Fast, Simple, Accurate: Modern Methods of Test for Amplifiers

Joel Dunsmore, Ph.D.
Agilent Fellow

Denis Gregoire
Senior Technical Consultant
# Detailed Agenda

**Morning: Complete Amplifier Test**
- Wideband Gain, Narrowband Gain
- Gain Compression
- Two-tone IMD
- Noise Figure
- Cal All
- DC control
- Stability
- Pulsed Response
- Active Load and Hot S22

**New mixer measurement and calibration techniques with PNA-X**
- Cal with phase reference
- Segment Sweep
- Swept LO group delay
- Higher Order Products

**Complete mixer characterization with PNA-X**
- IQ mixer balance measurements
- IMD, noise figure and GCA measurements
“World’s Most Powerful Measurement Platform”

Amplifier test
Single connection:
Gain compression,
IMD, noise figure,
harmonics,
true differential,
PAE, hot $S_{22}$

Antenna test

T/R module test

Pulsed RF
and DC

Millimeter
wave

Lightwave component
analysis

Mixer test

Metropolitan
Primary standards/
calibration & repair

Scalar/vector Cal
absolute group delay
embedded LO

Load-pull
noise parameters

Non-linear
Component
characterization
X-parameter* extraction
pulse envelope domain

Pulsed RF
and DC

Atomic
Force
Scanning
microscope

Satellite
payload test

Materials
measurements

Signal integrity

500 GHz & Beyond

325 GHz

110 GHz

67 GHz

50 GHz

40 GHz

20 GHz

13.5 GHz

6 GHz

PNA-X

PNA-L

PNA

www.agilent.com/find/pna

*X-parameters is a trademark of Agilent Technologies.
Power of the PNA-X

**SCMM**
Performs S-parameter, IMD, Gain Compression, Pulsed Parameter, and Noise Figure measurements with one insertion

**Gain Compression**
Simultaneously sweeps both frequency and output power at 1dB compression

**Sub-1dB Noise Figure**
Source match corrects to make high-accuracy noise figure measurements possible

**Swept IMD**
Performs a complete intermodulation distortion analysis over an entire range of frequencies

**Converters**
Accurately measures phase, frequency, and delay response of frequency translation devices, even with embedded LO’s

**NVNA**
Completely characterizes all linear and nonlinear properties of your active device by extracting X-parameters

**Pulsed Devices**
Internally generates modulated pulsed output to characterize pulse performance with up to 5 MHz bandwidth
It all starts with the PNA-X Block Diagram
4-port with Options 419, 423
PNA-X receiver linearity: Most accurate receiver in the world!

+-0.01 dB over 80 dB
Start out with S-parameter Measurements: Start with Un-calibrated Measurements
Look for Wideband and Narrowband Response
Now find the approximate compression point
Now that we know saturated power, set the source and receiver attenuators
Now find the REAL compression point
Next setup automated Gain Compression Application

Gain Compression Setup: Channel 3

- Sweep Type:
  - Linear Sweep
  - Log Sweep
  - Segment Sweep

- Data Acquisition Mode:
  - SMART Sweep
  - Sweep Power Per Frequency (2D)
  - Sweep Frequency Per Power (2D)

- Sweep Settings:
  - Number Of Points: 51
  - IF Bandwidth: 1.000 kHz
  - Start: 300.000000 MHz
  - Stop: 2.00000000 GHz
  - Center: 1.15000000 GHz
  - Span: 1.70000000 GHz

- Total Number of Points: 1071 (32001)
- Number of Power Points: 21
- Compression Method: Compression from Linear Gain 1 dB

OK Cancel Apply Help
Next setup automated Gain Compression Application
Next setup automated Gain Compression Application
Delta gain shows delta phase too
Example data

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>S11 Mag (dB)</th>
<th>S11 Phase (Deg)</th>
<th>S11 Mag (dB)</th>
<th>S11 Phase (Deg)</th>
<th>Pout Mag (dB)</th>
<th>Pout Phase (Deg)</th>
<th>S21 Mag (dB)</th>
<th>S21 Phase (Deg)</th>
<th>Delta Gain Mag (dB)</th>
<th>Delta Gain Phase (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00E+09</td>
<td>0</td>
<td>0</td>
<td>-16.089</td>
<td>47.9722</td>
<td>8.91063</td>
<td>47.9722</td>
<td>0</td>
<td>0</td>
<td>0.01199</td>
<td>0.048864</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>-0.99186</td>
<td>179.716</td>
<td>-20.0387</td>
<td>63.3331</td>
<td>-11.1401</td>
<td>111.354</td>
<td>8.89864</td>
<td>48.0211</td>
<td>-0.03548</td>
<td>0.094211</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>-0.9926</td>
<td>179.749</td>
<td>-17.0015</td>
<td>174.425</td>
<td>-8.268368</td>
<td>-137.508</td>
<td>6.87515</td>
<td>48.0664</td>
<td>-0.07393</td>
<td>0.037527</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>-0.98923</td>
<td>179.728</td>
<td>-14.0186</td>
<td>63.5915</td>
<td>-5.18192</td>
<td>-15.5458</td>
<td>8.83669</td>
<td>48.0457</td>
<td>-0.07393</td>
<td>0.073527</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>-0.98527</td>
<td>179.768</td>
<td>-11.0242</td>
<td>19.3483</td>
<td>-2.2647</td>
<td>67.3825</td>
<td>8.75094</td>
<td>48.0343</td>
<td>-0.15114</td>
<td>0.06205</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>-0.98457</td>
<td>179.847</td>
<td>-8.03281</td>
<td>167.764</td>
<td>0.555768</td>
<td>-144.167</td>
<td>8.58958</td>
<td>48.0693</td>
<td>-0.32105</td>
<td>0.097063</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>-0.98171</td>
<td>179.984</td>
<td>-5.38568</td>
<td>95.5211</td>
<td>3.18631</td>
<td>-47.4126</td>
<td>8.2249</td>
<td>48.1035</td>
<td>-0.68573</td>
<td>0.136283</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>-0.98125</td>
<td>179.952</td>
<td>-4.03943</td>
<td>162.267</td>
<td>3.93585</td>
<td>-149.606</td>
<td>8.02528</td>
<td>48.1251</td>
<td>-0.88534</td>
<td>0.152847</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>-0.9799</td>
<td>179.906</td>
<td>-3.56219</td>
<td>10.3817</td>
<td>4.35352</td>
<td>58.5271</td>
<td>7.91571</td>
<td>48.1454</td>
<td>-0.99492</td>
<td>0.173193</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>-0.97782</td>
<td>179.849</td>
<td>-3.04099</td>
<td>-110.889</td>
<td>4.73113</td>
<td>-62.7297</td>
<td>7.77202</td>
<td>48.1592</td>
<td>-1.1386</td>
<td>0.187034</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>0</td>
<td>0</td>
<td>-25</td>
<td>-17.9382</td>
<td>-70.7171</td>
<td>7.06182</td>
<td>-70.7171</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>-2.07747</td>
<td>8.36674</td>
<td>-19.8473</td>
<td>19.7923</td>
<td>-12.8201</td>
<td>-50.7237</td>
<td>7.02721</td>
<td>-70.516</td>
<td>-0.03461</td>
<td>0.201061</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>-2.08247</td>
<td>8.41904</td>
<td>-16.855</td>
<td>79.2937</td>
<td>-9.65472</td>
<td>8.80057</td>
<td>7.0003</td>
<td>-70.4931</td>
<td>-0.06153</td>
<td>0.223945</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>-2.08521</td>
<td>8.37575</td>
<td>-13.8834</td>
<td>8.52135</td>
<td>-6.90813</td>
<td>-61.9918</td>
<td>6.97523</td>
<td>-70.5131</td>
<td>-0.0866</td>
<td>0.20396</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>-2.05807</td>
<td>8.43118</td>
<td>-10.8943</td>
<td>31.6201</td>
<td>-3.99094</td>
<td>-38.8845</td>
<td>8.90333</td>
<td>-70.5046</td>
<td>-0.15849</td>
<td>0.212424</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>-2.05724</td>
<td>8.60536</td>
<td>-7.89405</td>
<td>101.912</td>
<td>-1.15615</td>
<td>31.4965</td>
<td>6.7379</td>
<td>-70.4152</td>
<td>-0.32392</td>
<td>0.301886</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>-2.05201</td>
<td>8.88637</td>
<td>-4.90173</td>
<td>0.023134</td>
<td>1.48449</td>
<td>-70.2782</td>
<td>6.38621</td>
<td>-70.3013</td>
<td>-0.67561</td>
<td>0.415752</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>-2.04917</td>
<td>9.04911</td>
<td>-3.90462</td>
<td>-65.5553</td>
<td>2.28975</td>
<td>-135.792</td>
<td>5.19437</td>
<td>-70.237</td>
<td>-0.85746</td>
<td>0.480097</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>-2.05015</td>
<td>9.14727</td>
<td>-3.34478</td>
<td>-161.487</td>
<td>2.71825</td>
<td>128.311</td>
<td>6.06303</td>
<td>-70.2021</td>
<td>-0.99879</td>
<td>0.515003</td>
</tr>
<tr>
<td>2.00E+09</td>
<td>-2.04565</td>
<td>9.24224</td>
<td>-2.90654</td>
<td>-59.9495</td>
<td>3.03771</td>
<td>-130.127</td>
<td>5.94425</td>
<td>-70.1773</td>
<td>-1.11758</td>
<td>0.539784</td>
</tr>
<tr>
<td>3.00E+09</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-18.5291</td>
<td>-171.542</td>
<td>5.82064</td>
<td>171.542</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Visualization: 3-D contours of Freq/Power/Gain
Now lets add two-tone measurements
First look at the IM Spectrum
Swept power Two-Tone IMD

> 1: -2.616 dBm -52.74 dBm
Swept power Two-Tone IMD
Use Marker->IM Spectrum to see the spectrum response
You can also do swept frequency IMD or swept tone spacing

<table>
<thead>
<tr>
<th>Sweep Type</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweep $f_c$</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>Sweep DeltaF</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>Power Sweep</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Swept IMD at fixed output power
Summary of where we are: show all windows and summarize the measurements
Now we can add noise figure:
Adjust noise figure settings Power, Freq., Points
Noise Figure normally MUST have a calibration: but we want calibration for all our channels
New Calibration Enhancements Simplify Power Gain, IMD and Noise Measurements

Enhanced Power Calibration adds *power meter* measurements to the PNA-X Cal Wizard

All Power Calibrations are **Fully Match Corrected**

S-parameter port-transfer means you only connect the power meter to a *single port*

Two Simple Steps

1) Connect the power meter to port 1

2) Make an S-parameter Cal between any or all ports

Use a power-meter as the NOISE reference! (calibrate receiver gain and Noise Bandwidth independently)
First Let’s Look at Power: Enhanced Power Calibration Wizard

Use the Check-Box to add power calibration
Enhanced Power Calibration Wizard

This new power page gives complete flexibility for setting:

- Power Accuracy, Iterations, Power meter type, and
de-embedding of any power meter adapter
Start with a normal 2-port calibration and receiver response calibration

S21 Trace is perfectly smooth

R1 Trace monitors source drive power

The power’s not flat due to S11 mismatch
Add a B-power measurement ($P_{\text{out}}$)

The output power has 1 dB of ripple.

The ripple is caused by input power ripple, AND output mismatch.
Mismatch in the Input and Output Power shows as a gain ripple for B/R

B/R can be displayed to show $P_{\text{out}}/P_{\text{in}}$ compared with $S_{21}$
But new Enhanced Power Calibration provides for **Match Corrected** Power Measurements

Match correction for power can be turned on or off
But new Enhanced Power Calibration provides for **Match Corrected** Power Measurements

B/R (power gain) matches S21 Exactly!

Now the output power ripple is only due to input power ripple

Mismatch adds an error to the source power cal, so R1 shows the true ripple of the input power
But, Since R1 measures the exact, match corrected input power, we can use it to level the source.

You can use any receiver to level any source, normally you use the reference receiver for that source.
Now, the input power is nearly **perfect**, the output power is exactly equal to S21*input power

Output power has almost no error. This is better than using a power meter!

Input Power error is less than 0.02 dB!
Simplified Single-Connection Calibration for All Measurements and All Channels: Cal-All

Calibrate All Selected Channels

<table>
<thead>
<tr>
<th>Enable</th>
<th>Channel</th>
<th>Measurement Class</th>
<th>Cal Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>☑</td>
<td>1</td>
<td>Standard</td>
<td>1 2</td>
</tr>
<tr>
<td>☑</td>
<td>2</td>
<td>Standard</td>
<td>1 2</td>
</tr>
<tr>
<td>☑</td>
<td>3</td>
<td>Gain Compression</td>
<td>1 2</td>
</tr>
<tr>
<td>☑</td>
<td>4</td>
<td>IM Spectrum</td>
<td>1 2</td>
</tr>
<tr>
<td>☑</td>
<td>5</td>
<td>Swept IMD</td>
<td>1 2</td>
</tr>
<tr>
<td>☑</td>
<td>6</td>
<td>Noise Figure Cold Source</td>
<td>1 2</td>
</tr>
</tbody>
</table>

Start Cal
Cal Wizard...
Cal All Wizard...
Cal Preferences...

RCS Calibration...
Return
Setup Standard

Agilent Technologies
Cal-All: One page gives all the options needed for each calibration channel
Cal-All: Next page lets you select ports; careful, if you want ports 3 and 4 calibrated, you must select
Cal-All uses a single “super-channel” to perform a first stage calibration; you can set the channel attributes here.

Normally, a moderately high source power is best for getting a good S-parameter calibration. Calibration can have low noise even if the channel is low power.

Attenuator offsets are handled in a later step.

A single IF BW is used for all acquisitions: all channels will be put in “stepped” mode to eliminate “dynamic” errors.

Power offset compensates for external gain or loss.
Cal-All: Select connectors and kits for ports just one time.
Cal-All: Setup the power sensor for source and receiver cal just one time
Cal-All: Only one measurements for creating all source and receiver calibrations

A different power can be set for the power meter acquisition step optimizing for best accuracy
This step is used to measure the gain-bandwidth product of the noise receiver, using the source.

This utilizes the new power-meter calibration method for the low-noise receiver. The technology requires a change in attenuator value to avoid overdrive, thus requiring an attenuator calibration.
Cal All: Finally, an Ecal step for each port, just like a normal S-parameter Cal
Cal All: But adds an extra measurement for each channel that has a different attenuator!

This provides the characterization of the attenuator needed for noise figure, and other calibrations.
The final result is a calset for each channel, and each channel is left with calibration on.
Cal All: A single-step approach to multifunction calibration!
Fixturing and De-embedding Enhancements: Receiver Power Cal Compensation

Normally: port 1 faces the test port. This makes de-embedding from port 2 cumbersome. Now, you can simply reverse the adapter direction.

Extrapolation lets you use adapters outside the characterized range: useful for things like attenuators.
Fixturing and De-embedding Enhancements: Add a 6-dB attenuator to port 1, and de-embed.

S-parameters are perfectly compensated.

Receiver power is also compensated, but now shows lower by the attenuator value, since there is no change in source power.
Fixturing and De-embedding Enhancements: Source and Receiver Power Cal Compensation

Now you can selectively turn on source power compensation for fixturing or de-embedding losses. This is off by default to avoid any overdrive issues.

Here the source power is adjusted to exactly compensate for the de-embedding loss.
Our DUT is mounted on a PC board: can we remove its effects?
Equation Editor  
If You Can’t Measure it, Compute It!!

Powerful and convenient tool to add computation results as a new trace to your measurement display.

• Equations can be based on any combination of existing traces or underlying channel parameters or memory traces along with any user defined constants.

• You can use any of the basic operators or choose from an extensive library of functions and standard constants.

• Equations can be stored for later use.

• Import your own compiled library of functions
Equation Editor
New “Best Fit” dll supports many features

Channel Power
Deviation from Linear phase using:
Least Squares
Min-Max
standard
min-max sq.
Sub-range
dB Flatness
Phase Unwrap
Slope of Line
Normalize to 1st pt.
Here’s an example of Best Fit: Min-max deviation from linear over a limited freq. range
We can use equation editors “marker tracking” feature for interesting examples: Stability Circles
Changing the marker changes the frequency where stability is computed (must use calibrated meas’t).
DC Source-Measure Unit and DC Meter Integration with the PNA-X VNA

Complete Characterization of active devices, components and modules
RF Device/Component Validation Bench

- Validation required for RF designs
- No standard configuration
- No traceability
- Integration of measurements varies
Why control DC with PNA-X?

Large opportunity for innovative solutions!

• PAE measurements especially for pulsed amplifiers
• Voltage Controlled Amplifier: VGA gain vs drive
• Device modeling and model extraction (X-Parameters)
• One display for multi measurement, frequency, power, DC …
• ?? New measurements/applications ??
PNA-X = “Rack in a Box”
> 10 instruments in one box – enables new measurements

- |Z| vs. \( f \)
- |Z| vs. \( V \)
- Impedance vs. Voltage (VCC)
- Impedance vs. Current (Icc)
- Power vs. Current (Icc)

- dBm vs. \( f \)
- RF Power
- Spectrum

NEW!!
New Solutions for RF Bench Validation

Fast, Accurate, Traceable, Repeatable Measurements

- Complete control over all DC parameters
- PNA-X sweeps DC meters and SMUs
- Single user interface
- Repeatable, traceable measurements
- Open interface enables user customization
Control of an SMU, DC source and/or DC meter

**External instrument “identification” by PNA-X**

DC source and DC Meter can be added as a “logical devices” to PNA-X. Then the firmware will take the control.

The control interface could be GPIB, USB or LAN, and you control the generic command sequences.

SMU control for B2900 and B6700 have built-in control functions.
Controlling the DC source and/or DC meter

Set the remote command for added instrument

- Behavior of SMU or DC meter is defined in PNA-X for each sweep – before, during or after a sweep or point measurement.
- User can input the external instrument’s remote commands. PNA-X will execute these commands for each behavior.
Controlling B2900 or N6700

Built-in Control and Software or Hardware (B2900) Trigger

Setup | Source | Voltage Meter | Current Meter

SMU Information:
- Voltage Sources: `smu1_VS1`, `smu1_VS2`
- Channel 1: `smu1_VS1`
- Channel 2: `smu1_VS2`

Setup | Source | Voltage Meter | Current Meter

SMU Channel: 1
Source Type: Voltage

Device Settings:
- Timeout: 20000 msec
- Dwell Before Sweep: 1000 msec
- Dwell After Point Set: 3000 msec
- Current Limit: 1.000 A

Trigger Settings:
- Trigger Mode: Software CW (Generator), Software CW (Generator)
- SMU Trigger In: Hardware List (B2900)
- SMU Trigger Out: DIO2

Source Correction On
- Offset: 0.0
- Scaling: 1.0

Output = (Set Value - Offset) * Scaling
DC sources can be ON or OFF on a per-port basis.
Controlling SMUs & Meters from the PNA-X

Full control built into the PNA-X firmware

- PNA-X is the “Solution Controller” in this application

- PNA-X uses GPIB, USB or LAN to control SMUs and meters

- PNA-X sets and reads external devices at each measurement point
Control of the DC source and DC meter

**DC meter control**

- DC meter is treated as a PNA receiver
- The measurement result of DC meter can be displayed as same as other PNA receiver
- Other examples of receivers include all channels (transmit and receive), power sensors and power meters, DC input and output (rear panel) and ratios (source/receiver ratios)
How to control the DC source and DC meter

DC source control

DC sweep is added to PNA-X. Sweep value can be defined. The sweep could be voltage or current sweep; synchronized with the VNA sweep.

<table>
<thead>
<tr>
<th>Name</th>
<th>State</th>
<th>Start DC</th>
<th>Stop DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>A01</td>
<td>OFF</td>
<td>0.500 V</td>
<td>1.000 V</td>
</tr>
<tr>
<td>A02</td>
<td>OFF</td>
<td>0.500 V</td>
<td>1.000 V</td>
</tr>
<tr>
<td>smu1_EV</td>
<td>ON</td>
<td>2.000 V</td>
<td>5.000 V</td>
</tr>
<tr>
<td>smu1_EV2</td>
<td>OFF</td>
<td>0.500 V</td>
<td>1.000 V</td>
</tr>
</tbody>
</table>
Sweep of DC source and display of DC meter

**DC (SMU) Stimulus/Response on a VNA!**

Voltage domain on the X and Y axis of a RF/uW Vector Network Analyzer!!

B2900 can sweep up to 1600 pts/sec in hardware control mode
Measuring RF and DC response vs Voltage

Variable Gain Attenuator: $S21$ vs. DC control voltage

Current of the Control Voltage

Current of the supply voltage

$S21$ (Y-Axis) vs Control Voltage (X-Axis) for 3 different supply voltages

Control Voltage
Measuring RF and DC response vs Frequency

Variable Gain Attenuator: S21 vs. Frequency

Current of the Control Voltage

Current of the supply voltage

S21 (Y-Axis) vs Frequency for fixed control voltage and 3 different supply voltages

Control Voltage
Measuring RF and DC response vs Frequency

**Variable Gain Attenuator: S21 vs. Frequency**

- Current of the Control Voltage
- Current of the supply voltage
- S21 (Y-Axis) vs Frequency for fixed control voltage and 3 different supply voltages
The Power I/O connector can be used to control devices, read voltages, and supply DC power.

<table>
<thead>
<tr>
<th>Pin</th>
<th>Num</th>
<th>Description</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+15</td>
<td></td>
<td>400 mA</td>
</tr>
<tr>
<td>2</td>
<td>-15</td>
<td></td>
<td>400 mA</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>AnalogOut1</td>
<td>+10 v@100mA</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>AnalogOut2</td>
<td>+10 v@100mA</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Gnd</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Gnd Sense</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>AnalogIn1</td>
<td>+10 v</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.22 mv res</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>AnalogIn2</td>
<td>+10 v</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.22 mv res</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Main Power</td>
<td></td>
</tr>
</tbody>
</table>
PAE vs. Drive Measurement Results

Voltage
Current
Output Power

PAE (22.6%)
Amplifier Characterization: Active Loads

Measure amplifier gain, power, under varying load conditions

- Traditional approach uses mechanical tuners
- Mechanical tuners are intuitive to use and can handle high power, but they are slow and cannot supply fully reflective loads ($\Gamma_s=1$)
Source Phase Control Provides Active Load Control

Active load control is fast and can provide full reflection

- Use second source at output of amplifier to electronically control reflection coefficient
- Measure amplifier output power, match, and gain under different load conditions
- Perform complete active load-pull measurements (with 3rd-party software)
Source Phase Control: What Is It Exactly?

- Set relative phase between two sources
- Typically, both sources are internal to PNA-X, but one or both could be external MXG signal generators
- Phase offset can be fixed (CW or versus frequency), or swept at a CW frequency
- Relative power is also controlled, using receiver-leveling
- Ref price: $5k USD
- Requires firmware A.09.33 or greater
Phase-Controlled Sources

Differential or quadrature source for amplifier, mixers

- Provide two signals with known phase relationship and (usually) same amplitude
- Example: differential drive to an amplifier
- Example: quadrature drive to a pair of mixers
Active Load: Four-Port Example

\[
\Gamma_L = \frac{A3}{B3} \quad \text{Port3 on}
\]

Source 1 = reference
Source 2 = controlled
Active Load: Two-Port Dual Source Example

Source 1

Source 2

Pulse generators

RF OUT

LO OUT

IF inputs

R1

R2

Test port 1

Test port 2

\[ \Gamma_L = \frac{A2}{B2} \]  
Port 2 on

\[ \rightarrow A2 \leftarrow \]  

\[ \rightarrow B2 \]  

© 2013 Agilent Technologies

Anticipate — Accelerate — Achieve
Active Load Measurement Example

\[ \Gamma_L = \frac{a_3}{b_3} \] (amplifier connected between ports 1 and 3)

Load circles:
- \( \Gamma_L \) (mag) = constant
- \( \Gamma_L \) (phase) = swept

Output power versus phase for various load circles
Phase Controlled Sources: Four-Port Example
Phase Controlled Sources: Two-Port Example

Rear panel

Source 1

OUT 1
Pulse modulator

OUT 2

LO
To receivers

R1

Test port 1

R2

65 dB

35 dB

65 dB

35 dB

Test port 2
Agenda

- Overview

- Setup and Calibration
Using External Sources

• If using an external source, configure it first
  • Add source via External Devices dialog
  • Enable with Frequency Offset dialog (requires Option 080)
• Don’t forget to hook up the 10 MHz references!
Sweep Type

Use for fixed active load or CW phase-controlled signals

Use for load circles

New!
Phase Control

For fixed phase

For swept phase
Phase Control Setup Dialog

- Use a(x)/b(x) for active load control
- Use a(x)/a(y) for defined phase between two sources

You can use receiver (A, R1) or wave (a3, b3) terminology
Power Control

Set power of controlled source in terms of dBc
Receiver Leveling

Phase control automatically sets up power leveling of receiver ratios.
Define Parameters

Source port must be set to controlled source

S-parameters are valid choices for active load setups
Match Correction

- For each port pair, both reference and test receivers are measured
- This yields match-corrected magnitude and phase
- Same approach as True-Mode Stimulus Option 460
S-Parameter Definition

\[ b_1 = S_{11}a_1 + S_{12}a_2 \]
\[ b_2 = S_{21}a_1 + S_{22}a_2 \]
Measuring S-parameters

Normally, only one port is on at a time

**Forward**

\[
S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1} \quad a_2 = 0
\]

\[
S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1} \quad a_2 = 0
\]

**Reverse**

\[
S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_2}{a_2} \quad a_1 = 0
\]

\[
S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_1}{a_2} \quad a_1 = 0
\]
Measuring S-parameters With Phase Control - Hot S-parameters!

Q: How do we measure S-parameters when two sources are on at the same time?

A: Use phase rotation to add more equations with same unknowns (this happens with background sweeps)

\[ b_1 = S_{11}a_1 + S_{12}a_2 \]
\[ b_2 = S_{21}a_1 + S_{22}a_2 \]

\[ b_1' = S_{11}a_1' + S_{12}a_2' \]
\[ b_2' = S_{21}a_1' + S_{22}a_2' \]
Calibration

- Requires source & receiver calibration for reference & controlled ports (reference and test receivers)
- Easiest to use new “Calibrate source and receiver power” feature
- Can use Smart Cal or ECal choices
- Provides corrected amplitude and phase at ends of test cables/probes
Let’s look at an amplifier in linear operation: CW frequency: with good load (-40 dB)
Same amplifier into a 10 dB RL load, sweeping phase. Notice the power changes with phase, load < S22*; while S-parameters are constant: i.e. Linear Operation.
Same amplifier into a 3 dB RL load, sweeping phase. Now Load > S22*; S-parameters are constant: i.e. Linear Operation

Output Power
Delivered Pwr
Pwr Reflected from the load
Same amplifier into a S22* dB RL load, sweeping phase. Here Delivered Power is maximum.
Let's do a power sweep on this amplifier: Normal measurements show S21 compression, but of course no change in S22 (S33 below): not Hot S22.

S21 Compression at about 0 dBm
Same amplifier into a 6 dB RL load, Higher Power: Now we see S22 changes as the phase changes; at max power, now S22* != Load
Here’s a close-up look at the Smith Chart
The load RL is changed to match the new S22*, resulting in higher delivered power.
At even higher drive power (+3 dBm in, more compression) S21 also changes with load impedance.
Pulse Operation

Phase controlled measurements can be done under pulsed conditions using wideband detection.
The Agilent Calibration Refresh Modules or CalPods are used to remove measurement variations due to test cable movement, thermal effects, and switch and connector repeatability, and some of the effects of drift in a vector network analyzer.
Calibration refresh modules (or CalPods) when used with an Agilent VNA can remove the environmental variations in the test cables.

- A calibration plane is established at the CalPod interface to the DUT.
- If a drift in the measured data is observed, the calibration can be refreshed at the push of a button.
- RF cable movement, thermal effects, and connector repeatability are then all removed from the measurement.
Typical performance for re-correction vs. loss
CalPod: Example Setup for a large system

- Source
- Spectrum Analyzer
- Power Meter
- Custom RF Devices
- Switch Matrix RF Path Conditioning
- Switch Matrix RF Path Expansion
- Vector Network Analyzer
- System PC

- USB 2.0 to LAN Cable
- DUT

Each CalPod “Drive Cable Path” must be less than 24 m (Cx + Cs) + Cd

Cx = 85554A CalPod Drive Cable Extension, 10 m
Cs = 85555A CalPod 1x12 Fan Out Splitter Drive Cable, 2 m
Cd = 85552A or 85553A CalPod Drive Cable, 2 m

“Drive Cable Path” must be less than 82 m (Cx+Cd)
CalPod: Calibration Refresh Modules

• Removes the effects of cables and switches between the PNA and the DUT
  • Can eliminate drift due to thermal effects in temperature chambers
  • Can remove stability effects on long cables
  • Use after a multiport switch matrix to remove switch errors
• 20 GHz and 40 GHz modules currently available
• Simple user interface requires only 3 commands:
  • Setup: define which CalPods are on which ports
  • Initialize: transfer the reference plane cal to the CalPods
  • Recorrect: Refresh the current calibration with the CalPods
• TVAC available upon special request
## CalPod Product Descriptions

<table>
<thead>
<tr>
<th>Items</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PNA option 301/302</td>
<td>Ambient/Temp Co Software for CalPod</td>
</tr>
<tr>
<td>PNA option 303</td>
<td>Multiport Software for Cal Pod (later release)</td>
</tr>
<tr>
<td>85523A</td>
<td>Controller</td>
</tr>
<tr>
<td>85530A</td>
<td>20 GHz Ambient CalPod Module</td>
</tr>
<tr>
<td>85531A</td>
<td>20 GHz Temperature Compensated CalPod Module</td>
</tr>
<tr>
<td>85540A</td>
<td>40 GHz Ambient CalPod Module</td>
</tr>
<tr>
<td>85541A</td>
<td>40 GHz Temperature Compensated CalPod Module</td>
</tr>
<tr>
<td>85552A</td>
<td>2 Meter 20 GHz CalPod drive cable</td>
</tr>
<tr>
<td>85553A</td>
<td>2 Meter 40 GHz CalPod drive cable</td>
</tr>
<tr>
<td>85554A</td>
<td>10 Meter CalPod drive cable extension</td>
</tr>
<tr>
<td>85555A</td>
<td>Splitter Drive Cable 2M</td>
</tr>
<tr>
<td>85556A</td>
<td>1X12 Fan out Cable Splitter</td>
</tr>
</tbody>
</table>
New techniques for Hi-Gain amplifier measurements

• Hi-Gain amplifiers pose particular problems
  • Low Power Drive means Calibrations are noisy
  • High-power and high gain may require port 2 attenuation
  • Low Power at port 1 means S11 measurements can also be noisy
• Most of these issues are resolved using careful calibration and measurement techniques
• Cal-All simplifies the process and solves other problems as well (when very low power measurements are needed)
• Re-configuring the test system may be needed in some cases
Setup: High-Gain amplifier, input -70 dBm. Simple Cal and Measurement

Red: Corrected!

Yellow: Raw Data
Setup: High-Gain amplifier, input -70 dBm. Now uncouple port powers, set port 2 to -10 dBm.
Setup: High-Gain amplifier, input -70 dBm. Now uncouple port powers, set port 2 to -10 dBm

Yellow: Ports Coupled
Blue: Ports Uncoupled
Port 2 pwr=0dBm

S21 Still rather noisy
Uncouple port powers, set port 2 to -10 dBm – AND – calibrate at -40 dBm, then drop to -70 dBm

Blue:
Ports Uncoupled
Port 2 pwr=0dBm
Cal @ -70 dBm

Yellow:
Cal @ -40 dBm,
then drop to -70dBm
Port 2 pwr=0dBm

S21 is now clean.
But S11 is still noisy!
High Gain Amplifiers (and converters): Reverse the port 1 coupler!
High Gain Amplifiers (and converters): Reverse the port 1 coupler!

Blue: Normal Coupler
Yellow: Reversed Coupler

S21 and S11 are now clean
And S12 has lower noise
All-in-one Measurement Systems

SCMM
Performs S-parameter, IMD, Gain Compression, Pulsed Parameter, and Noise Figure measurements with one insertion

Gain Compression
Simultaneously sweeps both frequency and output power at 1dB compression

Sub-1dB Noise Figure
Source match corrects to make high-accuracy noise figure measurements possible

Swept IMD
Performs a complete intermodulation distortion analysis over an entire range of frequencies

Converters
Accurately measures phase, frequency, and delay response of frequency translation devices, even with embedded LO’s

NVNA
Completely characterizes all linear and nonlinear properties of your active device by extracting X-parameters

Pulsed Devices
Internally generates modulated pulsed output to characterize pulse performance with up to 5 MHz bandwidth
Input and Output Channel Power measurements using IM Spectrum Mode:

PNA-X IM Spectrum

PSA Spectrum Analyzer
Equation Editor Functions allow direct measurement of Channel Power

Set start and stop of channel power integration function
You can view ACPR on PNA-X in IM Spectrum Mode: Thru measurement

Using equations on multiple traces allow separate computation of Main Channel Power and Adjacent Channel Power
You can view ACPR on PNA-X in IM Spectrum Mode: Amplifier Measurement show ACPR.
All-in-one Measurement Systems

SCMM
Performs S-parameter, IMD, Gain Compression, Pulsed Parameter, and Noise Figure measurements with one insertion

Gain Compression
Simultaneously sweeps both frequency and output power at 1dB compression

Sub-1dB Noise Figure
Source match corrects to make high-accuracy noise figure measurements possible

Swept IMD
Performs a complete intermodulation distortion analysis over an entire range of frequencies

Converters
Accurately measures phase, frequency, and delay response of frequency translation devices, even with embedded LO’s

NVNA
Completely characterizes all linear and nonlinear properties of your active device by extracting X-parameters

Pulsed Devices
Internally generates modulated pulsed output to characterize pulse performance with up to 5 MHz bandwidth
Radar and Electronic-Warfare

- Biggest market for pulsed-RF testing
- Traditional applications \( \leq 20 \text{ GHz} \)
- New applications in Ka band (26.5-40 GHz)
- Devices include
  - amplifiers
  - T/R modules
  - up/down converters
4-Port with Pulse Generators and Modulators

- **Source 1**
  - Pulse combiner
  - Pulse generators
  - Test port 1

- **Source 2**
  - Pulse combiner
  - Pulse modulator
  - Test port 4

- **Signal combiner**
  - J1, J10, J9, J8

- **Noise receivers**
  - 10 MHz - 3 GHz
  - 3 - 26.5 GHz

- **Mechanical switch**
  - To receivers

- **LO**
  - +28V

- **Test ports**
  - Test port 1, Test port 2, Test port 3, Test port 4
PNA-X Pulse Hardware

The customer can get access to the pulse hardware externally:

- The internal pulse modulator (s) can be pulsed externally
- The 4 pulse generator outputs can be accessed externally
- The internal narrowband IF receiver gates can be accessed externally

<table>
<thead>
<tr>
<th>Pin</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IFGateAIn</td>
<td>IF pulse gate input A (TTL)</td>
</tr>
<tr>
<td>2</td>
<td>IFGateBIn</td>
<td>IF pulse gate input B (TTL)</td>
</tr>
<tr>
<td>3</td>
<td>IFGateCIn</td>
<td>IF pulse gate input C (TTL)</td>
</tr>
<tr>
<td>4</td>
<td>IFGateDIn</td>
<td>IF pulse gate input D (TTL)</td>
</tr>
<tr>
<td>5</td>
<td>IFGateRIn</td>
<td>IF pulse gate input R (TTL)</td>
</tr>
<tr>
<td>6</td>
<td>DCOM</td>
<td>ground</td>
</tr>
<tr>
<td>7</td>
<td>PulseSyncIn</td>
<td>Pulse generator synchronization trigger input (TTL)</td>
</tr>
<tr>
<td>8</td>
<td>RFpulsemolIn</td>
<td>RF source pulse modulation drive input (TTL)</td>
</tr>
<tr>
<td>9</td>
<td>DCOM</td>
<td>ground</td>
</tr>
<tr>
<td>10</td>
<td>Pulse1Out</td>
<td>Programmable pulse train output #1 (TTL)</td>
</tr>
<tr>
<td>11</td>
<td>Pulse2Out</td>
<td>Programmable pulse train output #2 (TTL)</td>
</tr>
<tr>
<td>12</td>
<td>Pulse3Out</td>
<td>Programmable pulse train output #3 (TTL)</td>
</tr>
<tr>
<td>13</td>
<td>Pulse4Out</td>
<td>Programmable pulse train output #4 (TTL)</td>
</tr>
<tr>
<td>14</td>
<td>n.c.</td>
<td>no connect -- for future use</td>
</tr>
<tr>
<td>15</td>
<td>DCOM</td>
<td>ground</td>
</tr>
</tbody>
</table>

N1966A
Setting up Pulse Parameters: New Integrated GUI allows simple setup of pulsed S-parameter and Pulse Profile

Narrowband pulse requires option 008 or H08
Pulse Profile Measurements: changing the pulse period and width shows more pulses
Pulse Profile: Zooming scale on S21 (0.002 dB/div) shows the amplifier pulse response, Avg=100
All-in-one Measurement Systems

**SCMM**
Performs S-parameter, IMD, Gain Compression, Pulsed Parameter, and Noise Figure measurements with one insertion

**Gain Compression**
Simultaneously sweeps both frequency and output power at 1dB compression

**Sub-1dB Noise Figure**
Source match corrects to make high-accuracy noise figure measurements possible

**Swept IMD**
Performs a complete intermodulation distortion analysis over an entire range of frequencies

**Converters**
Accurately measures phase, frequency, and delay response of frequency translation devices, even with embedded LO’s

**NVNA**
Completely characterizes all linear and nonlinear properties of your active device by extracting X-parameters

**Pulsed Devices**
Internally generates modulated pulsed output to characterize pulse performance with up to 5 MHz bandwidth
Gain Compression Application

Gain Compression Setup: Channel 1

- **Frequency**
  - Sweep Type:
    - Linear Sweep
    - Log Sweep
    - CW Frequency
    - Segment Sweep
  - Data Acquisition Mode:
    - SMART Sweep
    - Sweep Power Per Frequency (2D)
    - Sweep Frequency Per Power (2D)

- **Power**
  - Number Of Points: 201
  - IF Bandwidth: 1.0000 GHz
  - Start: 10.000000 MHz
  - Stop: 29.5000 MHz
  - Center: 13.2550000 GHz
  - Span: 25.490 MHz

- **Compression**
  - Linear Power Level: -30.0 dBm
  - Reverse Output Power:
    - Source Attenuation: 0 dB
    - Receiver Attenuation (A): 0 dB
    - Source Leveling: Internal
  - Power Sweep:
    - Start (Min) Power: -30.0 dBm
    - Stop (Max) Power: -25.0 dBm
    - Power Points: 0.167 dBm

- **Total Number of Points:** 201 (20001)
- **Compression Method:** Compression from Linear Gain 1 dB

Compression Analysis

The compression data also includes AI1 and AI2 that can be used to compute PAE as a function of frequency and Power.
**All-in-one Measurement Systems**

**SCMM**
Performs S-parameter, IMD, Gain Compression, Pulsed Parameter, and Noise Figure measurements with one insertion.

**Gain Compression**
Simultaneously sweeps both frequency and output power at 1dB compression.

**Sub-1dB Noise Figure**
Source match corrects to make high-accuracy noise figure measurements possible.

**Swept IMD**
Performs a complete intermodulation distortion analysis over an entire range of frequencies.

**Converters**
Accurately measures phase, frequency, and delay response of frequency translation devices, even with embedded LO’s.

**NVNA**
Completely characterizes all linear and nonlinear properties of your active device by extracting X-parameters.

**Pulsed Devices**
Internally generates modulated pulsed output to characterize pulse performance with up to 5 MHz bandwidth.

© 2013 Agilent Technologies
Backup slides if we need them during the next week follow
Intermodulation Distortion (IMD) Measurements

Second Internal Signal Source eliminates external source and accessories for amplifier IMD measurements. For the first time, you can make S-parameter and IMD measurements with a single insertion.
2-Port PNA-X Two-Tone IMD Measurements

Source 1

Source 2

Options 219, 224

Rear panel

Test port 1

Source 2

Output 1

Source 2

Output 2

Test port 2

DUT
Setup requires only 2 keys: Freq & Power
Everything else is automatically computed
## Sweeping IMD Signals: Expanding Information

<table>
<thead>
<tr>
<th>Sweep Type</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweep fc</td>
<td><img src="image1" alt="Diagram" /></td>
</tr>
<tr>
<td>Sweep DeltaF</td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>Power Sweep</td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**Legend:**
- $f_1$, $f_2$: Frequencies
- $f_c$: Carrier frequency
- $\Delta f$: Frequency offset
- $f_1'$, $f_2'$: Modified frequencies
Swept IMD pre-defines many IM measurements, and allows simple selection and display

Measurements:
2\textsuperscript{nd} order, 3\textsuperscript{rd} order, 5\textsuperscript{th}, 7\textsuperscript{th}, 9\textsuperscript{th} orders.
Upper, Lower, or Avg.
Input or Output

Tone Power-
IMD relative to carrier-
Intercept Point
Input or Output refer-
Composite Triple Beat-
Composite 2\textsuperscript{nd} order-
IMD can be measured vs. Swept Power

Plotting all tone powers shows very interesting distortion curves
IMD can be measured vs. Swept Frequency

- Output Power
- IM 3 Power
- Output Intercept Point
Swept IMD Enhancements: Display worse case of upper and lower tones

Lowest OIP3

Highest IM3
Swept IMD Enhancements: Automatically equalize tone powers, and level at the amplifier output

Set Power at Output
Swept IMD Enhancements: Automatically equalize tone powers, and level at the amplifier output

Set Power at Output and equalize

OIP3

IM3
All-in-one Measurement Systems

SCMM
Performs S-parameter, IMD, Gain Compression, Pulsed Parameter, and Noise Figure measurements with one insertion

Gain Compression
Simultaneously sweeps both frequency and output power at 1dB compression

Sub-1dB Noise Figure
Source match corrects to make high-accuracy noise figure measurements possible

Swept IMD
Performs a complete intermodulation distortion analysis over an entire range of frequencies

Converters
Accurately measures phase, frequency, and delay response of frequency translation devices, even with embedded LO's

NVNA
Completely characterizes all linear and nonlinear properties of your active device by extracting X-parameters

Pulsed Devices
Internally generates modulated pulsed output to characterize pulse performance with up to 5 MHz bandwidth
4-Port PNA-X Noise Figure Measurement

- Noise source used for calibration only
- RF jumpers
- Receivers
- Mechanical switch
- Pulse generators
- Source 1
- Source 2
- Signal combiner
- Pulse modulator
- J1, J2, J3, J4, J7, J8, J9, J10, J11
- Test port 1
- Test port 2
- Test port 3
- Test port 4
- LO
- Receiver
- 10 MHz - 3 GHz
- 3 - 26.5 GHz
- Impedance tuner for noise figure measurements

Agilent Technologies
Noise Parameters

- Plots of noise figure circles versus impedance (at one frequency)
- $F_{\text{min}}$ is lowest noise figure and occurs at $\Gamma_{\text{opt}}$
- $F$ changes with $\Gamma$
- $F$ changes with device bias

* $R_n$ is the equivalent noise resistance and is a measure of the slope of noise figure versus impedance. Lower is better.
PNA-X’s Unique Source-Corrected Technique

- PNA-X varies source match around 50 ohms using an ECal module (source-pull technique)
- With resulting impedance/noise-figure pairs and vector error terms, very accurate 50-ohm noise figure ($\text{NF}_{50}$) can be calculated
- Each impedance state is measured versus frequency

$$(Z_1, F_1), (Z_2, F_2), \ldots$$

Z’s measured during cal
F’s measured with DUT
Example NF Measurements

- **PNA-X method using source correction**
- **Traditional Y-factor technique**
Calibrating at the Ends of Cables

1. Port cal

2. 1-port cal (remove adapter after cal)

3. This example may be more convenient due to length and placement of cable and position of PNA-X

Embed this section to move noise-cal reference plane to 2-port-cal reference plane