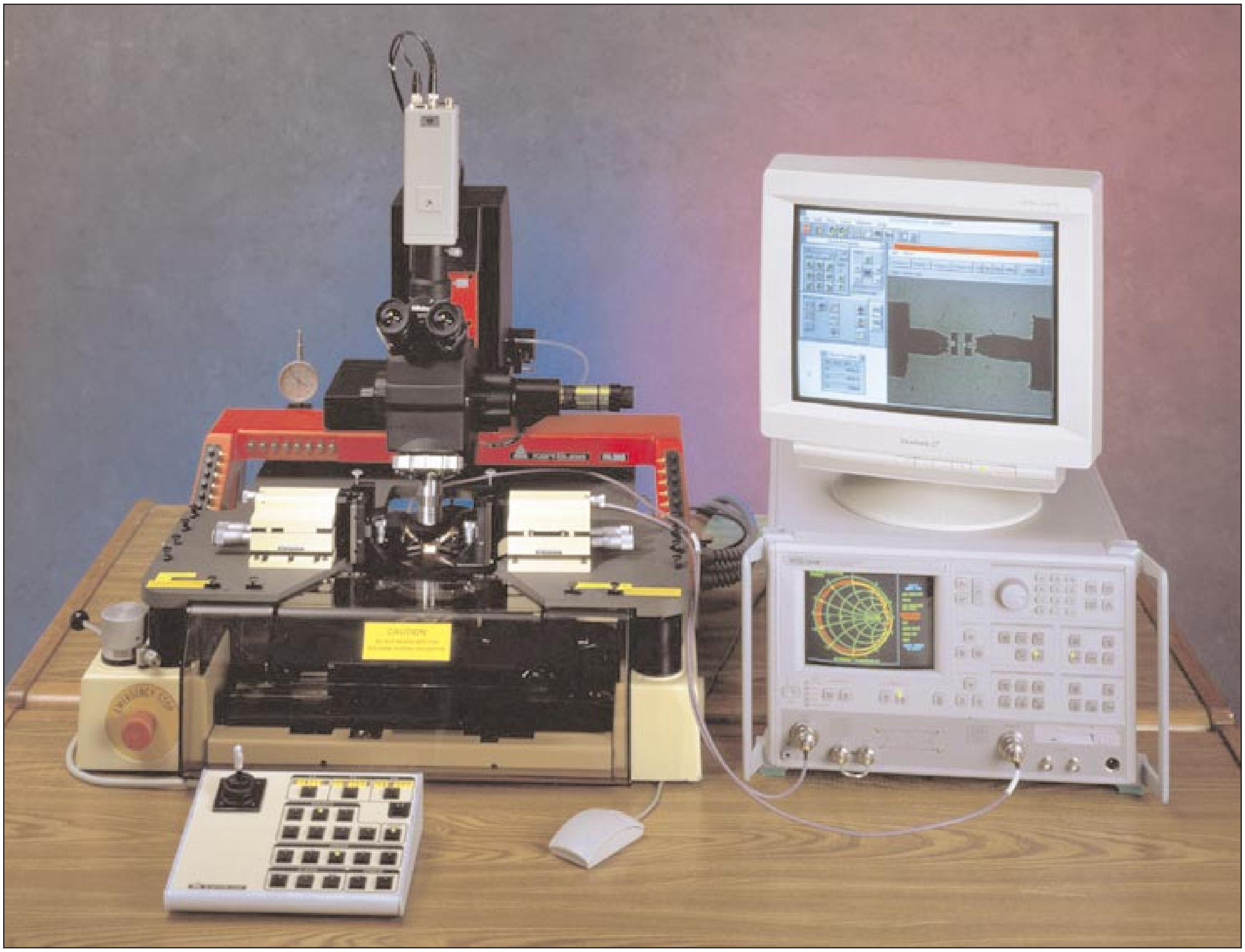
Anritsu

# 360B/37XXXA/B Series

## Vector Network Analyzers

Application Note



*On-Wafer Measurements to 110 GHz*

## On-Wafer Measurements

On-wafer measurements are becoming increasingly important in the microwave industry. Modern MMIC designs have opened the way to cost reduction and industry expansion in both military and commercial applications. The Anritsu 360B and 37XXXA/B series Vector Network Analyzers are used to make accurate, high-speed on-wafer measurements in both R&D and production environments. Rather than relying on models based upon low frequency measurements, the 360B VNA permits actual measurement of MMIC performance and accurate characterization of active and passive on-wafer components to 110 GHz. This application note addresses the specifics of such applications and how the Anritsu VNAs may be used to obtain accurate measurement results.

## On-Wafer Measurement Systems

The equipment required for on-wafer measurements is:

- 37XXXA/B Network Analyzer for applications below 40 GHz
- 360B Network Analyzer System for measurements to 110 GHz
- A Wafer Probe Station
- Wafer Probes
- RF Cables (semi-rigid or flexible)
- Calibration Standards

Additional software packages (optional) such as MMICAD or Anritsu's MIMIC Program support calibration flexibility, post-measurement analysis, etc.

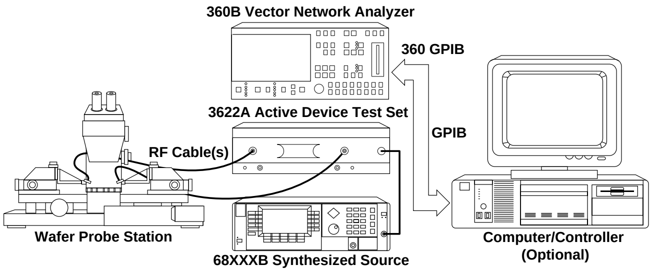


*Figure 1*

The Wafer Probe Station elements and accesories are relatively independent of one another and can be selected to best suit a specific application. Manual and autostepping microwave probe stations, an adaptation of sub micron IC probe stations, are available from a number of manufacturers. For operation to 110 GHz, wafer probes are available from GGB Industries Inc. The GGB CS4, 5 and 8 are widely used calibration standards for on-wafer measurements. GGBCAL is available to automate the calibration process for semi-automatic probe stations such as the SUSS PA200. The 110 GHz Anritsu 360B Vector Network Analyzer system offers the widest frequency range available in coax and is easily interfaced to your wafer probing station.

## Coaxial Performance

The V Connector® (1.85 mm) was developed as an extension of the industry standard 40 GHz K Connector® (2.9 mm). The V Connector exhibits mode-free operation to 67 GHz. It is assembled using procedures that are similar to those used on K Connectors. V085 semirigid coaxial cable is manufactured using microporous Teflon to provide a low loss, phase stable cable for test applications.

The Anritsu Model VNAs: 373XXA and 360B/362XA Test Set were designed for measurement of active devices. They provide programmable step attenuators for controlling Port 1 Power as well as Port 2 test signal level. Power levels as high as 1 watt can be measured. Internal bias tees provide dc bias on the test port center conductor.

The test port coupler design utilizes air dielectric stripline and offers excellent uncorrected directivity and test port match over the entire 40 MHz to 67 GHz frequency range. Figure 2 shows a time domain display which highlights these parameters and shows both to be greater than 20 dB. This performance is important to the user as better uncorrected parameters make the system less sensitive to cable/wafer probe loss and provide a better match for the test device.

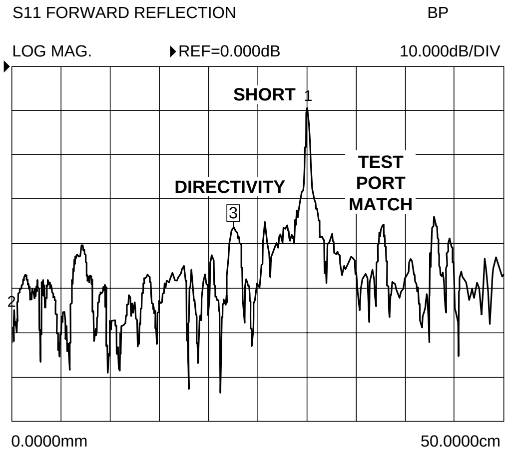


*Figure 2*

## 110 GHz–W Connector®

Anritsu developed the W connector (a 1 mm design) to extend broadband coaxial operation to 110 GHz. Unfortunately, the receiver technology used in lower frequency coaxial systems is not appropriate and it becomes necessary to use more efficient millimeter frequency converters. An effective approach is to combine two VNA systems both of which can be used separately-as shown in Figure 3. This provides a truly broadband 40 MHz to 110 GHz on-wafer measurement system. Bias injection is readily available through the coaxial VNA.

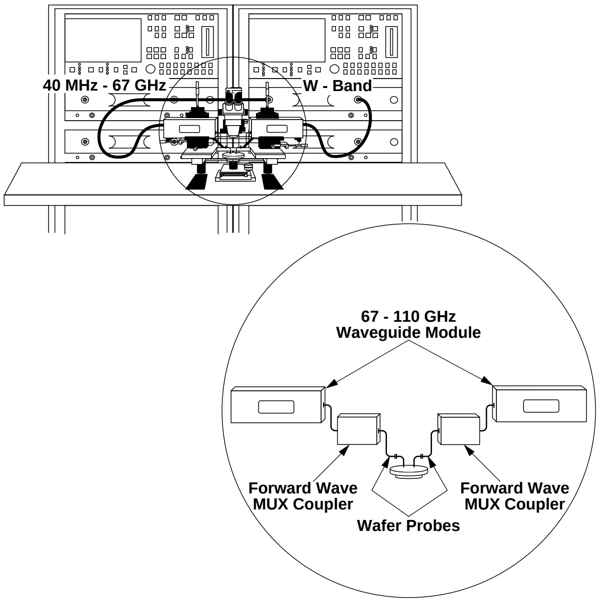


*Figure 3*

## Calibration

The Calibration process is vital to obtaining accurate on-wafer measurement data with a VNA. A great deal of work has been done in the area of on-wafer calibration and users now have several techniques from which to choose. Open-Short-Load-Through (OSLT), Line-Reflect-Line (LRL), and Line-Reflect-Match (LRM) are the most widely used and will be described individually. For more information on calibration techniques and accuracy concerns, consult the list of suggested readings on page 6.

### OSLT

This is the most common VNA calibration technique and it is very applicable to on-wafer measurements even for frequencies as high as 110 GHz! It's accuracy depends upon complete characterization of the four standards used. This characterization is also influenced by the wafer probe geometry. Therefore, probe manufacturers provide information for input to the VNA prior to calibration. For example the GGB40A 150 micron pitch probe recommends:

- Open Capacitance 6.5 fF
- Short Inductance 7.1 pH (This is also equivalent to an offset length of .043 mm.)
- Load Reactance

These parasitic reactances become more important at higher frequencies. At 40 GHz the 6.5 fF capacitance results in a reflection coefficient of minus 9 degrees. Figure 4 shows the result of a broadband calibration (X GHz) with and without the recommended load compensation.

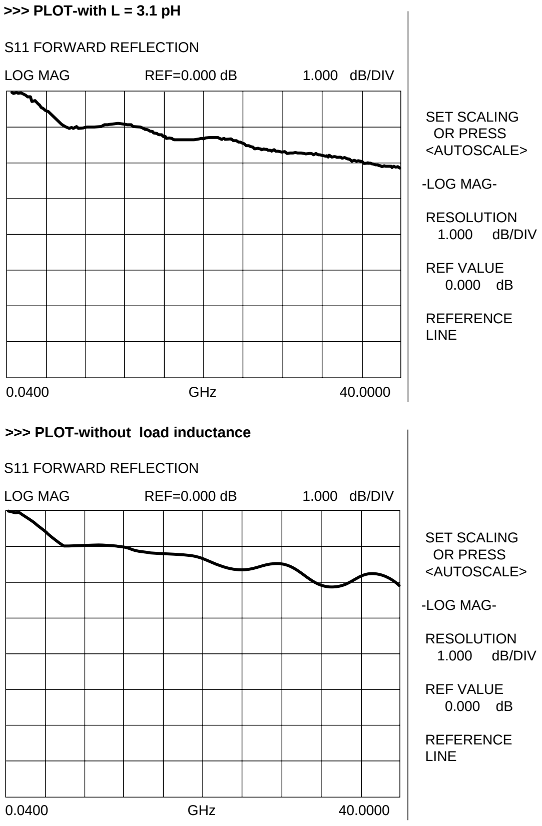


*Figure 4*

The OSLT technique permits calibration with a fixed probe-to-probe spacing if the calibration standards and device under test have the same spacing. This minimizes leakage and crosstalk errors.

### LRL

This technique relies upon transmission line quality for the impedance standard. The LRL technique gets around the requirement of exactly defining a reflection standard such as an open. However, it does require two (or more) transmission lines of different lengths, optimally spaced by $\lambda/4$. This line length dependence leads to frequency range limitation. The maximum recommended calibration frequency range is 9:1 for a pair of lines. The LRL technique is potentially very accurate as the quality of the impedance standard is determined primarily by dimensional precision. LRL standards can be developed as "on-wafer" calibration standards. LRL requires an undesireable change of probe-probe spacing during calibration.

### LRM

LRM can also be used for on-wafer calibration. The M(atch) must be an excellent broadband termination. As with LRL, the reflection standard only needs to be repeatable. The LRM technique also permits calibration with fixed probe-probe spacing. The Anritsu 360B supports true LRM calibration that permits the user to enter the line length of the through used during calibration. This establishes the reference plane at the center or at the ends of that line.

Figure 5 shows the plot of an on-wafer open-circuited transmission line after calibration. The smooth inward spiral indicates that the calibration has resulted in excellent corrected directivity and port match.

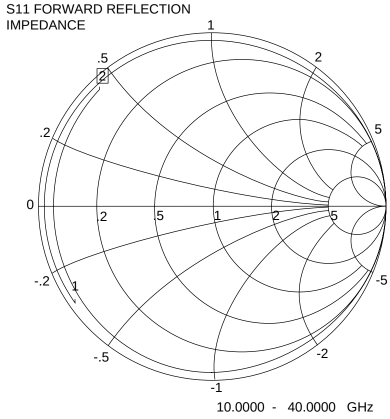


**Figure 5**

NIST (National Institute of Standards & Technology) has an active program for developing traceability for on-wafer measurements. As these techniques are refined they will enable users to evaluate the accuracy of their individual approaches.

## Practical Considerations

There are several practical considerations that significantly affect the quality of on-wafer measurements.

### Cable Losses

A cable and wafer probe are required between the test port connector and the actual on-wafer calibration and measurement port. If losses through the cable and probe are excessive, the result can be a poor calibration. Therefore, it is important to consider test set location and cabling, especially at higher frequencies, to optimize system performance. In general, if cable loss can be held to less than 5 dB at the highest frequency of operation, good results will be obtained. The Models 3612A and 3622A Test Sets contain all of the measurement components required for 62.5 GHz measurements in a single, compact unit – minimizing signal losses and improving amplitude and phase stability.

### Power Level

Power level is an important parameter for on-wafer measurements. The power level can be controlled from the front panel of the 360B. The 360B also provides Flat Test Port Power Correction to insure that linear operation is maintained at all frequencies.

If high-power devices are being tested, one must consider the maximum power that can be input to the VNA for linear sampler operation. All Anritsu Active Device test sets include a built-in 40 dB step attenuator in the foward transmission path. This permits accurate four parameter characterization of devices with output power in the range of +10 to +30 dBm. If on-wafer power dissipation must be minimized to avoid excessive heating, the Anritsu 360PS20A Pulse/CW VNA can be used to make full RF power S-parameter measurements with a low duty cycle pulsed RF stimulus.

### Measurement Speed and Stability

Many on-wafer tests involve hundreds of measurements that take hours to complete. As such, measurement speed and calibration stability become significant factors. The measurement speed of the Anritsu 360B is 8 ms per point with Full 12-Term error-correction applied and no averaging. This is 2.5 to 10 times faster than speeds offered by other VNA systems. Figure 6 shows a plot of the stability of a 360B/3622A system more than 24 hours after calibration. A combination of speed and stability saves test and re-calibration time.

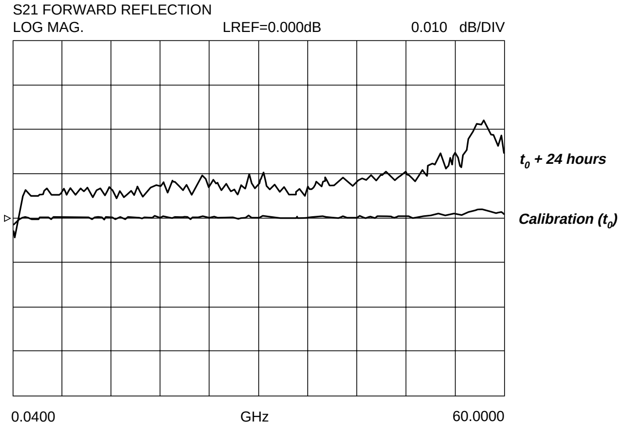


**Figure 6**

### Wafer Probe Placement Repeatability

One of the most common sources of calibration and measurement error is inconsistent placement of the wafer probe(s). This error is analogous to the connector repeatability error present in coaxial measurements. However, probe placement errors are typically much more significant given the nature of the connection between a wafer probe and calibration standard or DUT. For example, a 0.2 mil change in probe placement represents approximately 1 degree of variation in GaAs CPW at 60 GHz.

### Interface to Programs

Data can be obtained on floppy disks in the standard .S2P format for convenient entry into popular design software.

## Applications

### Component Modeling

One of the primary uses for on-wafer measurements is to establish correct models to support component design. The models are often based upon data collected at lower microwave frequencies. Many devices now in development have submicron gate widths with associated $f_T$'s well above 100 GHz. In the millimeter-wave frequency range, measurements must be made to determine parasitic parameters that must be included in these models for accurate device characterization.

It is important to measure the device in the same environment (microstrip, CPW, via configuration, etc.) as it will be used. For example, if the environment is microstrip, the user must de-embed the CPW to microstrip transistion. At 62.5 GHz, this can cause significant measurement error. In other words, an excellent calibration at the probe tips does not guarantee good measurement data.

Figure 7 shows the equivalent circuit of a FET. Figure 8 shows the excellent correlation between modelled and measured data from 0.5 to 60 GHz.

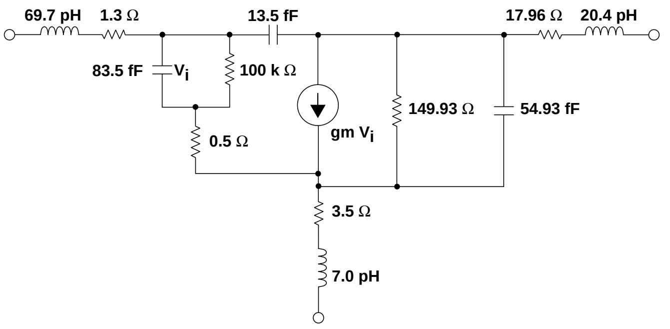


**Figure 7**

| 0.500 – 60.00 GHz | |
|---|---|
| E11 | 8.13 % |
| E12 | 9.92 % |
| E21 | 9.01 % |
| E22 | 4.27 % |
| Ft | 100.21 GHz |
| gm/C | 115.98 GHz |
| gmextr | 56.22 mS |
| gm | 70.00 mS |
| Cgs | 83.50 fF |
| Cgd | 13.50 fF |
| Cds | 54.93 fF |
| Tt | 0.20 pS |
| Rg | 1.30 Ω |
| Rgs | 100.00 Ω |
| Rin | 0.50 Ω |
| Rs | 3.50 Ω |
| Rds | 149.93 Ω |
| Rd | 17.96 Ω |
| Lg | 69.7 pH |
| Ls | 7.0 pH |
| Ld | 20.4 pH |

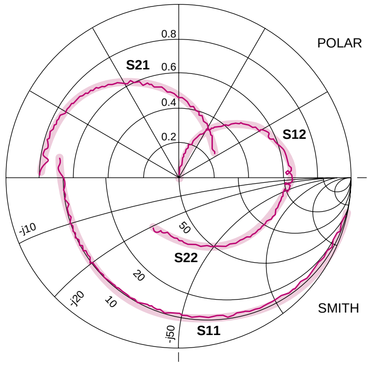


**Figure 8**

### Harmonics–IM Products

Anritsu VNAs offer a Set-On Receiver mode. This enables the user to determine nonlinear performance of devices by displaying harmonics or intermodulation products based upon single or two-tone inputs. Set-On Receiver mode eliminates the need for a spectrum analyzer – significantly reducing system costs. Figures 9 and 10 show the outputs available using this mode.

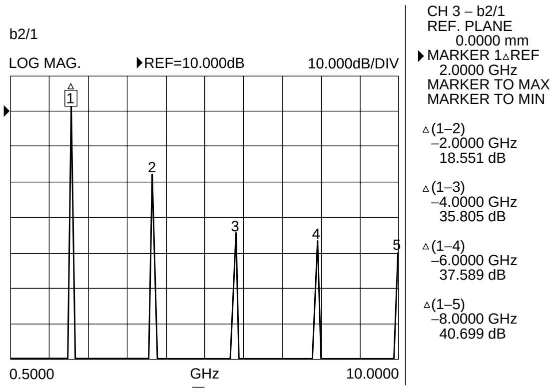


**Figure 9**

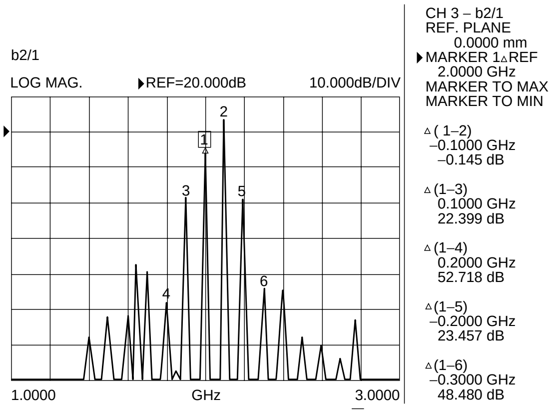


**Figure 10**

### *Suggested Readings*

1. Oldfield, Bill, “Development of Calibration and Verification Standards in Microstrip to 60 GHz,” 34th ARFTG Conference Digest, Winter 1989.
2. Marks, Roger and Phillips, Kurt, “Wafer-Level ANA Calibrations at NIST,” 34th ARFTG Conference Digest, Winter 1989.
3. Williams, Dylan A. and Whinnery, J.R., “On-Wafer Standards at NIST,” 34th ARFTG Conference Digest, Winter 1989.
4. Williams, Frank and Mattern, Jim, “Calibrating Microwave Probes,” Tektronix Application Note, May 1991.
5. Calibration Substrate CS-5, GGB Industries

## *APPENDIX A: On-Wafer Calibration Using The Anritsu VNAs*

On-wafer calibration standards are usually implemented in coplanar waveguide (CPW) to accommodate the CPW design of most microwave and millimeter-wave wafer probes.

The Anritsu VNAs support coaxial, waveguide and microstrip calibration. The geometries involved for on-wafer measurements are quite small and CPW has very little dispersion; therefore, coaxial calibration is appropriate.

- **Step 1:** Press the **BEGIN CAL** key.
- **Step 2:** Select change **CAL METHOD AND LINE TYPE**.
- **Step 3:** Select **STANDARD** (OSLT) or **LRL/LRM** calibration method.
- **Step 4:** Select **COAXIAL** transmission line type.

Proceed as prompted, selecting the calibration type, use of isolation, number of data points, and frequency range. These procedures are also outlined in the Operation Manual.

## *OSLT Setup*

- **Step 5a:** If the Standard (OSLT) method was chosen, select **PORT 1 CONN** from the CONFIRM CALIBRATION PARAMETERS menu (Figure 11).

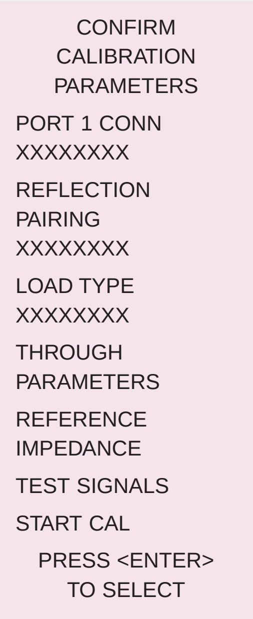


*Figure 11*

- **Step 6a:** Select **USER DEFINED**. Enter the capacitance coefficients and offset lengths recommended by the probe manufacturer. Offset lengths should be entered in mm (air). If the offset is given in time, convert it to distance using the equation:

  Offset Length (mm) =
  Offset Length (ps) x 50.29979

- **Step 7a:** Repeat steps 5a and 6a for the **PORT 2 CONN** selection.
- **Step 8a:** The order in which the Open and Short reflection standards are measured at Port 1 and Port 2 may be defined by selecting **REFLECTION PAIRING** Choose either **MIXED (OPEN-SHORT, SHORT-OPEN)** or **MATCHED (OPEN-OPEN, SHORT-SHORT)** pairing.
- **Step 9a:** The non-zero **THROUGHLINE PARAMETERS** must be defined. The 360B requires the length of the throughline in millimeters. Again, if the length is specified in units of time (ps), convert to distance (mm) as shown in step 6a.
- **Step 10a:** Select **OFFSET LENGTH OF THROUGH** and enter appropriate length.

## LRL/LRM Setup

- **Step 5b:** If the LRL/LRM method was chosen, select **LRL/LRM PARAMETERS** from the CONFIRM CALIBRATION menu.
- **Step 6b:** Select **ONE BAND** for a two-line or one-line/one-match calibration (Figure 12).

CHANGE LRL/LRM
PARAMETERS

NEXT CAL STEP

NUMSBER OF
BANDS USED

ONE BAND

TWO BANDS

LOCATION OF
REFERENCE
PLANES

MIDDLE OF
LINE 1 (REF)

ENDS OF
LINE 1

PRESS <ENTER>
TO SELECT

*Figure 12*

- **Step 7b:** The calibration reference planes may be positioned either inthe **MIDDLE OF LINE 1** or at the **ENDS OF LINE 1**. Select the position that best accomodates the physical configuration of the test device.
- **Step 8b:** Select **LINE 1 (REF)** and enter the length in millimeters.
- **Step 9b:** Choose between an LRL or LRM calibration by toggling between **LINE/MATCH** selections, respectively. If **DEVICE 2 LIN** is selected, enter its length in millimeters. If **DEVICE 2 MATCH** is selected, then the 360B assumes a fullband match standard will be used during calibration.
- **Step 10b:** Enter the manufacturer's recommended **OFFSET LENGTH** (mm) for the reflection standard.
- **Step 11b:** Select the type of reflection standard that will be used during calibration. If the reflection standard resembles an open circuit, select **GREATER THAN Z0**. If the reflection standard is a short circuit, select **LESS THAN Z0** Calibration Setup and Measurement.
- **Step 12:** The **REFERENCE IMPEDANCE** may be set to other than 50 ohms. This value determines the normalizing impedance used on the Smith Chart display.
- **Step 13:** If a constant power level is required at the input of the test device, select **TEST SIGNALS** to initiate the Flat Test Port Power Correction sequence. Refer to the Flat Test Port Power Correction Application Note (AN360B-1) for detailed equipment requirements, instructions, and application information.
- **Step 14:** Select **START CAL** to begin the calibration standard measurement sequence. Proceed with the calibration, connecting the appropriate standards as prompted by the 360B menus. The 360B will measure Port 1 and Port 2 standards simultaneously if **ENTER** is pressed, or one at a time if **1** (Port 1) or **2** (Port 2) numeric keys are pressed (Figure 13).

CALIBRATION
SEQUENCE

CONNECT
CALIBRATION
DEVICES

PORT 1:
XXXXXXXXXXXX

PORT 2:
XXXXXXXXXXXX

PRESS <ENTER>
TO MEASURE
DEVICE (S)

PRESS <1> FOR
PORT 1 DEVICE

PRESS <2> FOR
PORT 2 DEVICE

*Figure 13*

When the calibration sequence is done, the calibration coefficients, front panel setup, and flat power offset values (if used) can be stored using the **SAVE/RECALL** function of the 360B. Recalibration using the same setup parameters can be accomplished simply by selecting **REPEAT PREVIOUS CALIBRATION** when the **BEGIN CAL** operation is initiated.

*LRL/LRM–Calibration method of Rohde & Schwarz, Germany.*

*K Connector and V Connector are registered trademarks of Anritsu Company.*

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