Phase-Locked Loop"

Signetics Application Note 178 "Modeling the PLL"

Philips "Phase-Locked Loop Circuits: 74HC/HCT4046A & 74 HC/HCT7046A HCMOS Designer's Guide"

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