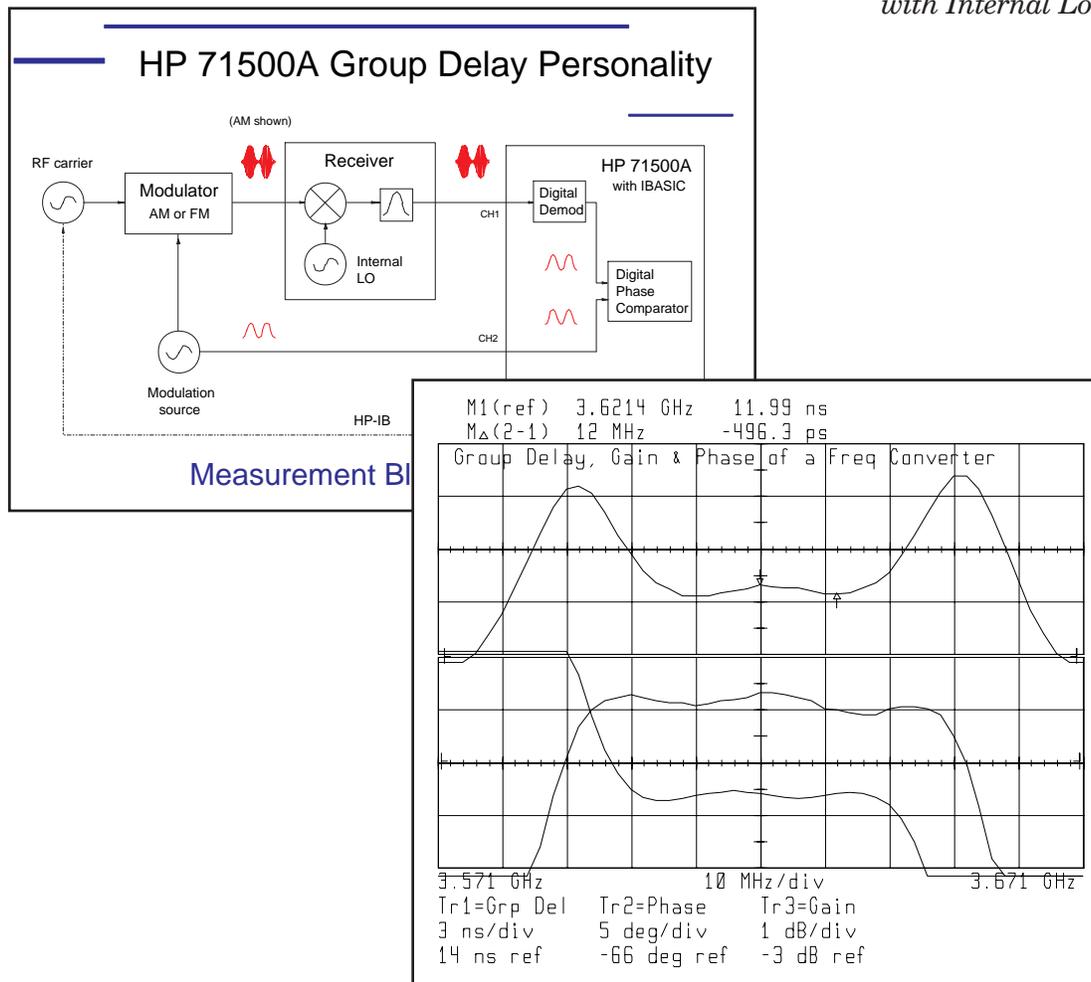# HP 71500A Microwave Transition Analyzer Group Delay Personality

Product Note 70820-10

**HP 71500A/70820A
Product Note Series**

*Measure Group Delay and Phase
through Frequency Converters
with Internal Local Oscillators*

HP 71500A Group Delay Personality

(AM shown)

RF carrier

Modulator
AM or FM

Receiver

Internal
LO

Digital
Demod

CH1

HP 71500A
with IBASIC

Digital
Phase
Comparator

CH2

Modulation
source

HP-IB

Measurement Bl...

```
M1(ref)  3.6214 GHz   11.99 ns
MΔ(2-1)  12 MHz       -496.3 ps
```

Group Delay, Gain & Phase of a Freq Converter

```
3.571 GHz              10 MHz/div           3.671 GHz
Tr1=Grp Del   Tr2=Phase      Tr3=Gain
3 ns/div      5 deg/div      1 dB/div
14 ns ref     -66 deg ref    -3 dB ref
```

- **Accuracy to .2 ns**
- **Uses envelope delay technique, with AM or FM**
- **Access to internal LOs not required**
- **Coverage to 40 GHz, without need for reference mixers or external converters**

Table of Contents

Introduction

Measuring absolute group delay through frequency translating devices such as downconverters or receivers is difficult at best, particularly at microwave frequencies. Vector network analyzers are excellent tools for measuring group delay relative to a "golden device", but they are difficult to use for absolute measurements. For microwave devices without access to internal local oscillators (LOs), the problem is especially difficult as vector network analyzers cannot be used at all. For these cases, a modulation technique must be used, which often involves a custom solution with external mixers, filters, LOs, and discriminators or detectors — in other words, complex and expensive. Customers have been asking for a better solution for a long time.

The HP 71500A microwave transition analyzer coupled with a downloadable Instrument BASIC (IBASIC) personality offers a cost-effective and simple solution for microwave group delay measurements of frequency translating devices.

Product Description

The group delay personality is a downloadable IBASIC application program that runs internally in the HP 71500A. It is targeted for measurements of microwave frequency converters and receivers with internal LOs, or any microwave frequency converter where absolute group delay is desired. It is intended for measuring sub-systems or systems where the source and the HP 71500A can be located near one another. It is not intended for end-to-end measurements separated by a long-distance, due to the need for the HP 71500A to measure both the RF and the baseband modulation source.

The program uses the modulation delay technique for measuring group delay, using either AM or FM. The modulated RF carrier is measured in channel 1, and the baseband modulation signal is measured in channel 2.

Why Measure Group Delay?

Ideal networks pass modulated signals containing information without inducing any additional distortion. They are characterized by both flat magnitude response and linear (constant slope) phase shift versus frequency. Since group delay is the derivative of phase with respect to frequency, this implies a flat group delay response. All of the frequency components of the signals passing through the device-under-test (DUT) will experience the same amount of time delay. The real world, however, is composed of non-ideal networks, which cause distortion due to amplitude and phase nonlinearities. Group delay is one measure of phase nonlinearity. It is particularly important to characterize group delay for systems where some type of phase modulation is used, such as FM, QPSK, or 64QAM.

Group Delay Techniques

Group delay is defined mathematically as the negative of the derivative of a network's phase versus frequency response:

Group delay $\quad t_d = -\dfrac{d\emptyset}{dw}$

$\quad$ (t_d in seconds, $\emptyset$ in radians, w in radians/second)

$\qquad$ *or*

$$t_d = -\frac{1}{360} \times \frac{d\emptyset}{df}$$

$\quad$ (t_d in seconds, $\emptyset$ in degrees, f in hertz)

There are two basic techniques for measuring group delay of a component or sub-system.

Direct Phase

For linear, non-frequency translating devices, the most commonly used technique is the direct phase method. A vector network analyzer is used to measure the phase response of a DUT, and a numerical differentiation is done to derive group delay. The derivative is approximated by using $\frac{\Delta\emptyset}{\Delta f}$, where delta phase is the phase difference between adjacent trace points, and delta frequency is the frequency step size (total frequency span divided by the number of trace points). Since delta frequency is a nonzero quantity, there is averaging occurring over this frequency interval. This interval is known as the measurement aperture. Larger apertures give less group delay resolution (more averaging occurs), but less trace noise. Conversely, a smaller aperture implies more resolution at the expense of a noisier measurement.

The direct phase technique requires that both the test and reference signals be at the same frequency in order for phase to be measured. For measuring frequency translating devices, a reference DUT or external mixer is needed to ensure this condition.

Modulation Delay

The second technique measures modulation delay. A modulated carrier is passed through the DUT, and then demodulated. The phase of the demodulated signal is compared to the original modulating signal to determine the delta phase at that particular frequency. The carrier must be stepped across the frequency band of interest for the complete group delay measurement. The modulation type can be AM, FM or PM. Group delay is calculated as:

$$t_d = \frac{\emptyset_e}{360 \mathrm{x} f_m}$$

(t_d in seconds, $\emptyset_e$ {envelope phase shift} in degrees, f_m {modulation frequency} in hertz)

The HP 71500A group delay personality uses this technique. The aperture of this measurement is equal to two times the modulation frequency.

Key Features and Benefits

The key features and benefits for the HP 71500A solution are described below. A more detailed comparison to other group delay techniques is provided in Appendix A.
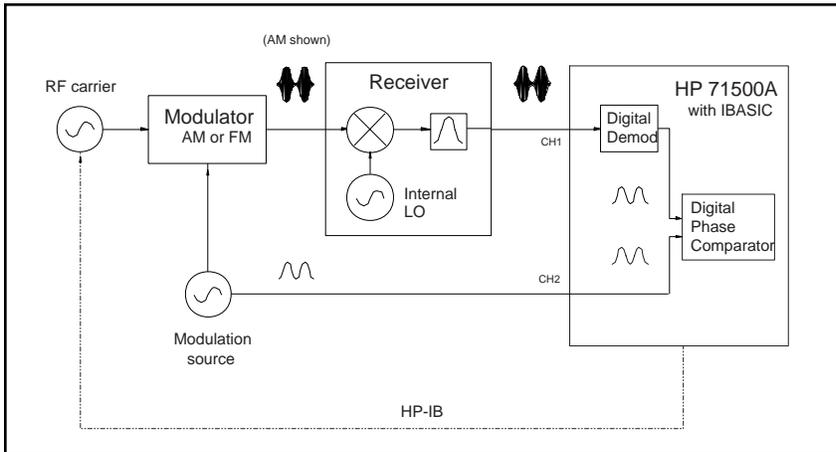

Figure 1: Measurement block diagram.

Accuracy to better than 1 ns. Using normalization and zoom FFT processing, accuracy down to +/- 0.2 ns can be achieved. This is adequate for most applications.

Access to internal LOs not required. Since it is the modulation on the carrier that is of concern and not the carrier itself, access to internal LOs or frequency references is unnecessary. The vector network analyzer method measures phase of the RF signals directly, and therefore requires LO or reference access.

No need for external reference mixers. The vector network analyzer approach needs an extra external mixer or DUT to provide a reference signal that is the same frequency as the test signal. While this method provides excellent relative measurements (referenced to a golden standard), absolute delay measurements are difficult due to the need to calibrate the mixers. The HP 71500A solution measures absolute group delay directly, providing a simpler and more traceable measurement. Frequency coverage extends to 40 GHz. No extra upconverters or downconverters are needed to cover most applications, such as satellite transponder measurements. This lowers the measurement system cost and complexity.

FM group delay. The FM demodulation routine internal to the HP 71500A eliminates the need for an external FM discriminator. Receivers that have internal limiters or saturated amplifiers require the use of FM, since any AM is stripped away. An example of a receiver with a saturated amplifier is a typical Ku band satellite transponder.

Amplitude and phase. The program also provides the amplitude and phase response of the DUT with no additional measurement time.

Simplified user interface.
Custom menukeys tailor the MTA's user interface for making group delay measurements without the need for an external computer.

Limitations

The key limitations of this application are that it is slower than most other solutions, and the relative accuracy, while adequate for most measurements, may not be as good compared to what customers have come to expect from instruments such as the HP 8510 vector network analyzer.

Measurement Overview

Measurement Block Diagram

A block diagram view of the measurement is shown in figure 1. The modulated RF carrier is measured in channel 1 of the HP 71500A, while the baseband modulation signal is measured as a reference in channel 2. The modulation source can be a stand-alone instrument or internal to the RF source.

Modulation Source

There are two basic measurement setups. The first setup (figure 2) uses the internal modulation capabilities of the source, such as (optionally) provided by the HP 8360 family of synthesizers. The second setup (figure 3) uses an external modulation source, controlled either manually or via HP-IB. Many non-HP-IB modulation sources have poor frequency accuracy. In some cases, it may be necessary to fine-tune the modulation frequency of the
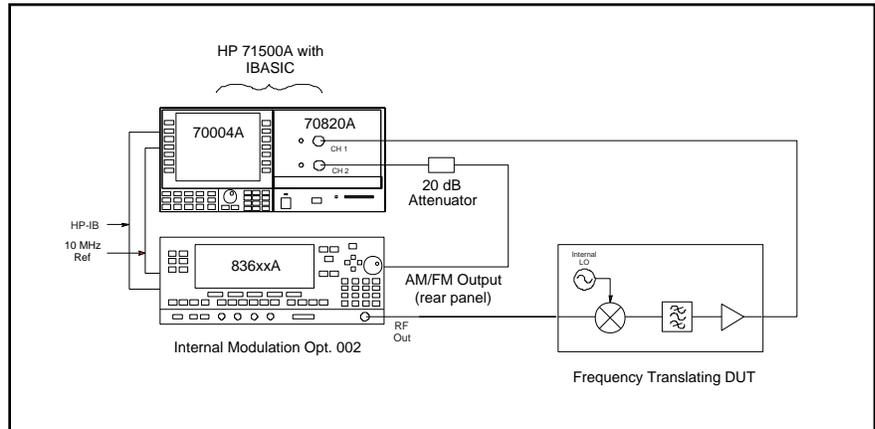
Figure 2: Measurement setup using internal modulation.
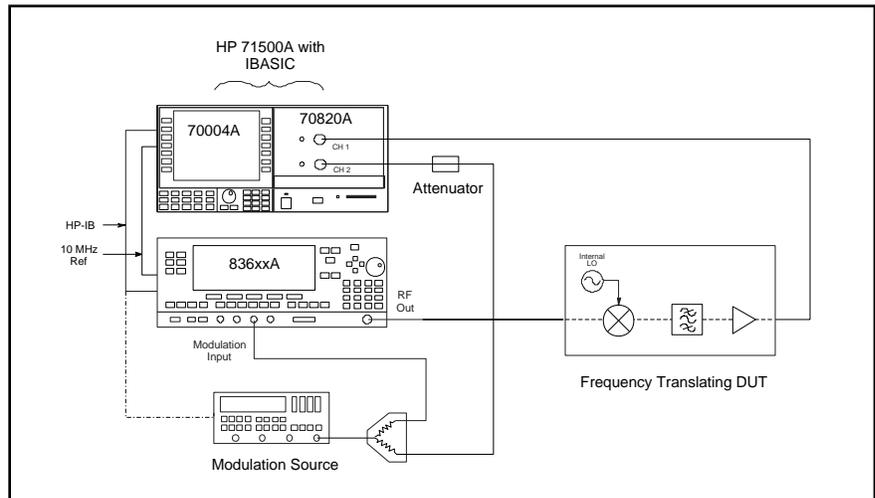
Figure 3: Measurement setup using an external modulation source.

source to match the value used in the program.

Note: when connecting synthesizers or modulation sources that are to be controlled via HP-IB, use the HP-IB connector on the rear panel of the HP 70820A module, NOT the HP-IB connector on the HP 70004A mainframe/display. Connecting the 10 MHz references of the HP 71500A and the sources together is recommended, but not required.

Synthesizer Support

The group delay program supports the HP 836xx, HP 834x, HP 70340A, and HP 3325A synthesizers. The program can easily be modified to drive other synthesizers if necessary (see **Adding Sources** on page 19).

The group delay personality does not require 1 Hz frequency resolution of the RF source, but this feature is very desirable for other measurements (such as pulsed-RF characterization) and is highly recommended if a new source is being ordered.

Measuring in the Frequency Domain

This program makes extensive use of the Fast Fourier Transform (FFT) to perform the group delay measurement. FFTs are used to demodulate the carrier and compute the phase of the baseband signal. Zoom FFTs are also used as a noise reduction technique. A zoom FFT takes a larger time record to get better frequency resolution, and displays only a portion of the frequency domain data.

The program operates in two basic measurement modes. The recommended practice is to use the zoom FFT mode. This mode yields the most accurate measurements. The user can select the trade-off between accuracy and measurement speed. The greater the amount of zoom used, the more accurately the carrier and modulation frequency must be known as well.

The direct demodulation mode does not use zoom FFTs and is generally faster than the zoom FFT mode, but not as accurate. It is less sensitive to frequency inaccuracy, and should be used when the carrier and modulation frequencies are not controlled well enough to use the zoom FFT mode. Trace averaging can be used with either mode to further improve measurement accuracy. For a given level of performance, the zoom FFT mode is faster than using the direct demodulation mode with averaging.
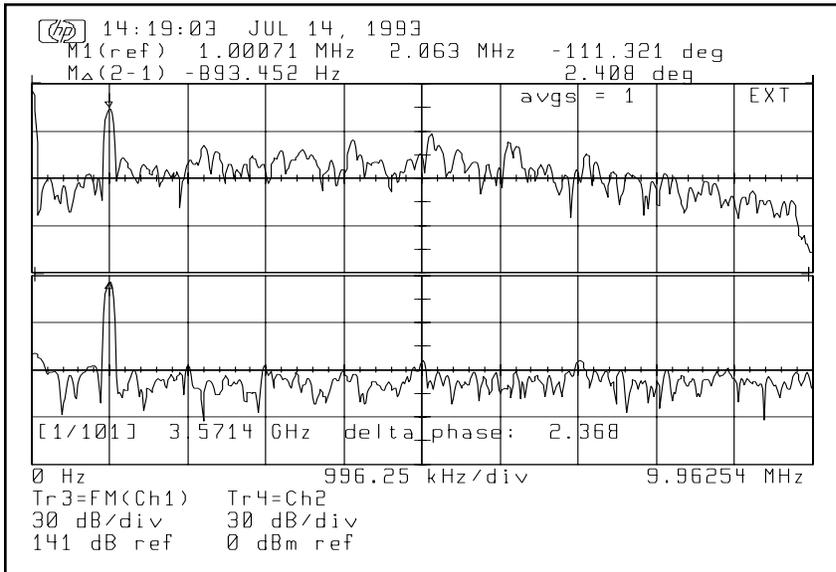
Figure 4: Screen display using direct demodulation mode (zoom FFT off). The upper trace shows the demodulated RF carrier. The lower trace shows the modulation signal. Both signals are in the frequency domain.

Direct Demodulation Mode (Zoom FFT Off)

This mode uses the built-in FM demodulation routine of the HP 71500A. Trace 3, which shows the demodulated carrier in the frequency domain, is defined as FM(CH1), and trace 4, which shows the modulation signal in the frequency domain, is defined as CH2. Both traces are transformed into the frequency domain using the FFT. The displayed signals appear at the far left-hand portion of the screen (figure 4). The markers take one reading on each trace, using the local peak function to ensure the signal peak is measured.

The RF signal is sampled such that the carrier is centered in the IF, and the modulation sidebands are unaliased (not folded about DC or the Nyquist frequency). If they were displayed, they would appear as they would on a spectrum analyzer (figure 5).

When using the direct demodulation mode (zoom FFT off), phase versus frequency data is available, however, amplitude versus frequency information of the DUT is not measured. Amplitude information is available when using the zoom FFT mode.

Zoom FFT Mode

With this mode, the user specifies the amount of zoom used, from 1 to 128. Higher zoom values result in better accuracy, but slower measurement times. Larger zoom values are analogous to smaller resolution bandwidths in a spectrum analyzer. A typical value which represents a good trade-off of accuracy versus measurement time is 16. Each factor of two increase in the zoom FFT value will slow the measurement time down by two as well. In this mode, trace 3 (the carrier) is defined as CH1, and trace 4 (the modulation signal) is defined as CH2.

In the zoom FFT mode, the RF signal is sampled so that the carrier gets mixed to the IF near DC, and half of the modulation sidebands are folded around DC such that sideband pairs of the same order end up very close together (for AM, there is only one pair of sidebands). If this result was displayed without the zoom FFT, it would look like figure 6. The zoom FFT is used to expand the first order sidebands. For FM, all sideband pairs higher than first order are ignored. Markers are used to measure the amplitude and phase of the sidebands, and the program uses this information to perform the necessary demodulation. Normally, if a modulation frequency of 1 MHz is used, the first order sidebands will be separated by 2 MHz. With the zoom FFT mode, the program sets the sampling frequency of the HP 71500A such that the sideband separation is reduced by about twice the zoom factor.
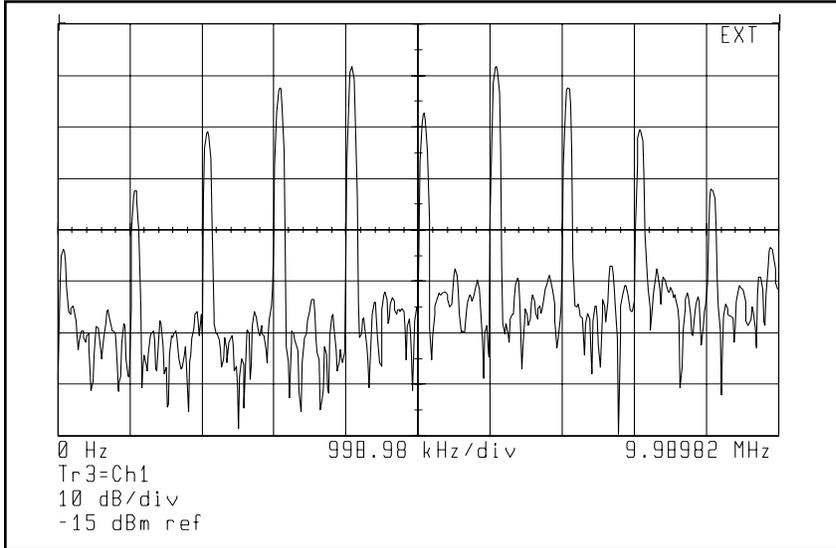
Figure 5: Screen display showing an FM modulated RF signal as it would appear in the IF using direct demodulation mode, but without the FM demodulation function applied.
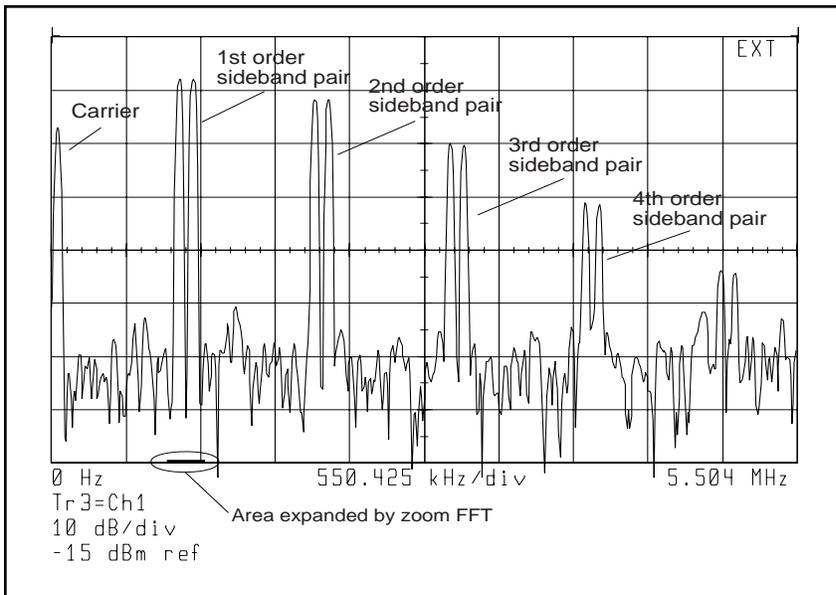
Figure 6: Screen display of an FM modulated RF signal as it would appear in the IF using zoom FFT mode, but without the zoom FFT applied.

When the program is running, the top trace of the display shows the first order sideband pair, and the bottom trace shows the baseband signal, but this time the signals are centered on the screen (figure 7).
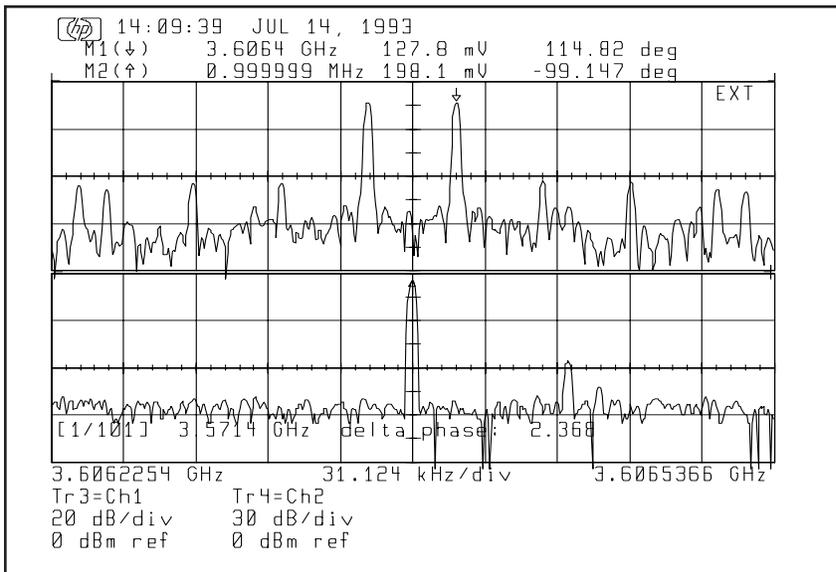
With the zoom FFT mode, both amplitude and phase versus frequency can be measured, with no additional measurement time.

Marker Options (zoom FFT on)

When the zoom FFT mode is selected, the group delay program defaults to placing the marker on signals using the highest peak function. This allows the measurement to be done even if the LO in the DUT drifts somewhat, causing the sidebands to move around, or if the modulation frequency is not known exactly (this is often the case when using an external signal generator to generate the modulation signal).

If there are contaminating signals present, it is possible that the marker will find an incorrect signal which may be bigger than a desired signal. This can happen, for example, when the DUT produces significant carrier harmonics that are not filtered away. To avoid this, an option is available to use direct marker placement and the local peak function. In this mode, the marker is set to where the signal is expected, and a local peak is done to ensure that the peak of the signal is found. However, if the


```
⟨hp⟩ 14:09:39  JUL 14, 1993
  M1(↓)     3.6064 GHz    127.8 mV      114.82 deg
  M2(↑)     0.999999 MHz  198.1 mV     -99.147 deg
                                                        EXT
[1/101]    3.5714 GHz   delta phase:   2.368
 3.6062254 GHz          31.124 kHz/div       3.6065366 GHz
Tr3=Ch1          Tr4=Ch2
20 dB/div        30 dB/div
0 dBm ref        0 dBm ref
```

Figure 7: Screen display using zoom FFT mode. The upper trace shows the first sideband pair of the modulated RF carrier. The lower trace shows the modulation signal. Both signals are in the frequency domain.

LO frequency of the DUT has drifted enough, or has significant amounts of residual FM, or the modulation frequency cannot be set accurately enough, the marker may be placed too far from the signal for local peak to work properly. This will result in a bad measurement. Direct marker placement with local peak should only be used in an environment with very stable and accurately known signal frequencies.

When using a manual modulation source, it may be necessary to fine-tune the modulation frequency to match the value used in the program, to ensure correct marker placement. If it appears that neither marker mode is finding the correct signals, then the direct demodulation mode should be used. The user can choose between highest or local peak, by using the `markers` softkey under the `Options` menu.

Normalization

Trace normalization is desirable for relative measurements, and required for absolute delay measurements. For obtaining the best relative accuracy, performing a normalization removes the group delay contributions of the interconnect cables and the test equipment. An absolute group delay measurement can only be done by first establishing a reference, which is the group delay of the test setup without the DUT in place. In general, normalization improves measurement accuracy considerably, but is not as good as what can be achieved using calibration standards and 12-term error correction as done in standard vector network analysis.

How to do normalization

Normalization is done by doing a measurement without the DUT, and then pressing the NORMALZ key under the Process menu to store the reference trace. The measurement configuration must be set up for a non-frequency translating measurement, by setting the LO frequency to 0 Hz and the RF and LO multipliers (N and M) to one, under the Config menu. Next, the DUT is inserted and another measurement is done, this time setting the correct LO frequency and multipliers that correspond to the frequency translation of the DUT (see step 3 on page 14 about the Config menu for a more detailed description of setting up a measurement). The reference and test measurements must have the same number of points, so set the start, stop, and step frequencies accordingly.

Care should be taken when measuring frequency-inverting devices, where the IF frequency sweeps downward in frequency as the RF is swept upward. In this case, the reference and test sweeps as measured at the HP 71500A input should both be in the same direction (i.e., either both upwards or both downwards in frequency). This means that the RF sweep direction will reverse from the reference to the test sweep.

What frequency span to use?

When performing a normalization on a frequency translating device, there are two choices for the frequency range to use for the reference sweep: either the frequency span corresponding to the DUT's input, or to its output. In both cases, either the input cable or the output cable will be measured during the reference sweep at a different frequency than during the test sweep. This will not be a problem if high quality interconnect cables of the appropriate type for the frequency range of the measurement are used. Cables such as these will have flat group delay over the full RF and IF frequency range. Their contribution to absolute delay will then be removed by the normalization process.

When using good cables, the choice of which frequency span to use for the reference trace is simple. For relative measurements, use the frequency span corresponding to the DUT output for establishing the reference trace. This will remove any measurement irregularities due to the HP 71500A (these are more significant at lower frequencies, especially below 300 MHz).

For absolute measurements, the first choice for establishing the reference trace is to use the span corresponding to the DUT input. This ensures that the delay contribution of the modulator will be removed. If the modulator delay is independent of carrier frequency, then the normalization could be done at the span corresponding to the DUT output, which has the advantage of removing any irregularities due to the HP 71500A. The delay of some FM modulators is also a function of the modulation frequency (this is true for the FM modulator in an HP 8360 series synthesizer). If the modulation frequency is changed after a normalization has been done, a new reference sweep is required.

When the group delay flatness of the cables is not a significant contribution to measurement error, the normalization process should be done with both the input and output cables present. If cable contribution is likely to be a significant factor over one or both of the frequency ranges used in the measurement, then the normalization can be done with only one of the cables. The other cable can then be measured separately over its intended frequency range, using the direct phase measurement (either with a vector network analyzer or the HP 71500A), and its delay contribution manually removed from the normalized test data. The group delay program currently does not incorporate a two-part normalization such as this. Measuring the second cable in this way is necessary for an absolute measurement, but may not be needed for relative measurements if its contribution would not be a significant factor in the measurement.

Unambiguous delay range

The nature of the modulation technique for measuring group delay is such that absolute group delay values are valid only for $0\pm(.5/fmod)$, where fmod is the modulation frequency used for the measurement. This corresponds to $0\pm180°$ of phase shift. After $+180°$, the measurement will wrap around to $-180°$, which changes the sign of the group delay from positive to negative. This is equivalent to subtracting 1/fmod worth of delay.

For the zoom FFT mode, the unambiguous range is further reduced by a factor of two to $0\pm(.25/fmod)$. If the absolute delay is beyond these limits, it will be displayed incorrectly. For example, if the absolute delay of a DUT and test setup was 273 ns, and the zoom FFT mode was used with a modulation frequency of 1 MHz, the program would measure -227 ns (273 ns - .5/1 MHz). If the direct demodulation mode was used (zoom FFT off), the program would measure the absolute delay correctly, since the maximum delay range in this case would be ±500 ns.

The maximum measurable delay range must be considered when measuring the absolute delay of a DUT if a normalized measurement is done with significant reference delay. The reference delay and the delay of the DUT must be less than the unambiguous range. For example, if the unambiguous range is ±500 ns, and the reference sweep had 373 ns of delay, then the DUT delay must be less than 127 ns. Beyond this, the delay value will be negative (until it wraps around a second time).

The only way to increase the unambiguous measurement range is to lower the modulation frequency. However, this reduces the aperture as well,

which increases measurement noise. If the measured absolute delay of your device changes significantly with decreasing modulation frequency (assuming normalization is done), then the electrical length of the device is too long for a valid measurement at that modulation frequency. If you know the approximate electrical length of your device and can therefore infer how many phase wraps occurred, then an invalid absolute group delay measurement can be corrected. If direct demodulation (zoom FFT off) was used, add $N \times$ (1/fmod); if the zoom FFT was used, add $N \times (.5/fmod)$, where N is an integer which accounts for the number of times the measurement wrapped around.

Negative delay

Negative values of group delay can occur when the measurement wraps around as described above, or when the reference path length is longer than the measurement path. The program has a flag which controls whether negative delay numbers are corrected or not. The default is set to show negative numbers (no correction). This allows normalization to work correctly when the reference path is longer than the measurement path. For example, if the reference measurement had -4 ns of absolute delay and the DUT measured 56 ns, then the normalized measurement would correctly show 60 ns of delay (56 ns - (−4 ns)).

Measurement Time vs. Trace Length
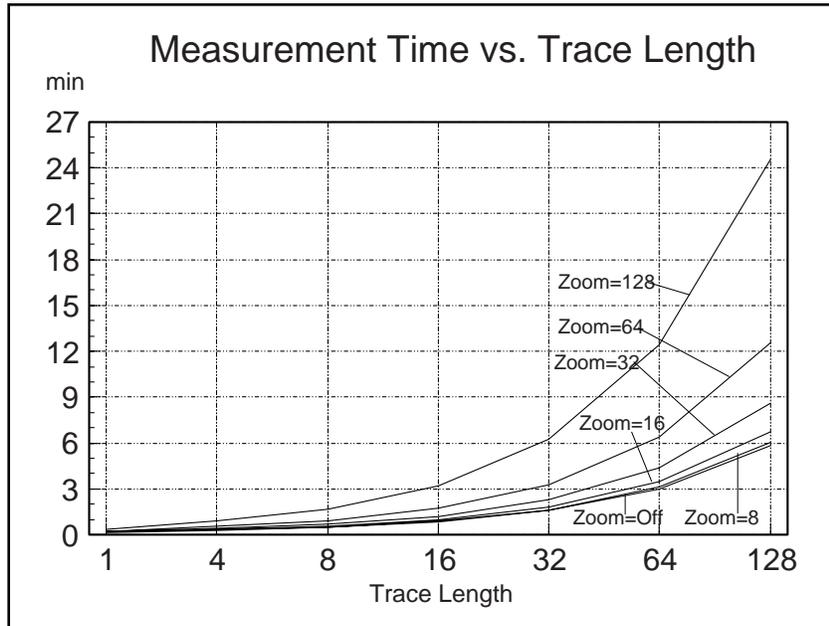
Figure 8: Measurement times versus trace length for various zoom factors. For N averages, the measurement times will increase by a factor of N.

If the flag is set such that negative delay values are corrected, then 1/fmod worth of delay is added when the direct demodulation mode is used, and .5/fmod worth of delay is added when the FFT zoom mode is used. This makes any negative values positive. This operating mode can correct a measurement when one phase wrap has occurred, but can make a normalized measurement invalid. Following the previous example (using the zoom FFT and 1 MHz modulation), the normalized measurement would show -440 ns, which is clearly not correct (56 ns - (-4 ns + 500 ns)).

To change the negative delay flag, the user must edit the program. The variable can be found in the Measure_group subroutine. With the USER keys active, type:

```
EDIT Measure_group
```

Set Neg_delay_flag to 0 to correct negative delay values; set to 1 to display negative numbers.

Measurement Times

The time required to perform a group delay measurement varies considerably, depending on the accuracy and resolution needed. Figure 8 shows typical measurement times versus trace length for various zoom values. These measurement times will increase by a factor of N when N averages are used.

Using the Personality

Obtaining the Program

The HP 71500A group delay personality is distributed free of charge on an "as is" basis, without a formal HP product number. It is neither a fully supported nor specified product. The user is free to modify the IBASIC code to customize it for their particular measurement application. The program can be obtained by contacting your local HP sales or application engineer.

Firmware Upgrades

What if I have an older instrument?

This personality needs firmware revision 1.1 or greater. If you have an HP 71500A or an HP 70820A module with firmware revision 1.0 or 1.01, then a firmware upgrade kit must be ordered (product number HP 70863A). This upgrade sells for $2000, and adds several new features besides the capability to run IBASIC programs. Additional features include increased trace memory for single-shot measurements, limit lines, and enhanced trace math operations.

Downloading the Program

The group delay personality must be downloaded into the memory of the instrument each time the instrument is powered up (program memory is volatile). There are two basic ways to accomplish this. One method

involves using an external computer, and the other uses the mass storage capability of the HP 70004A color display/mainframe. The latter method can load the program either from a floppy disk or a memory card. Since the program is likely to be supplied on a floppy disk, it is desirable to copy it to a memory card as soon as possible. Subsequent downloadings can then be done from the memory card, which alleviates the need to have an external computer or floppy disk drive.

Loading from an external computer

The most common way of downloading the program with an external computer is to use a floppy disk. Alternately, the program can be downloaded directly from the computer's hard disk drive. This is useful if the program was obtained via e-mail or ftp. Several choices for computers exist, such as an HP 9000 series 300 running HP BASIC/WS, an HP 9000 series 300/400/700 running HP-UX (with HP BASIC/UX running as an application), or a personal computer (PC) running HP BASIC/DOS. The computer must have an IEEE-488 (HP-IB) port to communicate with the HP 70004A mainframe.

From the HP BASIC operating environment, load and run the ASCII program DOWNLOAD. To load an ASCII file using HP BASIC, use the GET command. You may need to specify the mass storage logical name,

address and volume number. The following examples are for an HP 9122 or HP 9133 floppy disk drive set to HP-IB address 0:

```
GET"DOWNLOAD:CS80,700,1"
or
GET "DOWNLOAD:,700,1"
```

If you are not getting the program from a floppy disk, skip the ":,700,1" portion of the filename, but include the full path name for the file. The MSI command could be used to set the HP BASIC environment to the correct directory.

After loading the program, press the RUN softkey or type RUN, followed by the return key. The program will prompt you for the file name to download. In keeping with the above example using a floppy disk, you would type:

```
G_DEL_IB:,700,1
```

You should see the program lines displayed on the screen as the program is being downloaded to the HP 71500A. This process will take a few minutes to complete. At the end of the download process, the program will ask you if you want to store the program to the mainframe's default drive. If you have a formatted 128K RAM memory card available, and the default drive is set to MEMORY CARD (select under the DISPLAY keys: Mass Storage; msi), then enter "Y" to store the program. An alternate way to store the program to a memory card is described in the next

section, along with details of how to format a memory card.

If you are working in a UNIX® environment, it is possible to download the program directly from the hard disk drive using a script program, without having to run HP BASIC or use a floppy disk. This method is much faster than using the HP BASIC download program.

Storing to a memory card

Once the group delay program has been downloaded to the instrument, it can then be stored to a memory card. A 128K RAM memory card (HP 82215A) should be used.

Note: the memory card uses a CR2016 lithium battery. It is recommended that the battery be changed annually. To retain the data stored on the card, the battery should be replaced while the card is installed in the mainframe with the power on.

The memory card must be formatted before it can be used. To format a new card, press the MENU key below the display, followed by mass storage (more 2 of 2) under the States menu (page 2 of 2). Next, press more followed by FORMAT. You can select either DOS or LIF format. After the formatting is compete, press the USER key to activate the IBASIC keys. To save a program on the card, simply type:

```
SAVE "G_DEL_IB"
```

Either an HP-HIL keyboard can be used for entering the command (plugged into the front of the HP 70004A display/mainframe), or the "typing aids" key under the Utility menu of the USER keys. As the program is stored on the card, the LED to the left of the card will flash intermittently. If there is a problem with the mass storage definition, refer to chapter 3 of the HP 71500A Instrument BASIC User's Guide (70820-90055). After you have successfully stored the program onto the memory card, slide the write-protect switch to the outside position. This will prevent accidental erasure.

Loading from a memory card or disk drive

The second method of downloading the program is to use the mass storage features of the HP 70004A mainframe. Press the DISPLAY key under the display, followed by Mass Storage on the left, followed by msi on the right. Select MEMORY CARD if the program has already been stored to a memory card (see above), or HP-IB disk if loading from an external disk drive (connected to the HP-IB connector on the back of the mainframe). Using an HP 9122 or HP 9133 disk drive as before, make sure that the HP-IB ADDRESS is set to 0, the UNIT NUMBER to 1, and the VOLUME NUMBER to 0.

The next step is to actually load the program. The easiest way is to use the MENU keys of the HP 71500A. Press the MENU key below the display, followed by States (page 2 of 2) on the left, followed by mass storage (more 2 of 2) on the right.

Next, use the up/down stepkeys to highlight the file to be loaded. Then press LOAD FILE on the right. After the file has loaded, it will automatically run.

It is possible to have the program automatically load and run when you power up the analyzer, by having an "auto-start" file stored in addition to the group delay program. The HP 71500A will look for the auto-start file on whatever mass storage device was last used. If you are using a memory card to store the group delay program, use the procedure described previously to download and copy the program AUTOST from the floppy disk to the memory card. See page 3-8 of the HP 71500A Instrument BASIC User's Guide (70820-90055) for more information on auto-start files.

Menu Overview

The group delay personality provides the user with a custom menu structure, tailored to the group delay measurement application. These menus are accessed under the USER softkeys. Note that when the group delay program is running, successive presses of the USER key will toggle between the personality softkeys and the IBASIC softkeys. The personality softkeys are structured similarly to the standard MENU keys in that the left-hand keys are fixed, while the right-hand keys change according to which left-hand key is pressed. The personality has six left-hand menus to choose from:

Sweep: the start, stop, and step frequencies are set here, as well as the number of averages to use during the measurement. The VIEW SPECTRM key allows a preview of the measurement to confirm that everything is set up correctly. The MEASURE key starts the actual measurement. A HELP key is available.

Config: this menu is used to enter the parameters which define the hardware setup, such as mixing numbers and LO frequency, and the modulation type and frequency.

Options: this menu allows you to choose whether to turn the following functions on or off: single shot, FFT zoom, phase and amplitude traces, and invert phase mode. Also choose whether markers use highest or local peak mode. A HELP key is also available here.

Process: the normalization softkeys are located here, as well as an autoscale key. The FIND LO key invokes a signal identification routine, which is used to determine the exact LO frequency of the DUT.
Sources: set RF, LO, and modulation source type and addresses here.

Power: set the power levels of the various sources used. Also set the modulation depth (for AM) or modulation deviation (for FM) when using a source with internal modulation.

Setting Up and Doing a Measurement

The order of keystrokes for setting up a group delay measurement is not crucial. The HELP key under the Sweep menu describes one possible sequence:

1. *Configure the sources (*Sources *menu):* the personality allows for the HP-IB control for up to three sources (RF, LO, and modulation). At a minimum, you must have control of the RF source to perform a measurement. When entering an HP-IB address, use the last two digits only (for example, enter 19 rather than 819). If you are using an HP 8360 series synthesizer with the internal modulation generator option (Opt. 002), the mod address should be the same as the RF address, and both RF src: and Mod src: should be set to HP836XX.

    When using an HP 70340A synthesizer, set RF src: to HP 836XX.

2. *Set the power level of the sources (*Power *menu):* usually, only the RF power is set. If a non-HP-IB modulation generator or the internal modulation option of the HP 8360 is used, you need not set the MOD POWER. If the internal modulation option is available, set the AM DEPTH or FM DEVIATion, as appropriate. For best results with either internal or external modulation, use an

AM depth of 90%, or an FM deviation of twice the modulation frequency (ß=2). This will maximize the amplitude of the modulation sidebands of interest.

Note: that when measuring a multiplier with FM, the deviation must be corrected by the multiplication factor. For example, if using 1 MHz of FM to test a x3 multiplier, the deviation should be set to 2 MHz/3 or 667 KHz.

3. *Configure the system (*Config *menu):* the first step is to select the modulation type and frequency with the top two softkeys. Remember, the measurement aperture is equal to twice the modulation frequency, and is independent of the frequency step.

    Next, enter M, N and the LO frequency which correspond to the hardware setup. The following equation is used to compute the IF frequency at the output of the DUT:

    IF = M*RF + N*LO

    The signs of M and N are determined from whether the DUT is an up or downconverter, and whether it uses high or low-side LO mixing. The IF frequency must always be positive, but it can sweep either up or down in frequency. This flexibility allows measurement of frequency-inverting devices. Frequency inversion only occurs when measuring a downconverter where the LO frequency is higher than the

RF frequency. Use the following guide for setting M and N:

Upconverters:
M = 1, N = 1
(IF = RF + LO)

Downconverters:
For LO > RF,
M = -1, N = 1
(IF = LO - RF)*
For LO < RF,
M = 1, N = -1
(IF = RF - LO)

* frequency inversion occurs

If the DUT is a multiplier, set M to the correct harmonic number, and set N and LO to zero.

The softkey labeled RF is used for setting the synthesizer frequency after VIEW SPECTRM is pressed. The value for RF is normally the center of the passband of interest. During the actual measurement, this value is not used, as the synthesizer is programmed according to the start, stop, and step frequencies.

If the LO frequency is not known exactly, use the FIND LO routine under the Process menu. This routine also programs the synthesizer to the value set by the RF softkey. After the LO frequency is computed, it automatically updates the value for the LO softkey. This routine requires that M and N are set correctly.

The `circuit ON/OFF` softkey is used to display or disable the block diagram drawing. Although the drawing shows a connection of the 10 MHz reference between the sources and the HP 71500A, it is usually not necessary to do so.

4. *Choose the options (*`Options` *menu):* the `sglshot ON/OFF` softkey determines whether the measurement is performed in the single-shot or repetitive mode of the HP 71500A. This product note describes the operation when the single-shot mode is used, where the modulation frequency must be less than one half of the single-shot sample rate, which is usually between 10 and 20 MHz. The repetitive mode can be used for higher modulation frequencies, but all of the frequencies involved (including the LO in the DUT) must be known much more accurately than in the single-shot case. In general, it is recommended that everything be locked together for the repetitive mode. The zoom FFT mode is not available when `sglshot` is set to `OFF`.

The `zoom ON/OFF` softkey determines whether the zoom FFT mode (zoom ON) or the direct demodulation mode (zoom OFF) is used. When using FFT zoom, the `ZOOM FACTOR` softkey is used to enter the amount of zoom desired (see discussion of `Measuring in the Frequency Domain` on page 6). This zoom factor is only used during the actual measurement, and not when `VIEW SPECTRM` is pressed. The `markers` softkey is used

to select between the two marker modes, `LOCAL` or `HIGHEST` (see discussion of `Marker options` on page 8).

The phase `ON/OFF` softkey determines whether a phase trace is displayed below the group delay trace. When using the zoom FFT mode, an amplitude trace is also displayed when phase is set to `ON`.

When set to `ON`, the `invert ON/OFF` softkey adds 180°of phase shift to each measurement. This is to account for some modulators that perform an inversion of the modulation signal. This has the effect of adding .5/fmod worth of delay to all of the group delay values.

5. *Set the sweep parameters (*`Sweep` *menu):* enter the start, stop and step frequencies of the RF source with the top three softkeys. If the source is to be swept down in frequency, make the start frequency higher than the stop frequency, and enter a negative value for the frequency step.

Ideally, the frequency step should be equal to twice the modulation frequency for uniform sampling across the measurement band. This provides full group delay characterization with the minimum number of data points. Setting the frequency step smaller than this fills in the trace with more points, but doesn't provide any additional group delay resolution (over-sampled case). If the frequency step is larger than twice the

modulation frequency, a warning message is displayed on the screen to alert the user that group delay variations may be missed (under-sampled case). Care should be taken to make the measurement aperture and frequency step small enough to resolve all of the group delay variations which occur across the measurement band for the particular DUT being tested.

The `AVERAGE` softkey is used to enter the number of averages used during the measurement.

Before doing an actual measurement, it is a good idea to confirm that everything is set up correctly. One way to do this is to press the `VIEW SPECTRM` softkey. An FFT of the modulated carrier is displayed, centered at the DUT output frequency. If no signal appears, check that everything is correctly set in the `Config` menu. This spectrum display is very useful for setting the right amount of modulation when a manual modulation generator is used.

If the frequency span of the spectrum is too wide to clearly see the modulation sidebands, then the zoom transform can be used from the standard HP 71500A menus to expand the display (increase the frequency resolution). To access the zoom transform, press `MENU`, then `Traces`, then `trnsfrm control`. Set `zoom` to `ON` after setting the correct `CENTER` and `SPAN` values.

6. *Start the measurement (`Sweep` menu):* to invoke a measurement, press the `MEASURE` key. At any time during the acquisition of data, the `ABORT` key can be pressed to stop the measurement. It may take a few seconds before anything happens because the abort is processed after the current trace acquisition is completed. If the instrument appears to be frozen after pressing `ABORT`, press `INSTR PRESET` followed by the `USER` key to return to the personality.

If the top trace does not show a signal during a measurement, check that the stop, start, and step frequencies, and `N` and `M` are correctly set. As the program steps along, the IF frequency and delta phase of the point being measured is shown on the display.

7. *Normalize and scale the results (`Process` menu):* if the measured trace is to be used as a reference for normalization, then press the `NORMALZ` softkey (see the previous discussion about normalization on page 9). The `normal ON/OFF` key is used to turn normalization on or off. The trace definitions will change according to the status of this softkey (e.g., MEM1 for an unnormalized trace, and MEM1-MEM3 for a normalized trace).

The `AUTO-SCALE` softkey is used to automatically scale the traces to fit the screen. If a phase trace is displayed, then the electrical length is automatically subtracted to show deviation from linear phase. This auto-delay routine uses the entire phase trace to do a least-squares fit to a straight line. If it is desired to flatten out a smaller portion of the phase trace, such as the center of the passband of a filter, then the auto-delay routine must be done in conjunction with markers. The markers should be placed on trace 2 to define the frequency band of interest. The auto-delay routine can then be invoked again by pressing `AUTO-SCALE`. This routine can also be done via the `MENU` keys by pressing `AUTO DELAY` under the `Scale` menu (more 2 of 2). All of the traces can be manually scaled or offset if desired by using the appropriate keys under the `Scale` menu (more 1 of 2).

Printing/Plotting the Results

An HP-IB printer or plotter is needed to directly obtain a hardcopy of the traces. It should be connected to the HP-IB connector of the HP 70004A display/mainframe, and NOT to the HP-IB connector on the HP 70820A module. Make sure that the HP-IB switch on the rear panel of the display/mainframe is set to the on (up) position. Non-HP-IB printers such as LaserJets and DeskJets can be used with an HP-IB to Centronics converter, such as the HP 92203J/K.

The `PRINT` or `PLOT` keys on the display/mainframe are used to dump the traces to the printer or plotter. Hardcopy parameters such as printer type, and the address of the print or plot device are set under the `Hard Copy` menu of the `DISPLAY` keys. When using an HP-IB to Centronics converter, select either the THINK JET or the PAINTJT BLACK printer driver. Do not press any keys on the display until the printout is complete — otherwise, the printout will be aborted.

If the program was loaded into the memory of the HP 71500A via a memory card or external disk, and no computer is connected to the display/mainframe HP-IB connector, then the `PRINT` and `PLOT` keys on the display/mainframe work properly. If an external computer was used to download the program to the HP 71500A and it is still connected to the HP-IB bus, then it either must be physically removed from the bus, or it must relinquish bus control to allow the display/mainframe to control the printer or plotter. To remove the computer as a bus controller, type the following BASIC commands in the computer:

```
LOCAL 7
SEND 7; UNT UNL DATA
```

Now press the appropriate key on the display/mainframe to initiate a print or plot.

Accuracy Considerations

Typical Accuracy

Tables 1, 2, and 3 show typical measurement repeatability/accuracy versus zoom size at 1 and 20 GHz. These numbers do not take into account mismatch errors, or frequency normalization error, so they represent best case conditions (mismatch is discussed in more detail on page 18). Each data point in the table was derived from two non-frequency translating measurements of a cable, each with a 100 MHz span centered at the carrier frequency. The first measurement was used as the reference trace for a normalized measurement. The measurement was then repeated with normalization on, to determine how much trace noise was present. These values are typical of what would be achieved if normalizing to the DUT output frequency, which optimizes for relative group delay measurements. The RF carrier power was set to 0 dBm (the maximum allowable input), and no averaging was used.

Noise Reduction

Averaging

The results in Tables 1, 2 and 3 can be improved by averaging, at the expense of measurement time. N averages increase the accuracy and measurement speed by a factor of N. The accuracy improvement expressed in dB is 10*log(N). A 3 dB improvement requires doubling the number of averages.

Group Delay vs. Zoom Size

	RF=1 GHz	RF=20 GHz
Zoom = off	+/- 1 ns	+/- 3 ns
Zoom = 8	+/- 300 ps	+/- 1.2 ns
Zoom = 16	+/- 275 ps	+/- 1.1 ns
Zoom = 32	+/- 250 ps	+/- 1.0 ns
Zoom = 64	+/- 200 ps	+/- 750 ps
Zoom = 128	+/- 150 ps	+/- 500 ps

Table 1: Typical group delay accuracy versus zoom size with no averaging. Excludes mismatch error.

Phase and Amplitude vs. Zoom Size

	RF = 1 GHz	
	Phase	Ampl.
Zoom = off	+/- 1°	–
Zoom = 8	+/- .5°	+/- .1 dB
Zoom = 16	+/- .4°	+/- .1 dB
Zoom = 32	+/- .3°	+/- .05 dB
Zoom = 64	+/- .2°	+/- .05 dB
Zoom = 128	+/- .2°	+/- .05 dB

Table 2: Typical phase and amplitude accuracy versus zoom size with no averaging, at 1 GHz. Excludes mismatch error.

Phase and Amplitude vs. Zoom Size

	RF = 20 GHz	
	Phase	Ampl.
Zoom = off	+/- 5°	–
Zoom = 8	+/- 2°	+/- .2 dB
Zoom = 16	+/- 1°	+/- .15 dB
Zoom = 32	+/- .8°	+/- .15 dB
Zoom = 64	+/- .7°	+/- .1 dB
Zoom = 128	+/- .5°	+/- .1 dB

Table 3: Typical phase and amplitude accuracy versus zoom size with no averaging, at 20 GHz. Excludes mismatch error.

Smoothing

Smoothing may also be applied to the trace to reduce the excursions caused by noise. The smoothing function is implemented as a variable-length median smoothing filter. The number of trace points used to compute the median is set by the smoothing value. Smoothing tends to work best when the number of trace points is large.

The smoothing function is accessed via the MENU keys, under the Traces menu. Press avg,hld, followed by smooth ON|OFF until ON is underlined. Enter the smoothing value desired. The results of the smoothing can be compared to the original trace by toggling between on and off. While smoothing can be a useful tool to reduce displayed trace noise, too much smoothing affects the desired data, by reducing non-noise variations caused by the DUT itself.

Signal-to-Noise Ratio

The accuracy of the measurement is directly proportional to the signal-to-noise ratio (SNR) of both signals. For best measurement results, the signals at both inputs to the HP 71500A should be as close to (but not above) 0 dBm as possible. Tables 4, 5, and 6 show the accuracy degradation due to sub-optimum RF input signal levels.

When using the FFT zoom mode, choosing the modulation index to maximize the measured sideband levels is also important (see step 2 on page 14).

When measuring a DUT with a frequency response characteristic of a filter, the group delay accuracy will degrade when measuring the filter skirt, due to a smaller output signal level.

The bandwidth of the DUT will also affect the measurement. The narrower the bandwidth, the more accurate the measurement will be due to less noise. Similarly, a DUT with excess noise will degrade the measurement accuracy. DUT noise may be in the form of LO phase noise or broadband amplified noise.

Mismatch Error

Impedance mismatch in the system between cables, the DUT, and test equipment causes group delay, phase and amplitude ripples versus frequency. Error caused by mismatch can be difficult to eliminate since normalization only removes mismatch error present without the DUT in place. If the DUT has poor port matches, the mismatch error introduced when the DUT is added will be measured as part of the DUT's response. Judicious use of attenuators and isolators will improve port matches, insuring that the measurement contributions of the test setup are minimized.

Mismatch error can occur within the DUT as well. For this reason, a DUT consisting of a filter and a mixer may have significantly worse group delay performance as compared to the filter alone, due to the interactions between the filter, mixer and internal connections.

LO Stability

This measurement application assumes that both the internal LO and the RF source used as the stimulus are of high quality (i.e., typical synthesizer stability and phase noise). While the LO needs to be stable, its exact frequency need not be known initially. The `Find LO` routine can be used to determine the LO frequency with sufficient accuracy to perform a group delay measurement.

Group Delay vs. RF Input Power

	RF=1 GHz	RF=20 GHz
0 dBm	+/- 275 ps	+/- 1.1 ns
-10 dBm	+/- 300 ps	+/- 1.5 ns
-20 dBm	+/- 350 ps	+/- 2.0 ns
-30 dBm	+/- 500 ps	+/- 2.5 ns
-40 dBm	+/- 1.2 ns	+/- 3 ns
-50 dBm	+/- 4 ns	+/- 7 ns

Table 4: Typical group delay accuracy versus RF input power with no averaging. Zoom size = 16. Excludes mismatch error.

Phase and Amplitude vs. RF Power

	RF = 1 GHz	
	Phase	Ampl.
0 dBm	+/- .4°	+/- .1 dB
-10 dBm	+/- .5°	+/- .1 dB
-20 dBm	+/- .7°	+/- .1 dB
-30 dBm	+/- 1.0°	+/- .1 dB
-40 dBm	+/- 1.5°	+/- .1 dB
-50 dBm	+/- 10°	+/- .25 dB

Table 5: Typical phase and amplitude accuracy versus RF input power with no averaging. Zoom size = 16. Excludes mismatch error.

Phase and Amplitude vs. RF Power

	RF = 20 GHz	
	Phase	Ampl.
0 dBm	+/- 1.0°	+/- .15 dB
-10 dBm	+/- 1.5°	+/- .2 dB
-20 dBm	+/- 2.0°	+/- .2 dB
-30 dBm	+/- 2.5°	+/- .2 dB
-40 dBm	+/- 4°	+/- .3 dB
-50 dBm	+/- 10°	+/- .5 dB

Table 6: Typical phase and amplitude accuracy versus RF input power with no averaging. Zoom size = 16. Excludes mismatch error.

When using the FFT zoom mode, the highest peak function of the markers can be used to track an LO that is drifting slightly during the measurement. Larger zoom factors result in less tolerance to LO drift during the measurement, since the frequency span becomes smaller. If the sidebands drift out of the displayed frequency span, then obviously the measurement will be invalid. The direct demodulation mode has the most tolerance to LO drift and residual-FM. Even if the LO drift is small enough to allow the measurement to be done, it can cause degradation of the group delay accuracy.

Modifying the Program

The group delay personality for the HP 71500A may be modified as necessary to tailor it to your particular measurement needs.

Manuals

The following manuals will be helpful for modifying the code:
HP 71500A IBASIC User's Guide:
 70820-90055
HP 71500A Programming Manual:
 70820-90053
HP IBASIC User's Handbook:
 E2083-90005
HP BASIC Condensed Reference:
 98616-90005

All of the commands in the condensed reference which are compatible with IBASIC are indicated by *IN*. An asterisk * following the *IN* indicates that some restrictions or extensions may apply.

In addition to the above manuals, the command preview and key-logging capability of IBASIC allow you to see on the screen or insert in the program the remote command equivalents of front-panel key presses. This greatly reduces the need for the instrument programming manual. These features are accessed under the IBASIC `Miscel` menu, followed by `key log`. Select `PREVIEW` for screen display, or `ON` for inserting lines into the program. Press `OFF` to terminate the key-logging mode.

Changing Defaults

The program can be modified so that it comes up with the all of the variables preset to your measurement needs, with the exception of the source HP-IB addresses and types. To change the defaults, make sure the program is not running and the `USER` keys are selected, and type:

```
edit "default_values"
```

After you have changed the appropriate values, be sure to re-save the program onto a memory card or floppy disk. If you get an error indicating that the card or disk does not have enough room to hold the program, it may be necessary to delete the old file first, and then save the current program with the same name as before.

Adding Sources

To add support for a different synthesizer, the following routines in the program must be modified:

```
Easy_read
Reset_source
Set_freq
Set_mod_freq
Set_power
Set_output
Set_modulator
Set_mod_pct
Set_mod_dev
Check_assign
Source_menu
```

Where needed, add the appropriate output commands that are consistent with the programming syntax for the new synthesizer.

Appendix A

Comparison to Other Instruments

This discussion is meant to clarify where the HP 71500A fits in compared to other group delay measurement solutions.

Vector Network Analyzers

The most common tool for measuring group delay of linear devices is the vector network analyzer (VNA). VNAs utilize the direct phase measurement technique. They are very fast and accurate. A VNA by itself can only measure non-frequency translating devices. For frequency translating components, an external mixer or extra DUT must be used so that the frequency at the reference and test channels is the same. However, in order to make a group delay measurement, the LO for the external mixer must be phase locked to the LO used within the DUT. This can be accomplished by either providing or having access to the internal LO (or its frequency reference). This prevents VNAs from measuring components where the LO is embedded with no external access.

The VNA cannot directly measure absolute group delay either. Absolute delay must be inferred from several measurements involving swapping of mixers, or an assumption that the mixer contributes little delay. The HP 71500A can measure absolute delay directly, with a relatively simple normalization routine.

Trade-offs

Although the HP 71500A can make these absolute and relative group delay measurements, there is a trade-off in performance compared to using a vector network analyzer — reduced speed and accuracy. Measurement speed is slower for two reasons. The first is that a stepped CW approach is required, which is slower than using a continuous sweep. The second reason is that the noise reduction techniques needed for high accuracy measurements take a fair amount of time (FFT zoom, trace averaging, or both). An example of speed for a typical measurement using FFT zoom and no averaging, is about 2 minutes for a 32 point sweep (using a zoom factor of 16). For absolute delay measurements, there may be an overall measurement speed improvement because of a simpler calibration routine — no external mixer calibrations are needed.

The second disadvantage is that measurement accuracy is likely to be less than what can be achieved using a VNA due to lack of full vector error correction, and linearity limitations within the HP 71500A. An HP 8510C network analyzer can achieve relative group delay accuracies below 100 ps for linear devices, or for measurements relative to a golden standard.

Scalar Network Analyzers

Some scalar network analyzers (SNAs) can be configured to measure AM group delay, providing fast sweeps and medium accuracy for relatively low cost. Their primary target is for high volume manufacturing test, where throughput is more important than accuracy. SNAs use the AM envelope technique, using broadband diode detectors to strip the AM from the RF carrier. As such, they can measure both linear and frequency translating devices with internal LOs. The lack of capability to provide FM group delay precludes their use for some applications where AM can't be used. Although slower and more expensive, the MTA's main advantages are providing FM group delay and better accuracy.

Microwave Link Analyzers

The microwave link analyzer (MLA) provides fast and accurate FM group delay measurements, and also makes other important measurements on analog microwave radio links. For loop-back testing (testing a link over a short distance), one MLA is used. For end-to-end link measurements, two MLAs are used. MLAs are used directly only for IF-IF measurements (non-frequency translating links). For measuring frequency translating links, (RF-IF or IF-RF measurements), the system must provide the necessary converters and access to IF ports. For measuring subassemblies like frequency converters, extra components such as mixers, filters, and LOs would be needed, thereby greatly

increasing the system cost and complexity. The HP 71500A solution is much simpler, because it directly provides RF-IF or IF-RF measurements without additional components.

HP 11770A Link Measurement Personality

This personality provides the HP 8590 E-series spectrum analyzers with group delay measurement capability very similar to an MLA. This solution can measure devices from 300 KHz to 2.9 GHz; it is not limited to 70/140 MHz IFs as with a conventional MLA. Using two spectrum analyzers with this personality, RF frequency translating devices can be measured relatively inexpensively. The link analyzer personality has one potentially serious limitation — it cannot measure devices that perform a frequency inversion (i.e., the IF sweeps downward in frequency as the RF is swept upwards). This can occur when measuring downconverters such as direct broadcast satellite (DBS) tuners that use high-side LO mixing (LO > RF). The MTA does not have this limitation as it is tuned independently from the source.

Summary

For microwave measurements of frequency converters with internal LOs, the HP 71500A is the highest performance solution, especially when FM group delay is required. For RF measurements, the choices are greater. For many applications, lower cost solutions will suffice, such as an SNA, or two HP 8590 E-series spectrum analyzers with the link analyzer personality. The HP 71500A solution can fill certain niches such as when FM group delay of a frequency inverting device is needed, or where the instrument can provide additional measurements such as time domain pulsed-RF profiling, or dynamic AM-to-PM conversion measurements.

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