



# *“PA Load Pull Error Limits using Delta $G_t$ Contours”*

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- Load Pull tuners sweep all reflection coefficient space.
  - Maury Load Pull Tuner Systems are used for this presentation.
- Tuners characterizations are used in gain contour calculations:
  - Accuracy of S-Parameter characterization is critical.
  - Repeatability of connectors and cables are important.
  - The Power Block Diagram needs to be set up properly.
- Delta  $G_t$  can be used to confirm the system accuracy.
  - Insert a characterized low loss through between tuners.
  - Sweep out the reflection coefficients for the tuner.
    - Initially the outside ring with  $45^\circ$  points and the center.
    - Over-night sweeps of all reflection space and frequencies.
  - Both Source and Load tuners should be verified.
  - Start with a simple coax system and then progress to more complex on-wafer and diplexer or triplexes setups.



- The three types of RF Gain:

- **Available Gain** = (available output power)/(available input power)

$$G_a = f(\Gamma_S, [S]) = \frac{(1 - |\Gamma_S|^2) |S_{21}|^2}{|1 - S_{11}\Gamma_S|^2 (1 - |\Gamma_2|^2)} \text{ where, } \Gamma_2 = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S}$$

- **Power Gain** = (delivered output power)/(delivered input power)

$$G_p = f([S], \Gamma_L) = \frac{|S_{21}|^2 (1 - |\Gamma_L|^2)}{(1 - |\Gamma_1|^2) |1 - S_{22}\Gamma_L|^2} \text{ where, } \Gamma_1 = S_{11} + \frac{S_{21}S_{12}\Gamma_L}{1 - S_{22}\Gamma_L}$$

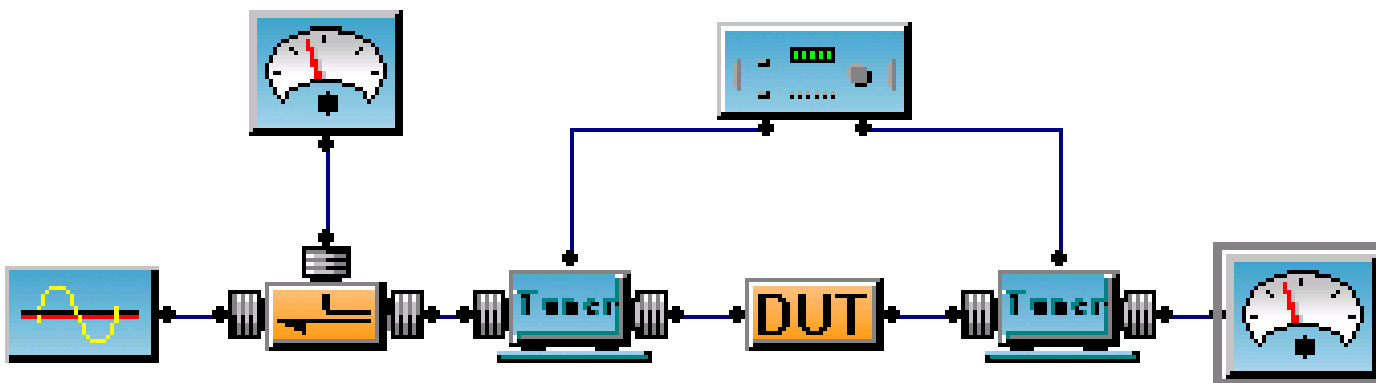
- **Transducer Gain** = (delivered output power)/(available input power)

$$G_t = f(\Gamma_S, [S], \Gamma_L) = \frac{(1 - |\Gamma_S|^2) |S_{21}|^2 (1 - |\Gamma_L|^2)}{|1 - S_{11}\Gamma_S|^2 |1 - \Gamma_2\Gamma_L|^2}$$

**A function of  
Both  $\Gamma_S$  &  $\Gamma_L$ .**



- Delta  $G_t$  (dB) =  $G_t\{\text{measured}\}$  (dB) -  $G_t[S]$  {calculated} (dB).
- **DUT Available Input Power** can be calculated rigorously:
  - Using Pre-Calibrated Tuner S-Parameters and  $Z_{\text{source}}$
- **Delivered Output Power** is measured by the Power Sensor.
- A low loss thru is used for the DUT in Delta  $G_t$  errors testing.
- Delta  $G_t$  error is minimum near  $Z_0$ , maximum at high VSWR.



Label: Delta\_Gt Minimum Configuration Test



- Delta  $G_t$  requires “Use DUT S-parameters in Power Measurement.

Main-Menu → Setup → Options → Use DUT-S

The screenshot shows the Snpw software interface with the 'Options Setup' dialog box open. The 'Power' tab is selected. The 'Use DUT-S in Power Meas' option is highlighted with a red box. Other options like 'Cal RF Source Match' and 'Prompt for PM Zero' are also highlighted with red circles. The 'Options Setup' dialog box has the following settings:

- System: [ ]
- Noise: [ ]
- Power: [x]
- Intermod: [ ]
- ACP: [ ]
- User: [ ]
- Cal RF Source Match:  No  Yes  Use .S1P file
- Prompt for PM Zero:  No  Yes
- Use DUT-S in Power Meas:  No  Yes
- Snap to Cal'd Power:  No  Yes
- Interpolated Tuning:  No  Yes
- Move Default Z from pull data:  No  Measured  Calculated
- PM Display Units:  dBm  Watts
- PM Display Offset:  No  Yes
- Pin Tolerance (dBm):  Pout Tolerance (dBm):
- Duty Cycle (%):  Pulse Repetition Rate (kHz):
- Spurious Sweep:  Exclude harmonics
- Signal Bandwidth (MHz):
- Sweep Range (GHz) Start:  Stop:
- Gain Reference: Type of Gain:   $G_t$    $G_p$  Reference Value Type:  Linear  Maximum
- Linear Gain Definition: Number of Points:  Tolerance (dB):



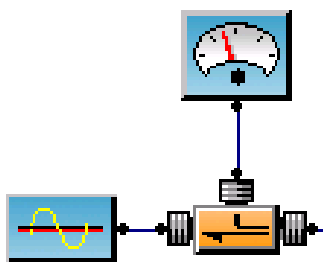
# Delta $G_t$ Contours: Power Calibration

Snpw - [C:\Program Files\Maury\ATS300\Delta\_Gt\_Test.cfg]

File Edit View Setup Calibrate Measure Fixture Window Help



## Power Blo



- Read Tuner Files
- SNP System...
- 2 Port S-Parameters...
- 1 Port S-Parameters...
- Noise
- Power**
  - New Cal...**
  - Get Cal File
  - Cal Vector
- Intermod
- ACP
- Save Power Cal...
- Initialize Tuners...
- Go to Z0

Power Calibration

Frequencies (GHz)

Available: 4.9000 GHz to 5.9000 GHz, 6 Frequencies

4.9000  
5.1000  
5.3000  
5.5000  
5.7000  
5.9000

Add Frequency

Add Frequency Range

Delete Frequency

Delete All Frequencies

Set to Available Frequencies

Thru s-parameters

S-parameter file name:

C:\Program Files\Maury\ATS300\Data\W8021A2thru\_8freq

Browse

Programmed power range (dBm)

Start: -30

Stop: 10

Step: 1

Offset of RF Source 2 compared to RF source 1:

0

OK

Cancel

Label: Delta\_Gt Minimum Configuration Test (Output=E4...

Do a new power calibration



# Delta $G_t$ Contours: Source Pull Set-up

Source Gamma  
Should be less  
Than 0.2 max.

**Snpw - [Power Calibration]**

Freq GHz	$\Gamma_{source}$ mag phase	P_programmed dBm	P_avail dBm	coupling dB
4.900	0.103 128.43	10.00	5.20	-10.46
		-10.00	-14.89	
		-9.00	-13.89	
		-8.00	-12.95	
		-7.00	-11.98	
		-6.00	-10.97	
		-5.00	-9.95	
		-4.00	-8.94	
		-3.00	-7.93	
		-2.00	-6.96	
		-1.00	-5.93	
		0.00	-4.91	
		1.00	-3.89	
		2.00	-2.94	
		3.00	-1.94	
		4.00	-0.93	
		5.00	0.12	
		6.00	1.12	
		7.00	2.14	
		8.00	3.16	
		9.00	4.17	
		10.00	5.68	-10.31
		-10.00	-14.30	

**Source**

**Snpw - [Power Calibration]**

Connect thru for power calibration

**Snpw - [Power Calibration]**

Connect output power sensor to power reference

**Snpw - [Power Calibration]**

Re-connect output power sensor to circuit and connect reflection power sensor to power reference

**Snpw - [Power Calibration]**

Re-connect reflection power sensor to circuit

Cable Loss +3dB Pad.



# Delta $G_t$ Contours: Measure $\rightarrow$ Power

The screenshot shows the Snpw software interface with a test configuration and a 'Power Measurement' dialog box open.

**Test Configuration:**

- Menu: Measure > Power
- Block Diagram: Signal source  $\rightarrow$  BiasT  $\rightarrow$  Tuner  $\rightarrow$  DUT  $\rightarrow$  Tuner. A Bias System block is connected to the BiasT block.
- Label: Delta\_Gt Minimum Configuration Test (Output=E441)

**Power Measurement Dialog:**

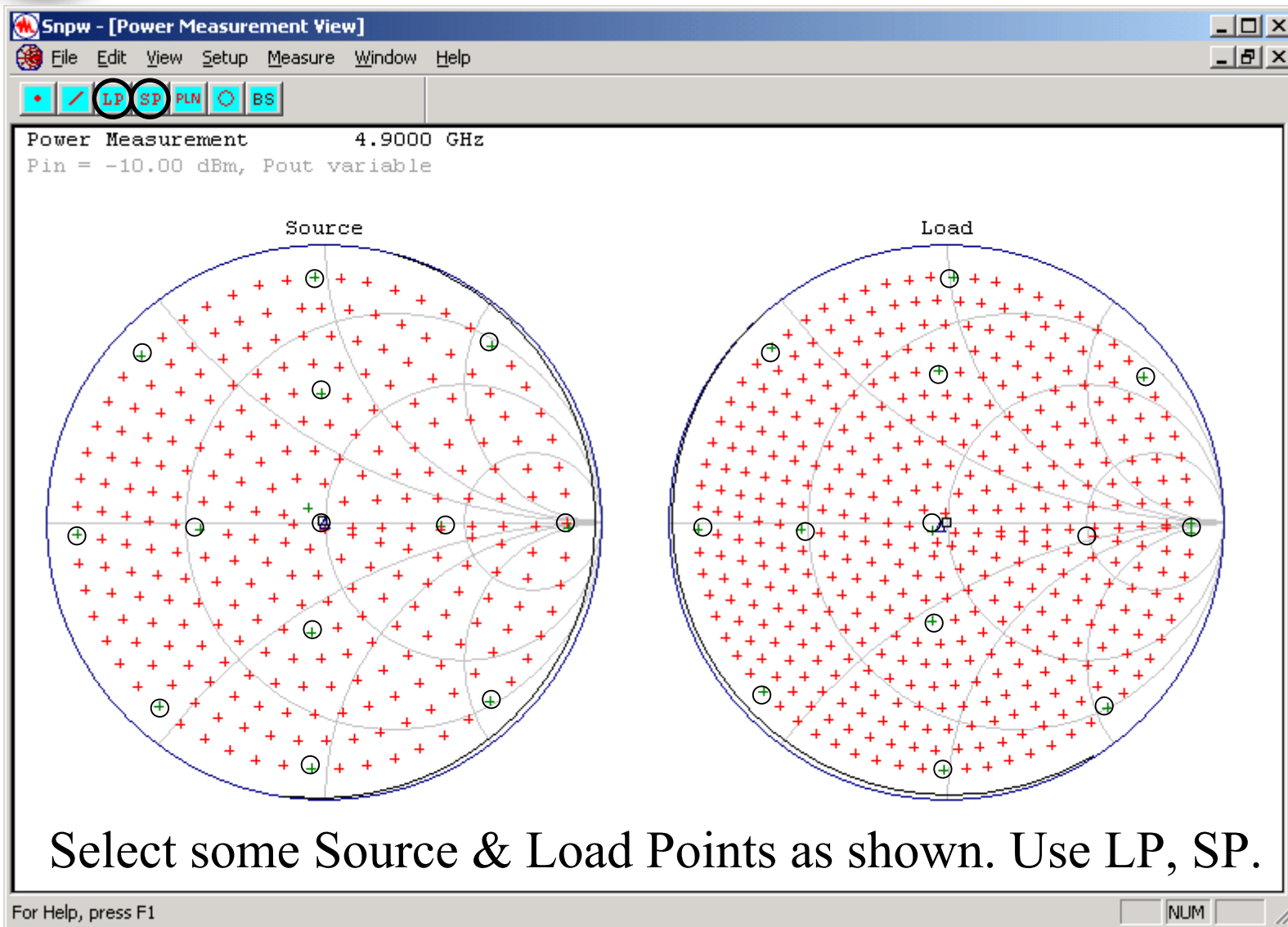
- Section: Frequencies (GHz)
- Text: Select A Frequency (GHz):
- List: 4.9000 (selected), 5.1000, 5.3000, 5.5000, 5.7000, 5.9000
- Section: DC Bias
- Text: Bias Mode 4: Specify V<sub>out</sub> only
- Text: V<sub>out</sub> (Volts): 3.3
- Text: 0
- Section: DUT S-parameters
- Text:  Use S-Parameters
- Text: Show S-parameters
- Text: Read S-parameter File
- Buttons: OK, Cancel

Measure power amplifier performance vs. impedance





# Delta $G_t$ Contours: Measurement Pre-Checks





# Delta $G_t$ Contours: Table

Snpw - [Fixed Pull vs Phase]

File Edit View Window Help

Fixed Pull vs Phase  
 Source Pull at 4.9000 GHz  
 Label:  
 ZLoad (Ohms) = 49.24 + j 1.92

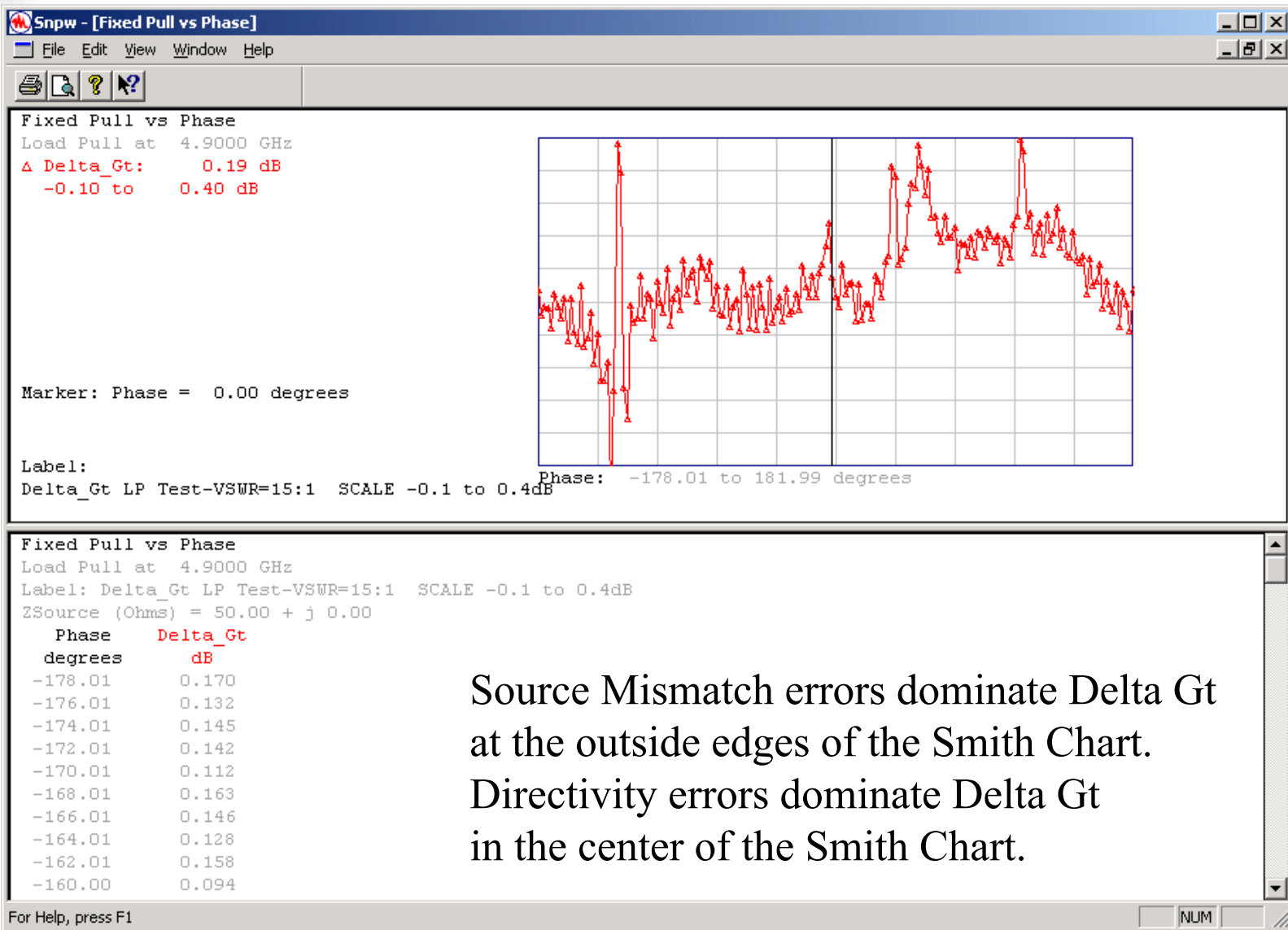
Phase degrees	Gt dB	Gt (s) dB	Delta_Gt dB	Pin_avail dBm	Pin_deliv dBm
-178.85	-6.706	-5.524	-1.182	-10.000	-19.425
-130.55	-7.150	-5.767	-1.384	-10.000	-19.764
-91.01	-7.044	-6.405	-0.638	-10.000	-19.141
-88.01	-1.431	-1.193	-0.238	-10.000	-11.636
-46.42	-6.595	-6.920	0.325	-10.000	-17.743
-32.28	-0.053	-0.031	-0.023	-10.000	-10.137
-1.22	-0.592	-1.089	0.496	-10.000	-10.550
3.57	-5.900	-7.098	1.198	-10.000	-16.866
41.38	-5.705	-6.913	1.208	-10.000	-16.282
84.79	-0.660	-0.993	0.332	-10.000	-10.825
92.30	-5.611	-6.502	0.891	-10.000	-16.719
138.19	-6.300	-6.012	-0.288	-10.000	-18.164
173.15	-1.398	-0.831	-0.568	-10.000	-11.821
181.15	-6.706	-5.524	-1.182	-10.000	-19.425

For Help, press F1

NUM



# Delta $G_t$ Contours Phase Plot for VSWR=15



Source Mismatch errors dominate Delta  $G_t$  at the outside edges of the Smith Chart.  
Directivity errors dominate Delta  $G_t$  in the center of the Smith Chart.

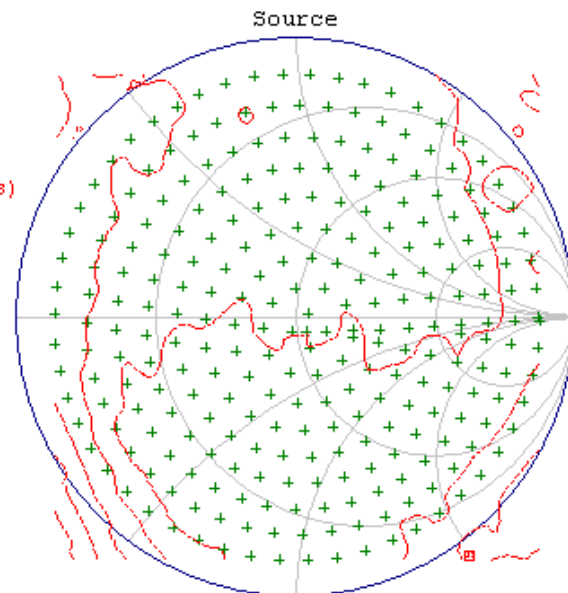


# Delta $G_t$ Contours All Points Plot

- **Source Delta\_  $G_t$**   
**#contours = 1**  
**@ 0.25dB/step**  
**maxDeltaGt=0.9dB**  
**A reasonable error.**

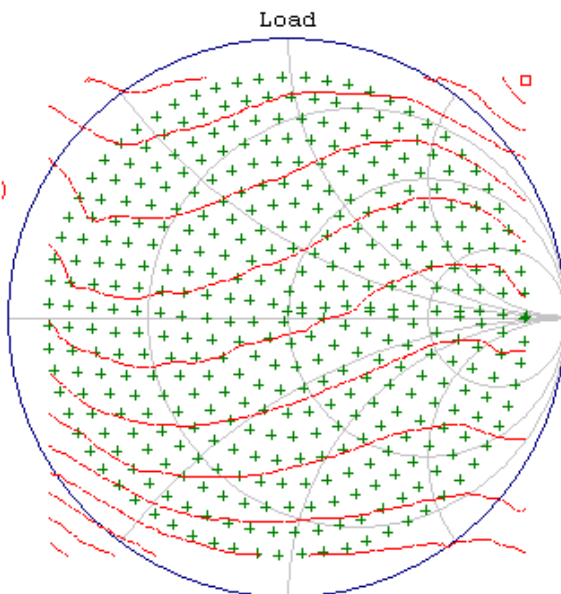
Swept Source Pull  
 Freq = 5.3000 GHz  
 ZLoad (Ohms): 50.00 + j 0.00

Delta\_  $G_t$  max = 0.94 dB  
 at -7.03 - j98.47 Ohms  
 (Pin\_avail=-10.00 dBm, 267/267 pts)  
 124 contours, 0.25 dB step  
 (-30.00 to 0.75 dB)  
 Specs: OFF



Swept Load Pull  
 Freq = 5.3000 GHz  
 ZSource (Ohms): 54.49 - j12.68

Delta\_  $G_t$  max = 1.49 dB  
 at -29.82 + j115.49 Ohms  
 (Pin\_avail=-10.00 dBm, 399/399 pts)  
 124 contours, 0.25 dB step  
 (-29.50 to 1.25 dB)  
 Specs: OFF



- **Load Delta\_  $G_t$**   
**#contours = 8**  
**@ 0.25dB/step**  
**maxDeltaGt=1.75dB**  
**Undesirable Errors.**



# Delta $G_t$ Contours: ANA Accuracy.

- ANA characterization accuracy for S-parameters:



Typical Automatic Network Analyzer Accuracy Comparison:

Repeatability of thru calibration after 4~24hours and 2~5C change.

<b>5~6GHz</b>	<b><u>PNA</u></b>	<b><u>8510</u></b>	<b><u>8720</u></b>	<b><u>8753</u></b>	
S11	-60	-55	-50	-45	dB
S21	0.001	0.005	0.007	0.01	dB

The optimum frequency range is 1/2 to 2/3 of the maximum.

Connectors are the major factor in ANA reconnect repeatability.

Cables are a major factor in ANA accuracy & stability.

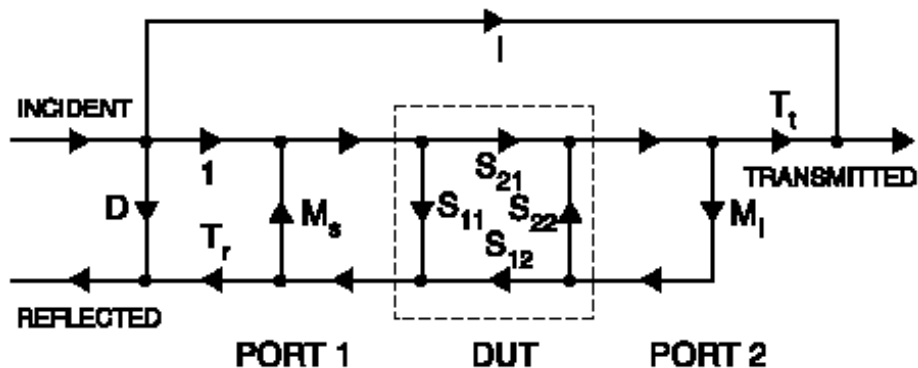
Temperature coefficient of S21 is about 0.001dB/degree.

Hint: Cal with IF BW=10Hz, Measure with IF BW=100Hz & Avg=1, On.



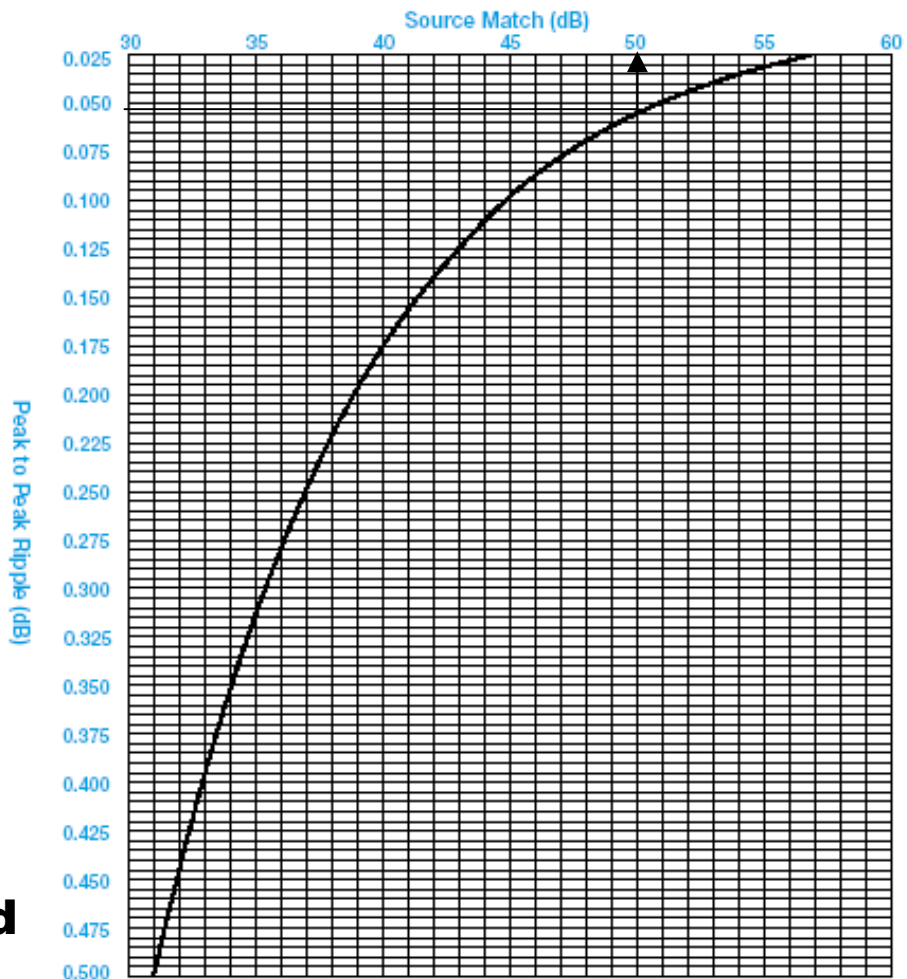
# Delta $G_t$ Contours: ANA Errors

- ANA verifications should be performed after calibration:



- D = Directivity
- $T_r$  = Reflection Frequency Response Tracking
- $M_s$  = Source Match
- I = Isolation
- $M_l$  = Load Match
- $T_t$  = Transmission Frequency Response Tracking

Source Match(dB) vs. Peak to Peak Ripple(dB)

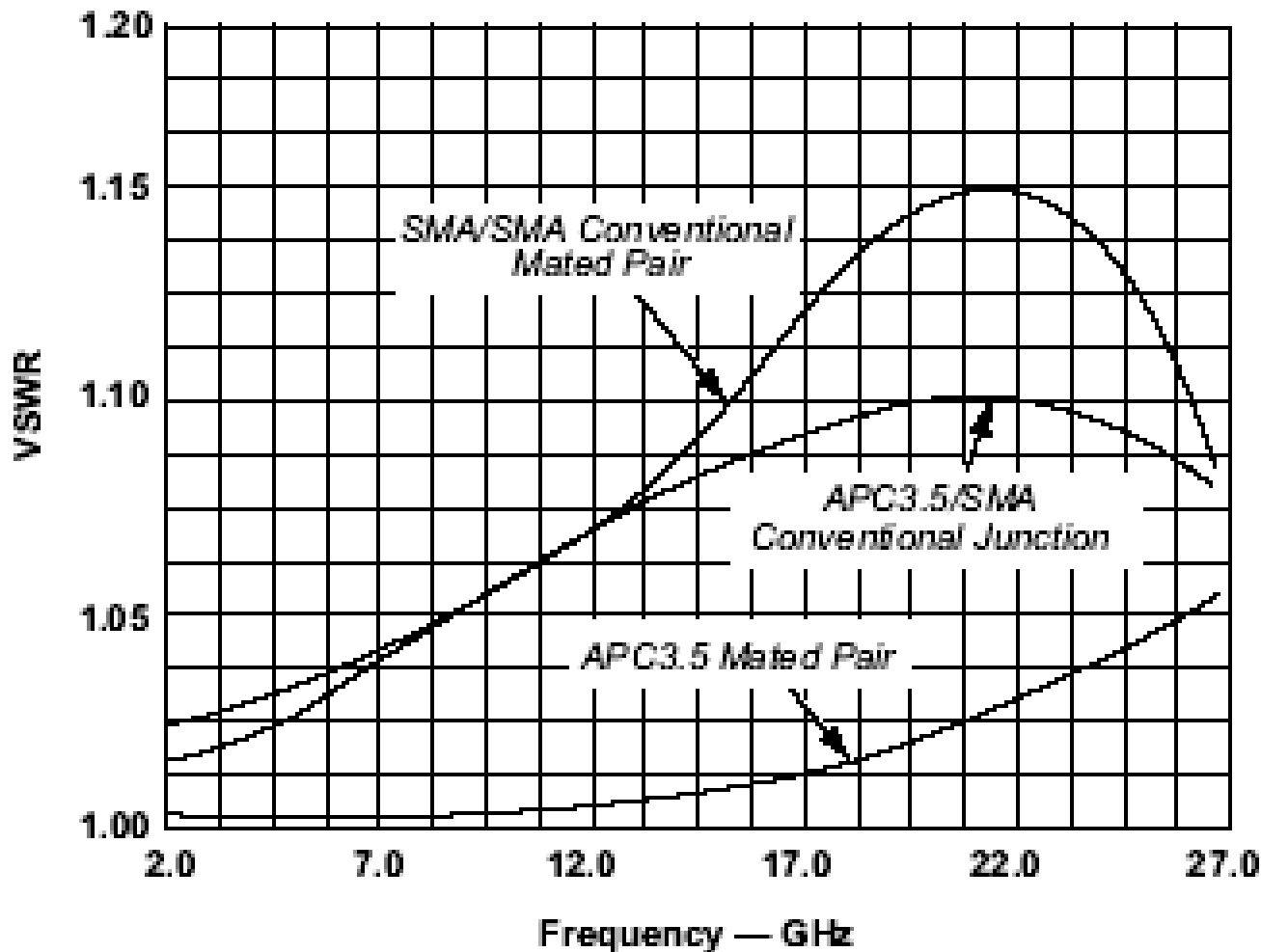


- Use clean calibrated standards.
- Confirm with a verification kit 10cm precision airline terminated with a short. Examine the ripple.



# Delta $G_t$ Contours: SMA vs. 3.5mm

- SMA vs. 3.5mm mated pair VSWR: Use 3.5mm or better connectors!





# *Delta $G_t$ : Connector Repeatability.*

- Connectors affect the repeatability of VNA S-Parameters.

<b>Type</b>	<b>Freq.(GHz)</b>	<b>VSWR</b>	<b>Directivity</b>	<b>Zs Match</b>	<b>Torque</b>
Type N	18GHz	1.030+0.003f	42dB	32dB	12 in.lb.
7.00mm	18GHz	1.003+0.002f	52dB	42dB	12 in.lb.
SMA	18GHz	1.050+0.005f	3XdB	2XdB	<b>5</b> in.lb.
3.50mm	26.5GHz	1.010+0.004f	44dB	34dB	8 in.lb.
2.92mm	40GHz	1.0X0+0.00Xf	40dB	34dB	8 in.lb.
2.40mm	40GHz	1.0X0+0.00Xf	38dB	33dB	8 in.lb.
1.85mm	60GHz	1.0X0+0.00Xf	36dB	29dB	8 in.lb.
Connector repeatability should be better than 50dB					
If a slotless center connector is used, increase this by 8dB.					
Overtorquing and rotating are major connector wear problems.					
Clean connectors are imperative.					





# Delta G<sub>t</sub> Contours Sweep Plan Use

**Snpw - [Power Measurement View]**

File Edit View Setup Measure Window Help

Single Measurement  
Power Sweep  
Bias Sweep  
Load Pull  
Source pull  
Incremental Mode  
VSWR Circle  
Optimum search  
**Sweep Plan**  
Move Tuners  
Initialize Setup  
Go to Local

Power Measurement  
Pin = -10.00 dBm,

Start sweep plan

**Sweep Plan Measurement - Setup**

Available Freqs: 4.9000 to 5.9000 GHz, 6 frequencies

Measurement Frequencies (GHz)

4.9000	Add
5.3000	Add Range
5.9000	Delete
	Delete All
	Select All Available

Tuners, impedance pull

Fundamental Source  Yes  No

2nd Harmonic Source  No

3rd Harmonic Source  No

Fundamental Load  Yes  No

2nd Harmonic Load  No

3rd Harmonic Load  No

Bias Range

Start: 3.3 Stop: 3.3 Step: 1

Bias Variable: V\_out (Volts)

Input Power Range (dBm)

Available Pin\_avail range: -33.5053 dBm to 3.4926 dBm

Start: -10 Stop: -10 Step: 1

Maximum Compression (dB): 6

Read File Save File

< Back Next > Cancel Help

NUM

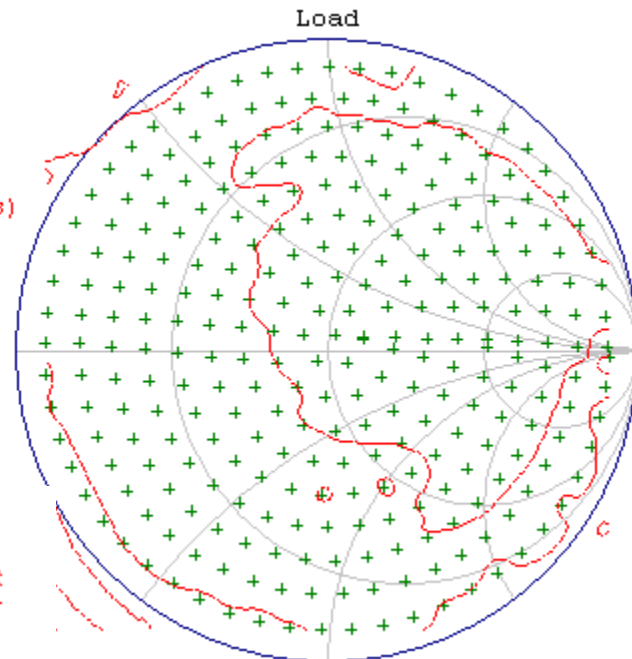


# Delta G<sub>t</sub> Contours All Points Sweep

- **Load Delta\_Gt**  
**#contours = 72**  
**@ 0.25dB/step**  
**maxDeltaGt=0.8dB**

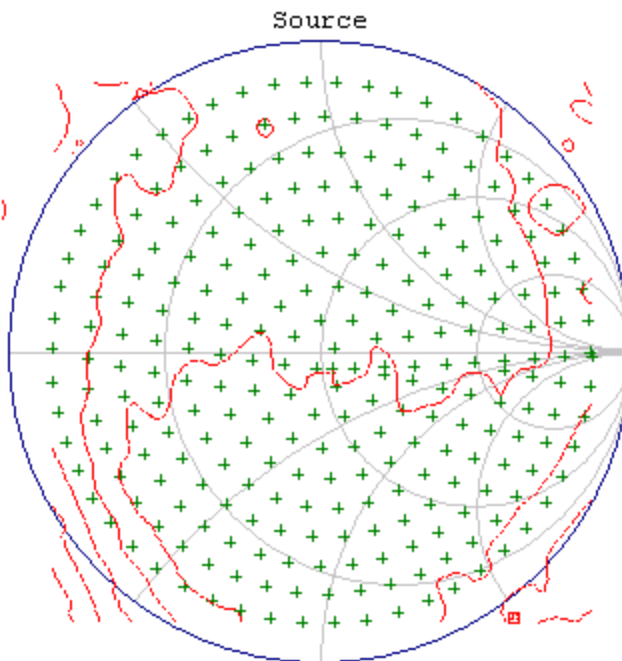
Swept Load Pull  
 Freq = 5.3000 GHz  
 ZSource (Ohms): 50.32 - j 0.64

Delta\_Gt max = 0.81 dB  
 at -6.95 - j20.32 Ohms  
 (Pin\_avail=-10.00 dBm, 287/287 pts)  
 124 contours, 0.25 dB step  
 (-30.00 to 0.75 dB)  
 Specs: OFF



Swept Source Pull  
 Freq = 5.3000 GHz  
 ZLoad (Ohms): 50.00 + j 0.00

Delta\_Gt max = 0.94 dB  
 at -7.03 - j98.47 Ohms  
 (Pin\_avail=-10.00 dBm, 267/267 pts)  
 124 contours, 0.25 dB step  
 (-30.00 to 0.75 dB)  
 Specs: OFF



- **Source Delta\_Gt**  
**#contours = 3**  
**@ 0.25dB/step**  
**maxDeltaGt=0.9dB**



- Delta  $G_t$  verification tests should be run prior to any Load Pull.
- $G_t$  is the most appropriate gain parameter since it contains both source and load matching terms.
- S-Parameter characterizations are a major source of uncertainty in the Delta  $G_t$  Load Pull system test.
  - Calibrations, connectors, and cables are very important.
  - Upgrading to new cables and connectors may be required.
- Contours are an easy way to view Delta  $G_t$  data.
  - Increase the number of contours to the 128 maximum
  - Select the Max or Min value to best display results.
  - Count the number of contours to get an estimate.
  - Select points at min & max area's to determine values.
- Re-calibrate & Re-characterize to reduce errors <0.5dB.



- **References:**

1. Guillermo Gonzalez, *"Microwave Transistor Amplifiers: Analysis and Design"*, pp183 Prentice Hall 1997
2. "Measurement of Large Signal Device Input Impedance During Load Pull Applications", Maury Microwave Application Note 5C-029 [[www.MauryMW.com](http://www.MauryMW.com)]
3. Joel Dunsmore & Dennis Poulin, Personal Communications, Aug.~Sept. 2003.
4. "Verifying the Performance of Vector Network Analyzers", Maury Microwave Application Note 5C-026 [[www.MauryMW.com](http://www.MauryMW.com)]
5. "Improving SMA Tests with APC3.5 Hardware", Maury Microwave Application Note 5A-011 [[www.MauryMW.com](http://www.MauryMW.com)]
6. "Microwave Coaxial Connector Technology: A Continuing Evolution", Mario Maury Microwave Journal, 1990 State of the Art Reference pg. 39~59
7. Connectors: [www.amphenolrf.com](http://www.amphenolrf.com), [www.agilent.com](http://www.agilent.com), [www.us.anritsu.com](http://www.us.anritsu.com)