



Basic Verification of Power Loadpull Systems

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What is Loadpull System Verification and Why Do It?

Loadpull relies on *a priori* s-parameter characterization of RF/microwave signal conditioning hardware and power calibration to accurately deembed and characterize DUT parameters, such as power, PAE, and ACPR. The tuners used to present variable source and load impedance must also be *a priori* characterized using s-parameters, relying on Maury's exceptionally well-designed tuners for consistency and repeatability during subsequent measurements.

The data provided by Maury's ATS are a complex function of the individual behavior and mutual interaction of a multitude of individual RF/microwave components and a power calibration. To ensure accurate characterization of the DUT, a structured and well-defined procedure is needed to verify system performance. For basic loadpull system verification, Maury recommends the following procedure:

- Identification of sources of error with a first-order influence on the accuracy of the deembedded DUT characterization data. Note that the significance of a particular type of error is a function of the type of measurement being done.
- Development of a method to measure and quantify error and its subsequent effect on deembedded DUT characterization data.
- Development of a means for controlling and minimizing the error.
- Adoption of a process control methodology to observe system error trends over long timespans.

Verification is done, not in an arbitrary manner, but in a structured and consistent manner, to ensure that the data provided by loadpull represents the actual performance of the DUT, repeatably and accurately.

The present Application Note describes a structured and well-defined technique of identifying, quantifying, and controlling error in a typical loadpull system. An example is provided, using PAE as a means for establishing acceptable system error. A second example is also provided, using an alternative approach.

Common Sources of Error in Loadpull

Improper VNA calibration technique or improper selection of VNA calibration algorithm is the most common, and significant, source of error in loadpull. For common wireless applications, Maury recommends that 7mm TRL calibration be used for all tuner characterization, while 7mm two-tier TRL calibration is recommended for fixture characterization. For higher frequencies in which coaxial fixturing is adopted, 3.5mm or 2.4mm is recommended; SMA connectors should never be used under any circumstances.

Two-tier LRRM or LRM is appropriate for on-wafer applications, either using an ISS or with on-wafer calibration standards. Alternatively, Maury's ATS also provides a proprietary *in situ* calibration method, similar to two-tier calibration. This method is recommended primarily in noise applications where the user has not extracted probe files prior to their insertion into the loadpull system.

Use of SOLT, in either a fixture-based application or an on-wafer application, will result in generally unacceptable errors, and is not recommended.

Poor fixture design or improper wafer-probing etiquette are two common, and very significant, sources of error. Let us consider each of these.

Proper fixture design is based on reliability and ease of calibration and long-term repeatability, in addition to the obvious electrical and mechanical con-



siderations. A splittable fixture, using thin-film substrates with 7mm connectors, is recommended. It is acceptable to use a substrate similar or identical to that used in the final application, although low-cost substrates, such as FR-4, and soft substrates, such as Duroid, should be avoided. In general, bias networks and remote sensing should be on-fixture. Under no circumstances should SMA connectors be used, due to their limited repeatability.

Proper wafer-probing etiquette, including properly planarized probes and secure RF cables, is essential for accurate and repeatable on-wafer measurements. On-die probe alignment scribes are recommended for improved repeatability, especially for high VSWR or mm-wave loadpull. Another common problem with on-wafer probing is use of the incorrect probe type to match the metal system of the die: tungsten probes, or Cascade-Microtech Infinity probes, must be used for aluminum-based metal systems, such as CMOS. Probe loss is a major factor in reducing the DUT reference-plane VSWR.

Less common, but still significant, sources of error, are insecure connections made between signal conditioning components, e.g. a directional coupler and bias tee, or use of damaged signal conditioning components. Every effort should be made to properly torque all components, and ensure their RF performance is acceptable prior to use in loadpull. As a general rule, each and every component's performance should be verified before initial insertion in a loadpull system.

The final source of error in loadpull to consider is the source terminating impedance. The impedance, looking back into the source from the source tuner, has a direct

influence on the DUT source impedance. Maury's ATS allows this impedance to be measured and used to properly establish the correct DUT source impedance. This is particularly important under high VSWR applications, such as 50:1 or more.

Quantifying and Controlling Error in Loadpull

Source and Load Signal-Conditioning Hardware and Test-Fixture/Wafer-Probes

Due to the complex interaction of signal conditioning hardware, microwave tuners, and test-fixtures/wafer-probes, quantifying error is initially best done by characterizing each component separately. Following this step, assembling the hardware in aggregate and measuring specific system parameters, such as Delta_Gt, enables verification of total system performance. We shall describe this procedure presently, including two examples using Delta_Gt for system verification.

Figure 1 shows a block diagram of a basic loadpull system, with blocks delineated for source hardware, source tuner, source fixture/probe, load fixture/probe, load tuner, load hardware, and load power sensor.

Quantifying error begins by first ensuring VNA calibration integrity. Refer to Maury Application Note 5C-026, *Verifying the Performance of Vector Network Analyzers*, for details on VNA calibration.

Following s-parameter characterization of each of the components and blocks described in Figure 1, next remeasure each block using a new VNA calibration. There should be less than 1% difference between each

Power Block Diagram

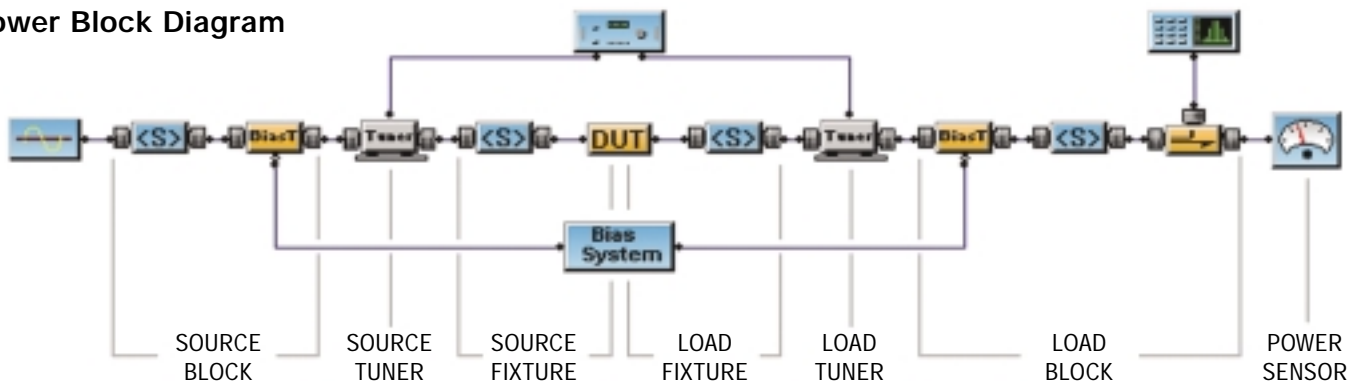


Figure 1. Typical setup for performing power measurements.



measurement for both magnitude and phase of each s-parameter; often just a spot check of a few frequencies is adequate. Note that it is good engineering practice to characterize each component, e.g. directional couplers, prior to insertion in a loadpull system, to ensure functionality. This will greatly reduce the probability of measurement errors later.

For the test-fixture verification, insert the THRU standard¹ and attach port 1 of the fixture to port 1 of the VNA and port 2 of the fixture to port 2 of the VNA. Insert the resulting two-port s-parameter data into an s-parameter simulation tool, such as Agilent ADS. Next,

insert the s-parameter files for each fixture half into the s-parameter simulator and connect port 2 of the source fixture to port 2 of the load fixture, emulating the configuration of the hardware measurement. Perform an s-parameter simulation of the concatenated fixture halves and compare the simulated s-parameters to those measured previously. Often it is best to plot error, as Figure 2 shows. The fixture used to generate this data was based on 99% alumina with thin-film. An error more than a few tenths of a percent indicates a problem in the measurement or the calibration. For comparison, Figure 3 shows an unacceptable response for the fixture concatenation test.

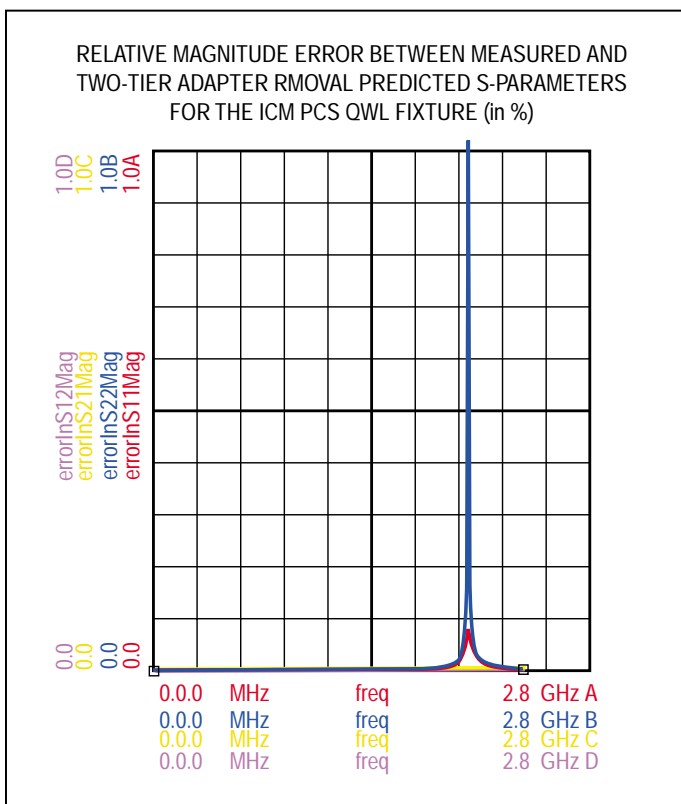


Figure 2. Error response of test-fixture concatenation test showing typical response of a high-performance fixture and calibration. Note that this test can be used to determine the $B\Omega$ of the TRL calibration, since the effect of the $\lambda/2$ degeneracy is clearly manifested as a spike in the error response.

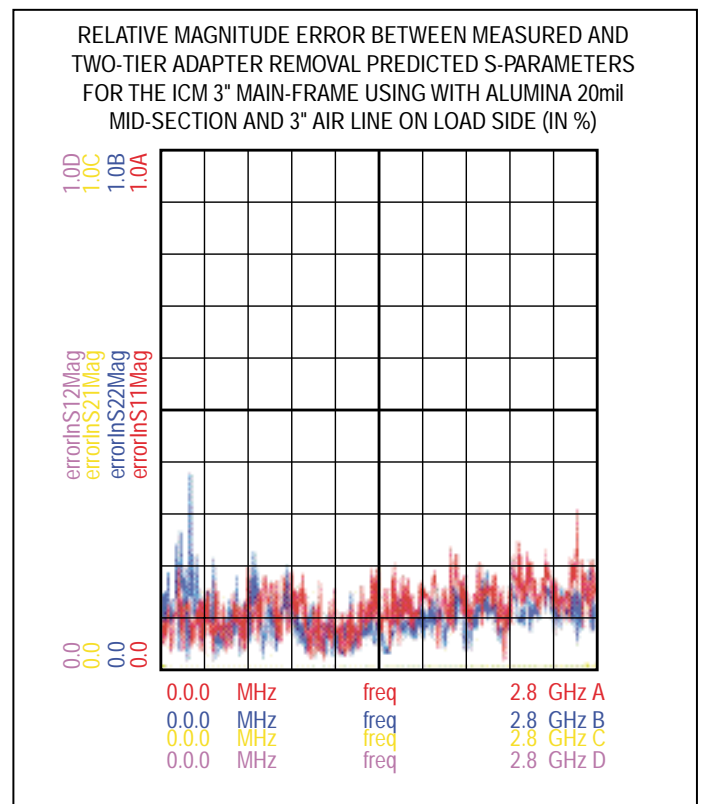


Figure 3. Error response of test-fixture concatenation test showing undesirable response.

¹ In the case of a splittable test-fixture, the THRU is an abstraction in the sense that both fixture halves are actually just concatenated together; this test is often referred to as the fixture concatenation verification.



This procedure can be repeated for an on-wafer system, using the THRU standard on the ISS. Particular care must be used to ensure consistent probe-tip alignment. Again, alignment scribes are helpful.

These tests are intended to identify any significant issues before connecting all the hardware comprising the loadpull system. Satisfactory completion of these tests is a reliable indicator that system calibration is okay. The next test is intended to determine relative system error with all hardware components and tuners connected together.

Introduction to Delta_Gt and Verification Example #1

Delta_Gt verification can be applied in a variety of fashions, although the physical basis of it does not change. The Delta_Gt verification compares the measured transducer gain, G_t , to that predicted by cascading the s-parameters of each of the blocks of the loadpull system shown in Figure 1[1]. The THRU standard must be defined for this test. If the test is conducted by concatenating the two fixture halves, it is assumed to be an ideal THRU standard.² If the THRU standard is inserted to emulate a package, with a THRU standard in place of a transistor, for example, then the s-parameters of the THRU must be known. Considering the former, it becomes an ideal THRU and the transducer gain is simply the mismatch loss between the source and load tuners. This is expressed as

$$G_t(s) = \frac{[1 - |\Gamma_{source}|^2][1 - |\Gamma_{load}|^2]}{|1 - \Gamma_{source}\Gamma_{load}|^2} \quad (1)$$

For this Delta_Gt example, first perform a power calibration (or two-tone or digital modulation calibration) that spans a region near the noise floor of the system to the point near compression at the maximum power point. The available power range should be at least 15 dB to 20 dB. Prior to

performing calibration, ensure that any power amplification present in the loadpull system has reached thermal steady-state, as any temperature-induced gain variation in the PA will show up directly in the Delta_Gt test. It may also be desirable, depending on the linearity of the PA, to use "Snap to Cal'd Power" in the <Power> options; this will turn off power interpolation during subsequent loadpull measurements. Figure 4 shows how to implement this setting.

At the completion of the power calibration, next execute a measurement from the <Measurement> menu. For example, if a CW calibration was performed, then select <Start CW Measurement> from the <Measurement> menu. Alternatively, use the <Alt+W> hotkey to directly access the CW Power Measurement option.

When this is selected, the window shown in Figure 5 appears. Ensure that the "Use S-Parameters" option is selected and that the power range is appropriate, as described previously. Also ensure the correct file name is entered that describes the s-parameters of the THRU. Then press <OK>.

The Power Measurement Screen next appears. Bring up the Measurement Parameter Selection window and activate $G_t(s)$, G_t , Delta_Gt, Pout, and Pin_avail; deactivate all other parameters. Figure 6 shows this window with the appropriate settings.

Next ensure that the source and load tuners are at the default 50Ω position. Execute a power sweep using the default minimum and maximum available source power. At sweep completion, plot $G_t(s)$, G_t , and Delta_Gt.

This sweep verifies that the source and load signal conditioning hardware are properly deembedded, since the tuners are merely acting as 50Ω transmission lines. This sweep can also be used to isolate issues between the source and load tuners, fixture/probes, and source and load signal conditioning hardware. Gross issues with either source or load tuner files would appear here as well.

² Subject, essentially, to the repeatability of inserting the THRU standard.

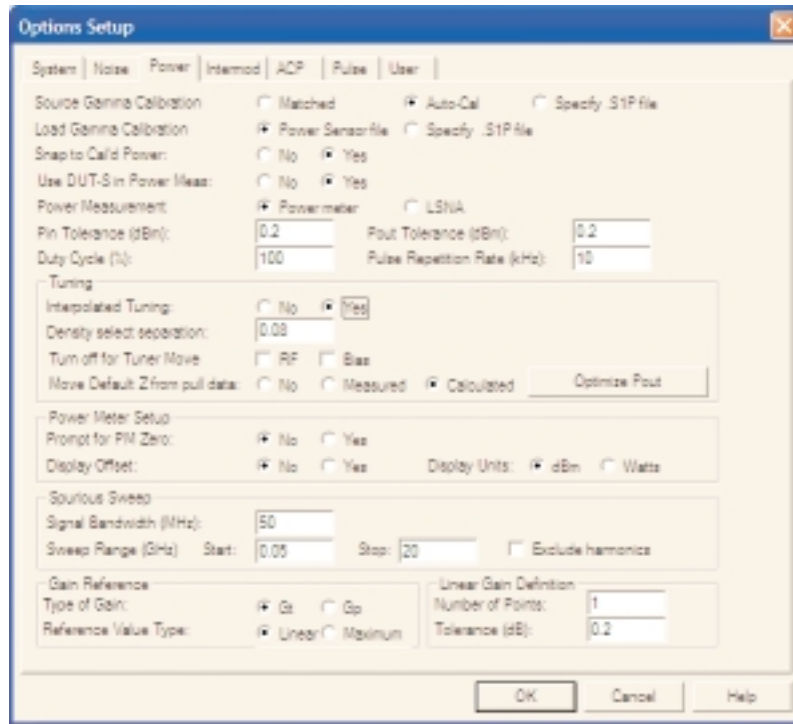


Figure 4. Power options control panel illustrating where to set “Snap to Cal'd Power” option. Execute <Options and Configuration> and then select the <Power> tab. Alternatively, use the <Ctrl+K> hotkey to bring up the Options Control Panel.

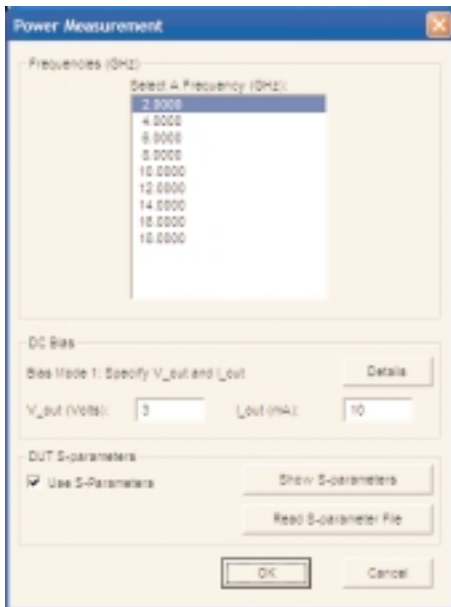


Figure 5. Power Measurement window illustrating the settings for “Use S-Parameters” prior to starting power measurement for system verification.

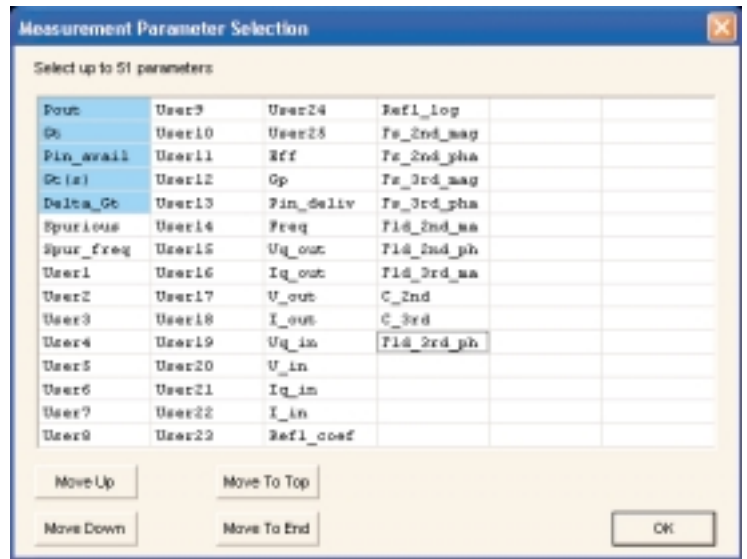


Figure 6. Measurement Parameter Selection window showing proper selection of Gt(s), Gt, and Delta_Gt.



Figure 7 shows a typical response at 1.95 GHz. A range of ± 0.05 dB is normal for this step of the Delta_Gt verification.

The next step of the Delta_Gt verification involves examination of Delta_Gt under mismatch. Generally, this step is done at a couple of impedances that are close to the edge of the Smith chart, near the expected region of DUT characterization. It can also be supplemented by verification at other regions of the Smith chart.

Since most power applications are near the left side of the Smith chart, the present example will use source and load impedances in this region. Begin by returning to the power measurement screen and selecting a source and load impedance near the left edge of the chart at the maximum VSWR. The impedances need not be identical, and will seldom be, since no two turners are exactly alike. Try to

choose approximate conjugates of each other for source and load impedance.

Next execute a power sweep. Note that the available power for this sweep will be lower than the previous sweep, since the loss of the source tuner has increased. Figure 8 shows a typical response at 1.95 GHz. A range of ± 0.1 dB is normal for mismatch up to about 50:1, with ± 0.3 dB normal for mismatch in the 100:1 range. As an example of a lower limit on Delta_Gt under very high mismatch, [2] shows a test-fixture design using thin-film alumina with a 500:1 mismatch and less the 0.1 dB Delta_Gt.

While the Delta_Gt test is useful for ensuring proper relative calibration of a loadpull system (note that it does not verify absolute power) the question still remains to address item 3 from the verification list in the first section: developing a means of controlling and minimizing the error. This we will do in the next section.

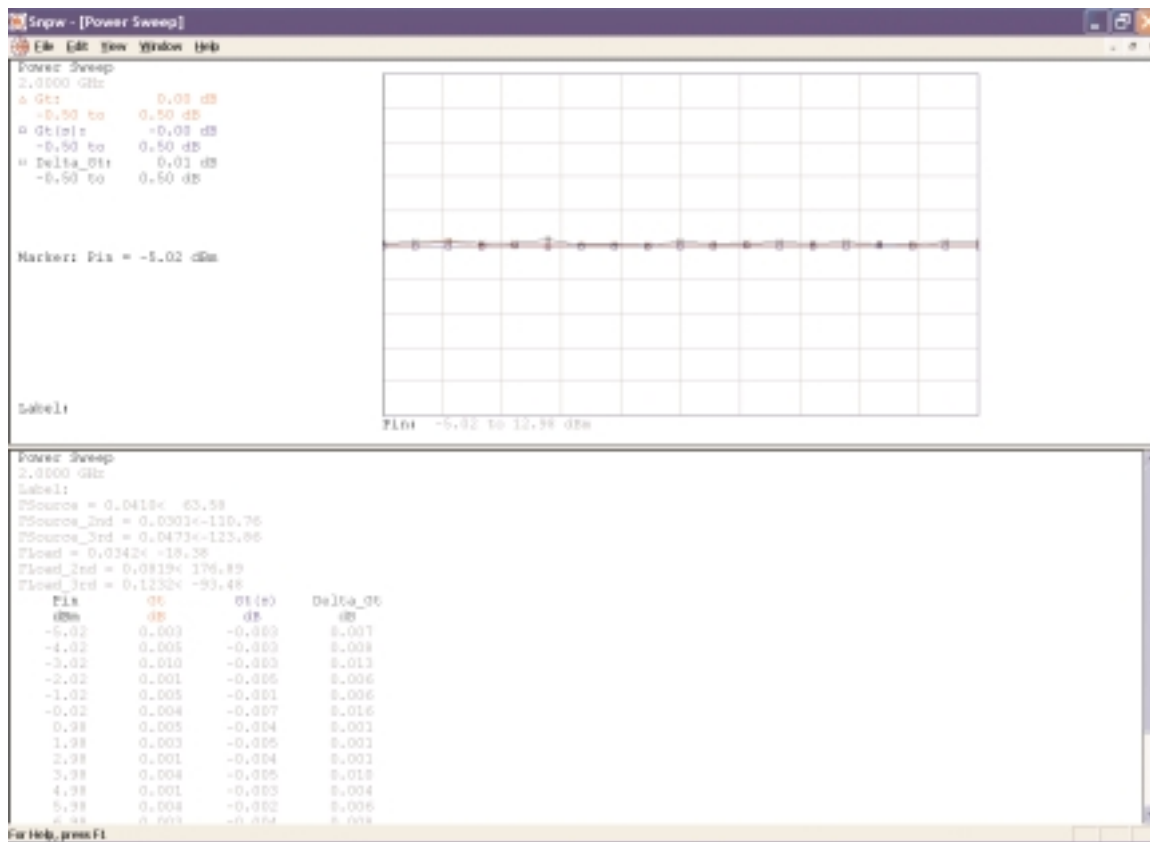


Figure 7. 50 Ω Delta_Gt test illustrating expected response.



How Small Should Delta_Gt Be?

In the first section we described four elements of loadpull verification: identification of sources of error, development of a method to quantify the error, development of a method to control and minimize the error, and implementation of a method to track calibration (process) data over long time spans. The first two have been considered. Presently we are concerned with how small Delta_Gt should be to control or minimize the error.

The answer to this question depends on the type of characterization being done. For example, the two most common applications of loadpull are to establish optimum performance bounds of a particular device technology and identification of source/load impedance and bias for optimum DUT performance in a circuit.

Establishment of optimum performance bounds is generally related to pizza-mask evaluation of wafer-lots from a fab, particularly during the process development phase. Here loadpull repeatability and parametric

resolution are paramount, more so even than tuner impedance accuracy. It is often said during this type of characterization that it is better to be repeatably wrong than randomly right, since the ability to resolve -65 dBc EDGE ACPR from slight changes in epitaxial material is essential as various wafer-lots are evaluated.

Identification of optimum source/load impedance and bias is generally needed by PA designers to properly terminate and bias a DUT to achieve a desired level of performance. Here the ability to repeatably resolve impedance and bias are paramount, since the next step for the designer is to duplicate the loadpull conditions in the circuit to achieve the performance observed under loadpull.

To illustrate a method for identifying how small Delta_Gt should be, we consider an example related to use of loadpull for identification of optimum source/load impedance for PA design. The idea is to relate Delta_Gt to a parameter in the PA target specification which has a known range of accept-

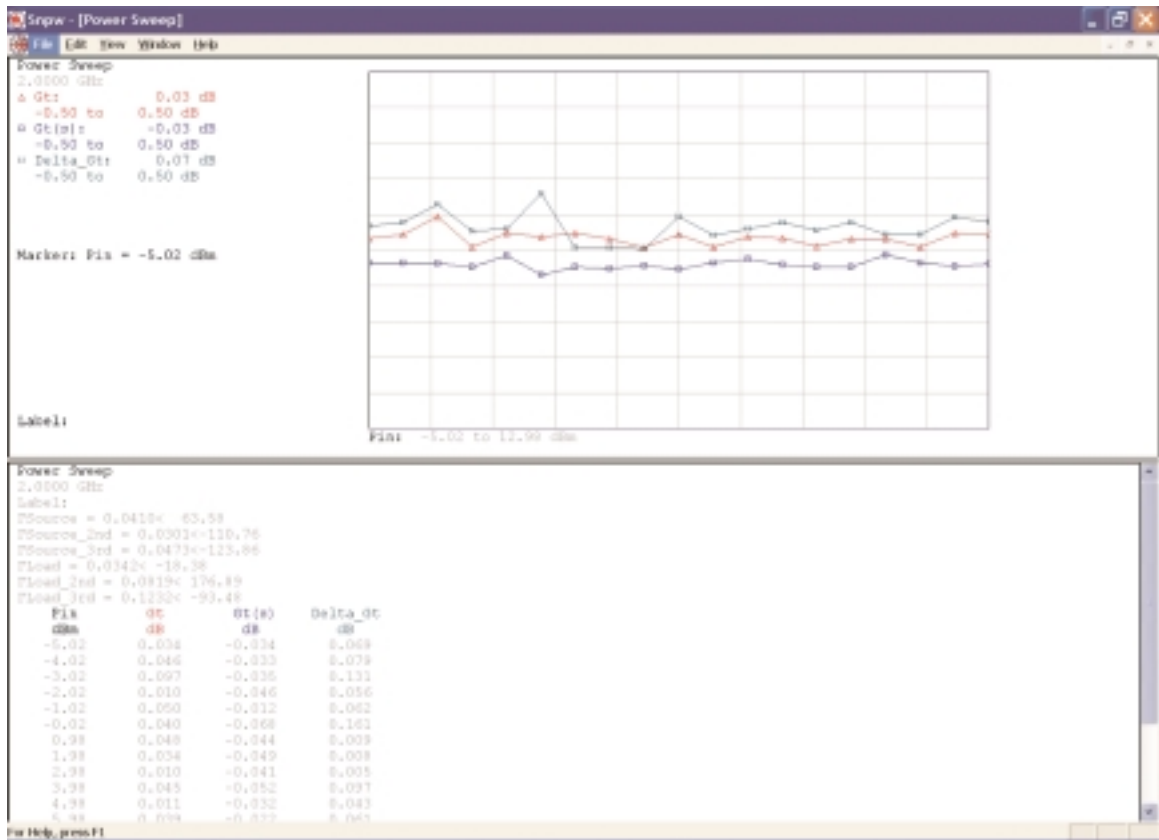


Figure 8. High VSWR Delta_Gt test illustrating expected response.



ability. Knowing this range, we can estimate what the acceptable range of Delta_Gt is to ensure the resultant uncertainty of the PA level specification is acceptable.

PAE is a critical specification for virtually all PA designs. Therefore, it is a logical choice to consider relating PAE, and its acceptable range, to Delta_Gt. A typical GSM PAE specification will have a typical PAE requirement of 57% and a minimum PAE requirement of 53%. Since PAE is a direct function of Gt, we can attempt to relate the range of acceptable PAE to an acceptable range of Delta_Gt by making some worst-case assumptions³.

Assuming the load impedance transformation network loss is 0.5 dB, a typical value, then the loadpull PAE must range from 59% to 64%. If we assume an otherwise ideal loadpull system, except for an error in gain or power, and assume all the gain error is present at the load side, then we see that insertion loss can be treated as Delta_Gt. Figure 9 shows a plot of measured PAE versus actual PAE for various values of insertion

loss. We can see at the typical specification of 57% that the range of observed PAE goes from 65% to 72%, a change of 7% over a 0.5 dB change in gain.

From this, we can conclude that the PAE uncertainty with Delta_Gt of 0.5 dB could be, under worst-case conditions, 7%, which exceeds the allowable typical-to-minimum difference in PAE as prescribed in the target specification. Working backwards this time, with the 4% range from the target specification, we can estimate Delta_Gt to be approximately 0.4 dB. In fact, for small changes such as this, in the neighborhood of 60% PAE, the change in Delta_Gt is nearly linear with respect to a change in PAE.

Thus, a useful rule-of-thumb is that every percent allowable range in PAE is a tenth of a dB in Delta_Gt. Therefore, for most wireless applications, a Delta_Gt of 0.2 dB to 0.4 dB is acceptable, although every effort should be made to obtain the smaller value of 0.2 dB. For device process characterization, Delta_Gt of 0.2 dB or less is desirable.

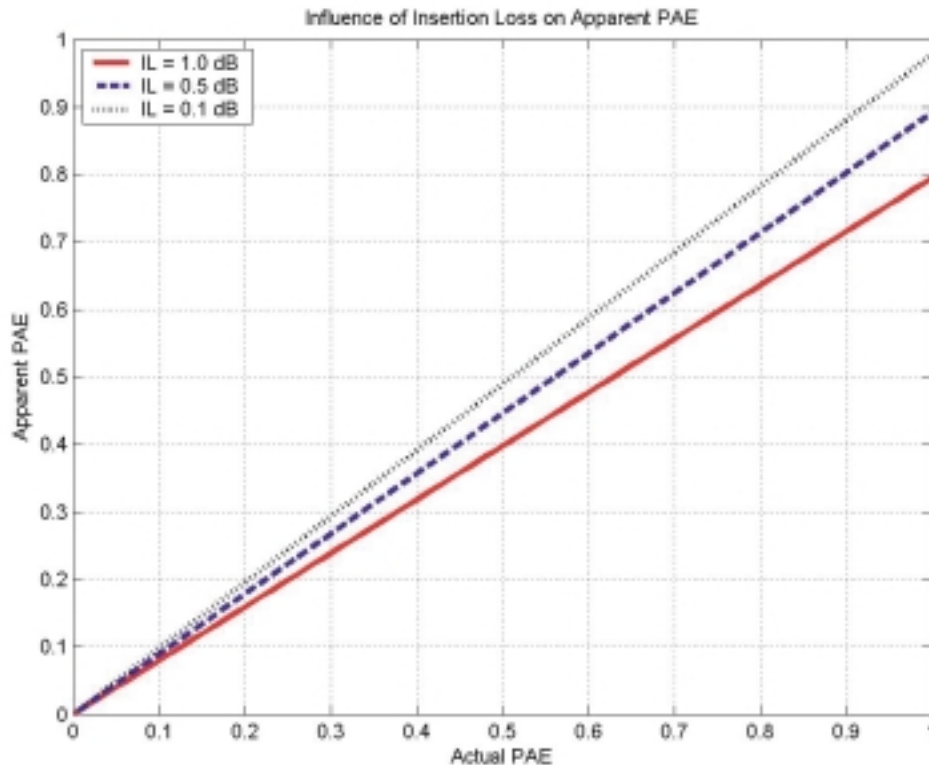


Figure 9. Plot showing the effects of insertion loss, assumed to be lumped together in Delta_Gt, on apparent and actual PAE to estimate the Delta_Gt value necessary for a given level of uncertainty.

³ Strictly speaking, it is Gp, power gain. We assume zero reflected DUT power, yielding Gp = Gt, a worst-case assumption.



Verification Example #2

The example given previously offers some useful advantages, such as the ability to relate Delta_Gt to a DUT parameter, thereby enabling an analysis to determine an acceptable Delta_Gt [1]. In addition, the method enables easy process tracking of Delta_Gt over time by recording each of the Delta_Gt data, with respect to power. As the number of samples increases, any deviation from expected behavior is readily observable, flagging the user to the presence of a calibration issue.

This method is somewhat limited, however, with respect to viewing impedance error over the entire Smith chart in one plot. To do this, we present in this section another method for using Delta_Gt. Consider (1) with the source tuner set for 50Ω . This yields

$$Gt(s) = 1 - |\Gamma_{load}|^2 \quad (2)$$

Now consider what happens if we keep the magnitude of Γ_{load} constant and sweep the phase and compare the predicted mismatch with that measured by ATS. In general, we will see a ripple pattern, which is an indicator of error present in the system.

For this Delta_Gt example, first perform a power calibration (or two-tone or digital modulation calibration) that spans a typical power range for your application; be sure to be sufficiently high in power to avoid the noise floor of the system. The available power range should be at least 15 dB to 20 dB. Prior to performing calibration, ensure that any power amplification present in the loadpull system has reached thermal steady-state, as any temperature-induced gain variation in the PA will show up directly in the Delta_Gt test. It may also be desirable, depending on the linearity of the PA, to use "Snap to Cal'd Power" in the <Power> options; this will turn off power interpolation during subsequent loadpull measurements. Figure 10 shows how to implement

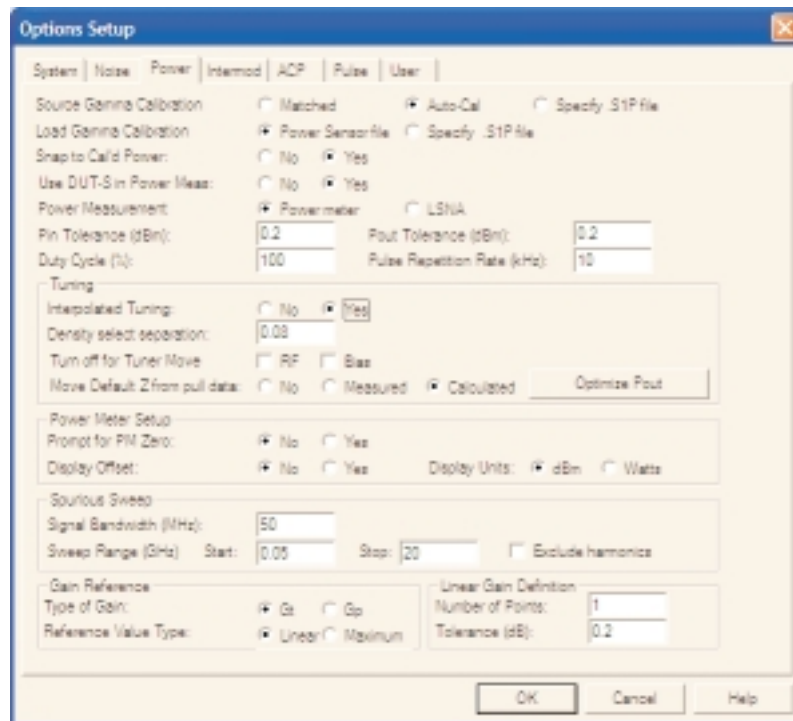


Figure 10. Power options control panel illustrating where to set "Snap to Cal'd Power" option. Execute <Options and Configuration> and then select the <Power> tab. Alternately, use the <Ctrl+K> hotkey to bring up the Options Control Panel. Interpolated tuning is also set here, which should be set to "YES".



this setting. Also in this dialog, “Interpolated Tuning” must be set to “YES.”

At the completion of the power calibration, next execute a measurement from the <Measurement> menu. For example, if a CW calibration was performed, then select <Start CW Measurement> from the <Measurement> menu. Alternatively, use the <Alt+W> hotkey to directly access the CW Power Measurement option.

When this is selected, the window shown in Figure 11 appears. Ensure that the “Use S-Parameters” option is selected and that the power range is appropriate, as described previously. Also ensure the correct file name is entered that describes the s-parameters of the THRU. Then press <OK>.

The Power Measurement Screen next appears. Bring up the “Measurement Parameter Selection” window and activate Gt(s), Gt, and Delta_Gt, Pout, and Pin_avail; deactivate all other parameters. Figure 12 shows this window with the appropriate settings.

Next ensure that the source tuner is set for the default 50Ω position. From the <Setup> menu, chose <Set

power Level> (or alternatively, use the Ctrl+A hotkey) and choose a reasonable power level. Next, go to the <Measurement> menu and chose <Constant VSWR Loadpull> (or alternatively, use the Alt+V hotkey). In the dialog box, enter a VSWR that puts the load tuner near its maximum range; use the default phase settings and keep the circle centered at the origin.

At sweep completion, plot Gt(s), Gt, and Delta_Gt. Depending on the frequency, the tuner, and VSWR, a Delta_Gt of 0.2 dB to 0.4 dB is typical. Figure 13 shows a typical response at 1.95 GHz. a range of ±0.3 dB is normal for this step of the Delta_Gt verification with a 30:1 VSWR.

This sweep illustrates any gross errors in tuner files and source and load deembedding files. Disadvantages of this method of Delta_Gt include limited ability to relate measured Delta_Gt to a DUT parameter to estimate a reasonable Delta_Gt and lack of a swept power dimension. Nevertheless, the data can be recorded and tracked over time; any deviation from expected performance will readily appear, and corrective action can be taken to ensure proper calibration.

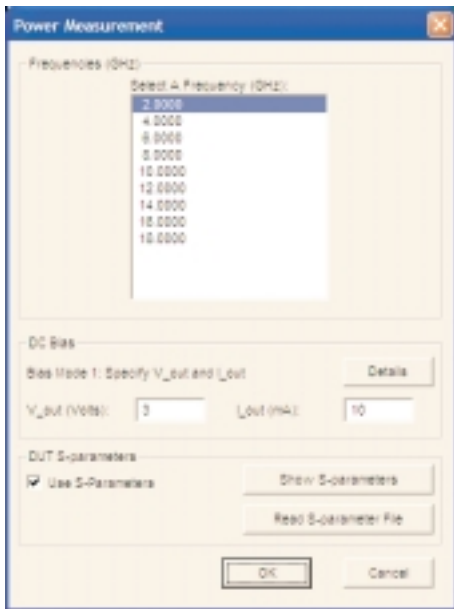


Figure 11. Power measurement window illustrating where to set “Use S-Parameters” prior to starting power measurement for system verification.

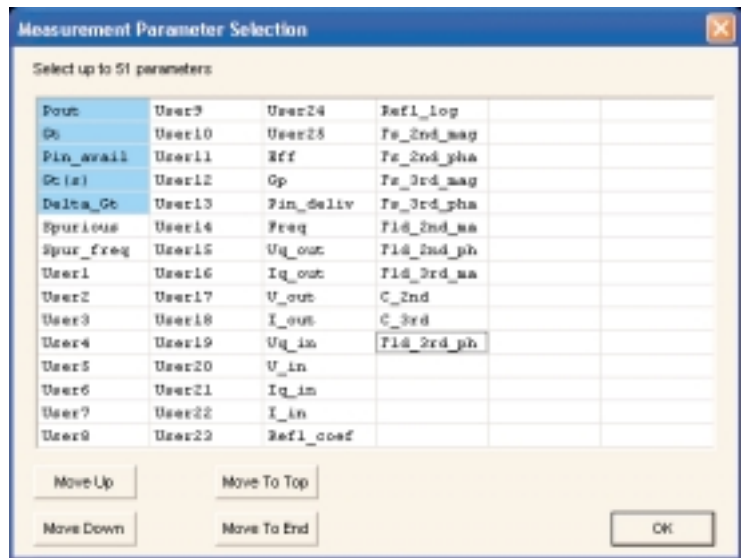


Figure 12. Measurement Parameter Selection window showing proper selection of Gt(s), Gt, and Delta_Gt.

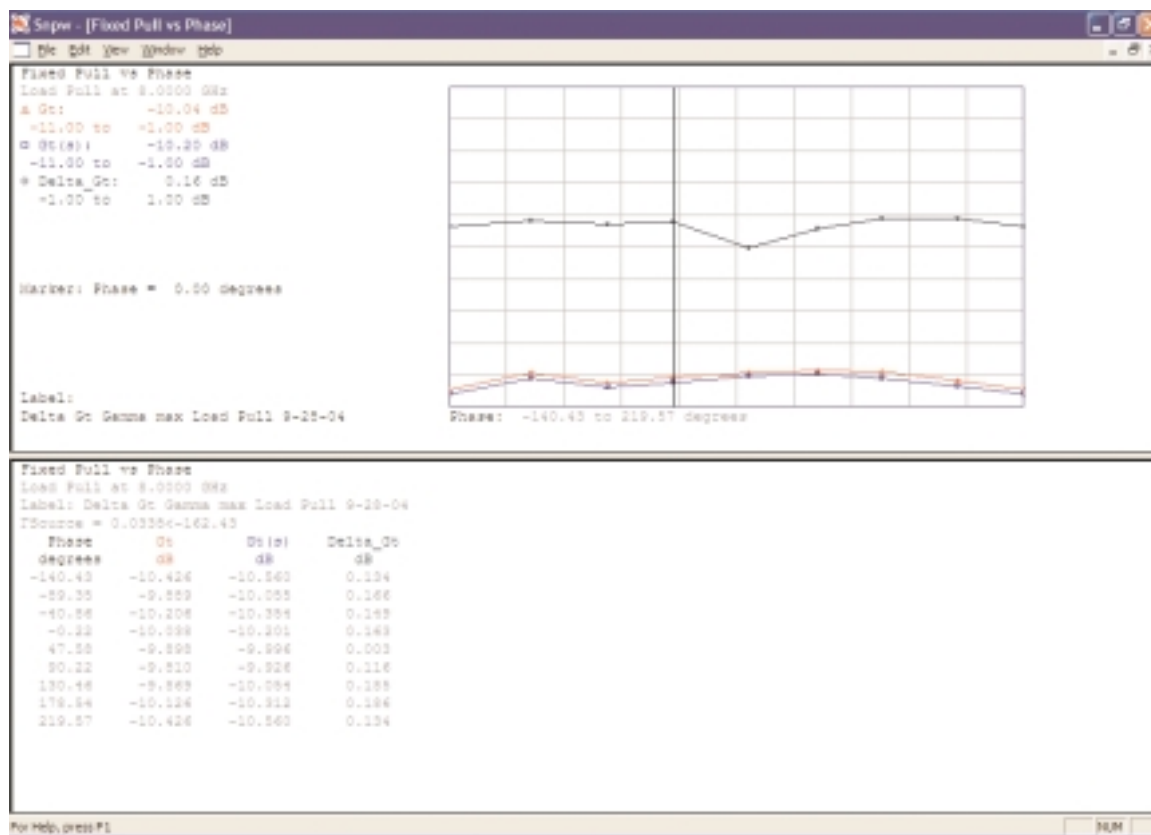


Figure 13. A typical response at 1.95 GHz. A range of ± 0.3 dB is normal for this step of the Delta_Gt verification with a 30:1 VSWR.

Summary

This application note has presented a rigorous method of verifying loadpull calibration for power applications. By comparing expected Gt, using s-parameters, with the Gt measured by the loadpull system, an estimate of system error can be derived using Delta_Gt.

For basic loadpull system verification, the following criteria were presented:

- Identification of sources of error with a first-order influence on the accuracy of the deembedded DUT characterization data. Note that the significance of a particular type of error is a function of the type of measurement being done.
- Development of a method to measure and quantify error and its subsequent effect on deembedded DUT characterization data.
- Development of a means for controlling and minimizing the error.
- Adoption of a process control methodology to observe system error trends over long time spans.

Two examples were given, using Delta_Gt, to illustrate application of these criteria. The first example illustrated a means for relating Delta_Gt to allowable variation of a DUT parameter, PAE, to guide how small Delta_Gt should be. This is a major advantage of the procedure presented in this example.

The second example presented a method that allows gross errors to be readily captured. Both examples enable capturing of process data to track system performance over time to identify when there is an issue with calibration.

Following these simple guidelines from Maury will ensure your ATS provides accurate, precise, and repeatable data.

References

- [1] Internal Report, J. Sevic; Qualcomm, Inc. 1997.
- [2] J. Sevic, "A Sub-1 Ohm Load-Pull Quarter-Wave Pre-Matching Network Based on a Two-Tier TRL Calibration"; *Proceedings of the 52nd ARFTG Conference*, pp. 73-81, 1998.