Beyond S-parameters: Modern Network Analyzer Architectures and Algorithms

Presented by:

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Agilent Technologies

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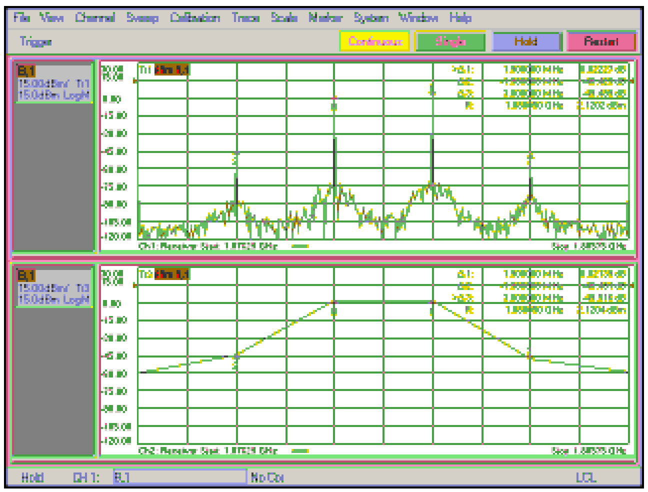
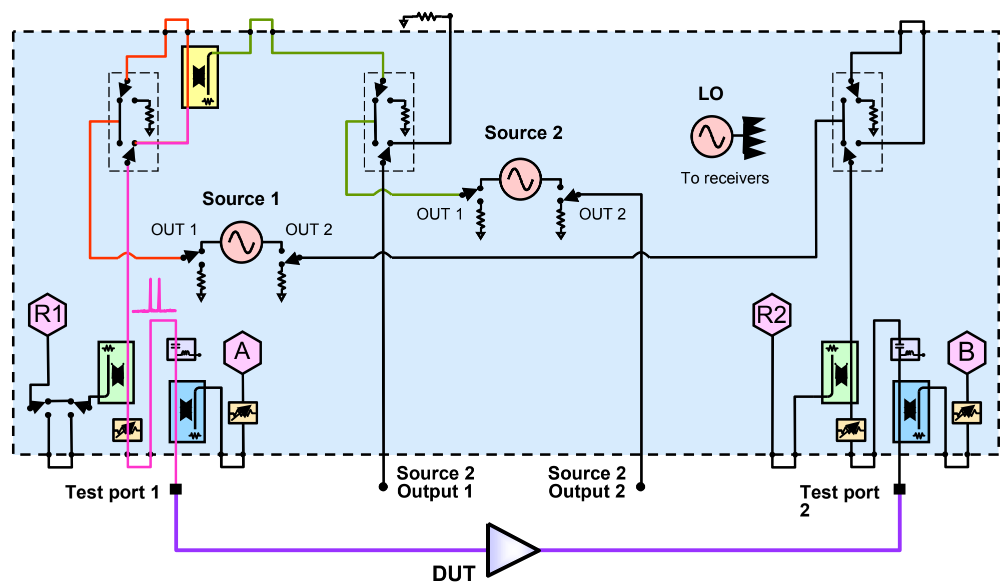
Objectives

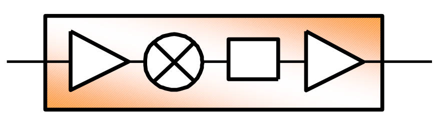
- Examine architectures of modern vector network analyzers (VNAs)
- Provide insight into **nonlinear characterization** of amplifiers, mixers, and converters using a vector network analyzer
- Understand associated calibrations for non-S-parameter tests



Agenda

- **Overview of Component Testing Using a VNA**
- **Modern VNA Architectures**
- **Nonlinear Amplifier Tests**
  - Intermodulation distortion
  - Phase versus drive
  - Hot S22
  - True-mode stimulus
  - Single connection, multiple measurements
- **Mixer and Converter Tests**
- **Applications**
- **Amplifier Measurements**
- **Summary**



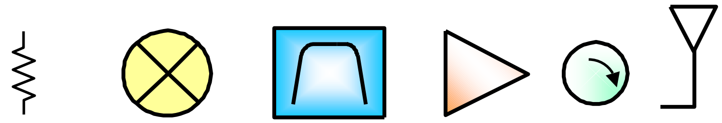


Single Connection Multiple Measurement System

SCMM System to PNA-X

The Need for Component Test

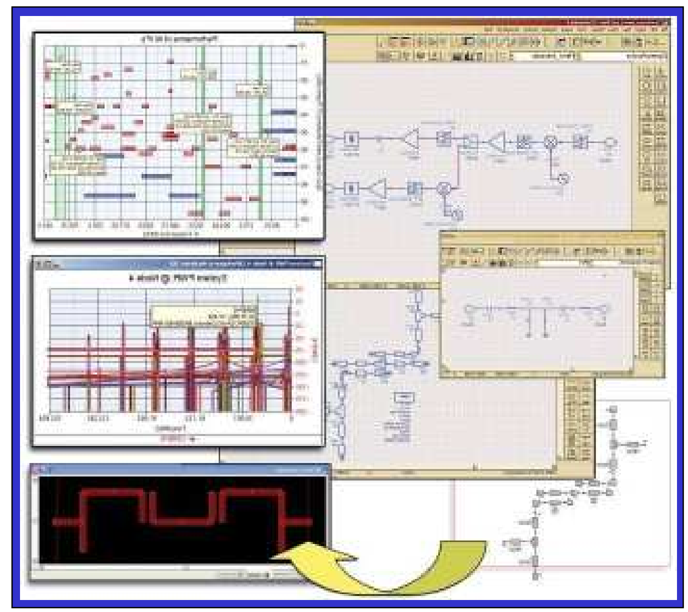
- Components are underlying **building blocks** of RF systems



- Magnitude and phase information crucial for **simulation** during design stage
- Ensure devices meet **specifications** during manufacturing

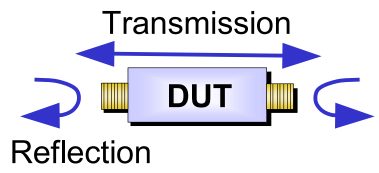
Monolithic Amplifiers • Surface Mount • DC to 8000 MHz

Model Number	Frequency Range (MHz)		Gain (dB) Typ.	Max. Power Output @ 1 dB comp. (dBm) Typ.	N.F. (dB) Typ.	IP3 (dBm) Typ.	VSWR (:1) Typ.		Device DC Operating Power	
click for data	Low	High					In	Out	Voltage (V)	Current (mA)
(+) Symbol indicates this Model is available as RoHS Compliant/Pb Free.										
<< SORT >>	<..>	<..>	<..>	<..>	<..>	<..>	<..>	<..>	<..>	<..>
ERA-1+	DC	8000	10.9	13.0	4.3	36.0	1.5	1.5	3.4	40
ERA-2+	DC	6000	14.4	13.0	4.0	26.0	1.3	1.2	3.4	40
ERA-3+	DC	3000	16.9	12.5	3.5	25.0	1.5	1.4	3.3	35
ERA-4+	DC	4000	13.4	17.3	4.3	34.0	1.3	1.3	4.5	65
ERA-5+	DC	4000	18.5	18.4	4.3	32.5	1.3	1.2	4.9	65
ERA-6+	DC	4000	12.3	17.9	4.5	36.0	1.3	1.6	5.0	70

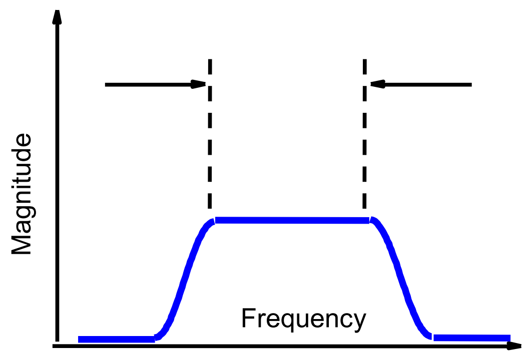


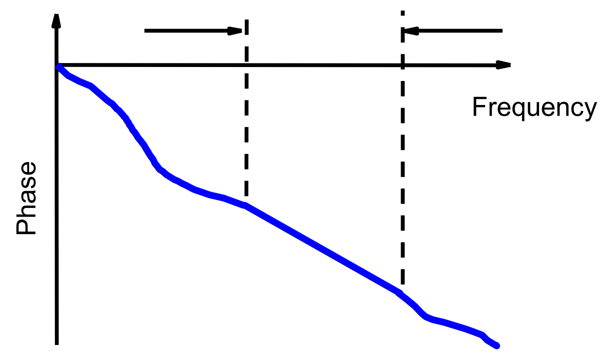
S-parameters: Core of Linear Characterization

- S-parameters: complex (magnitude and phase) reflection and transmission in forward and reverse directions



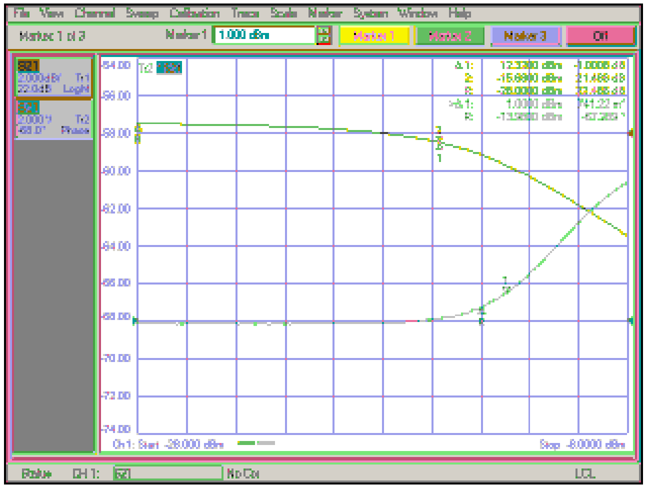
- Fully describe linear behavior of RF components
- Distortion caused by non-flat amplitude and deviation from linear phase/constant group delay
- Necessary, but not sufficient for full system simulation

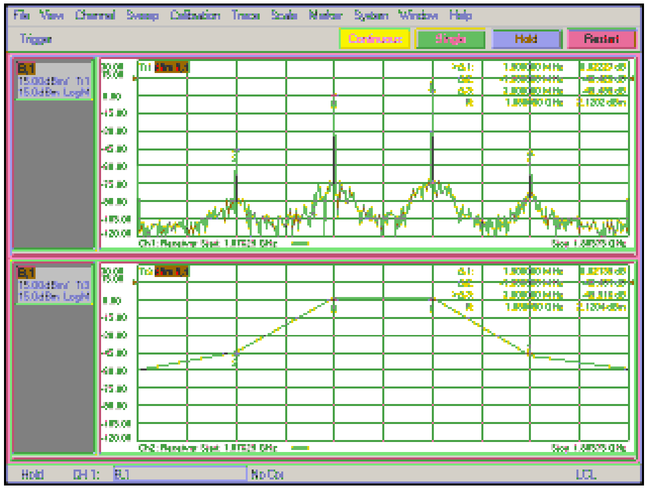




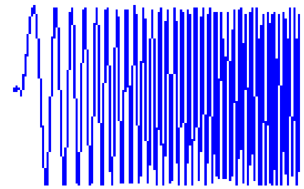
Non-Linear Distortion of Active Devices

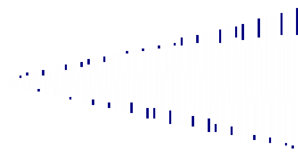
- System impairments also result from nonlinear device behavior
- Important to include nonlinear characteristics in simulation
- Nonlinearities usually dependent on power presented to device
- Common measurements include gain compression, AM-to-PM conversion, and harmonic and intermodulation distortion





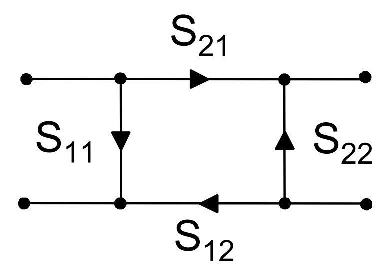
Vector Network Analyzers Key to Component Test

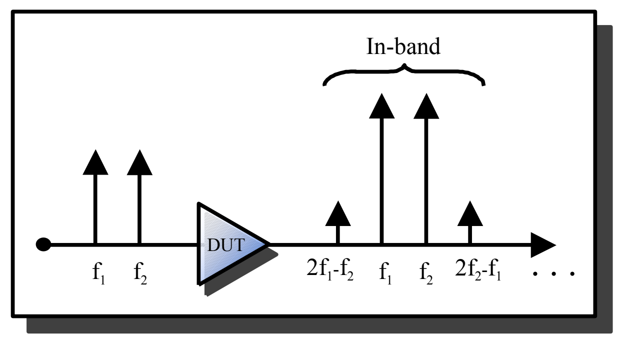




Vector network analyzers (VNAs)…

- Are stimulus-response test systems
- Can sweep frequency or power
- Characterize linear (S-parameters) and nonlinear (compression, IMD, etc.) performance
- Are very fast for swept measurements
- Provide the highest level of measurement accuracy





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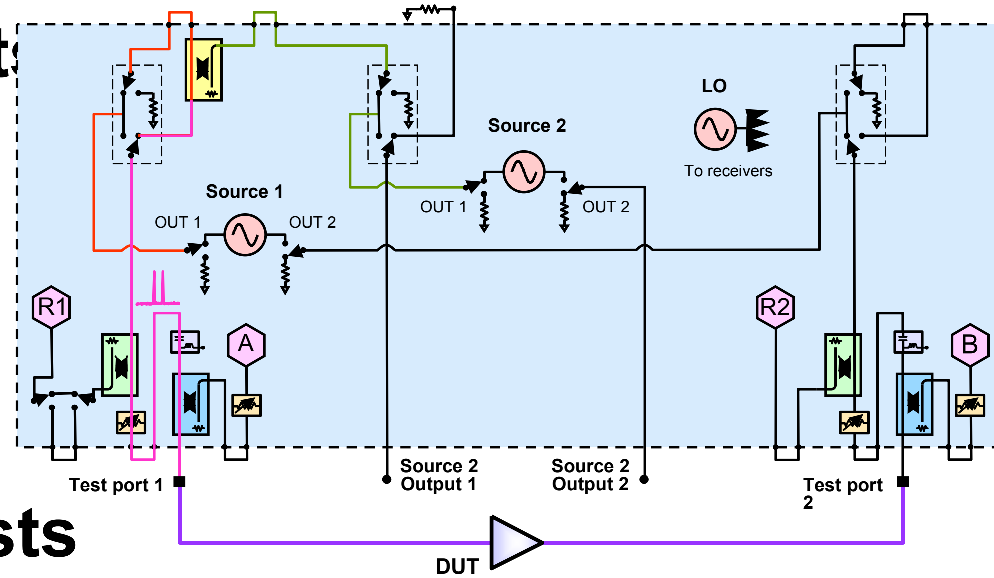
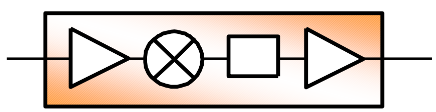
  - Single connection, multiple measurements

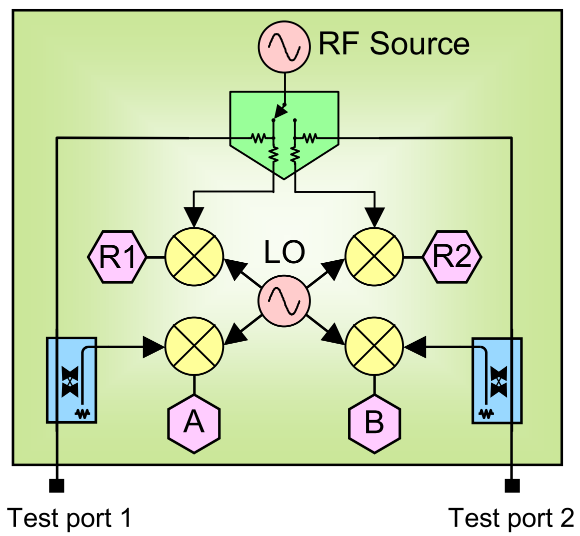


- **Mixer and Converter Tests**
- **Summary**

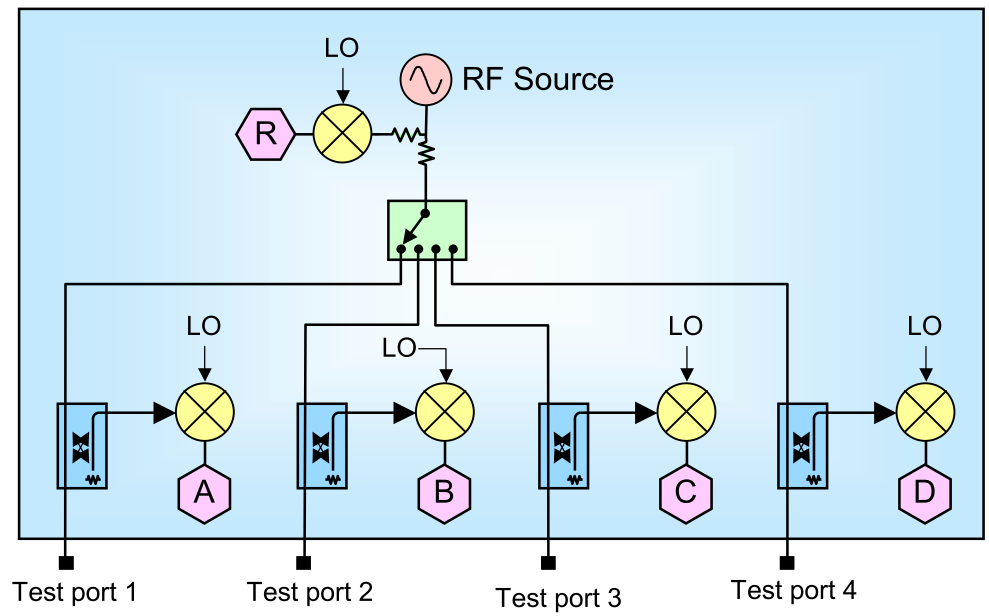


Traditional VNA Architectures

- Traditional VNAs have one RF source, two test ports
- Four-port analyzers are common now



Reference receivers for each test port



Reference receiver shared among all test ports

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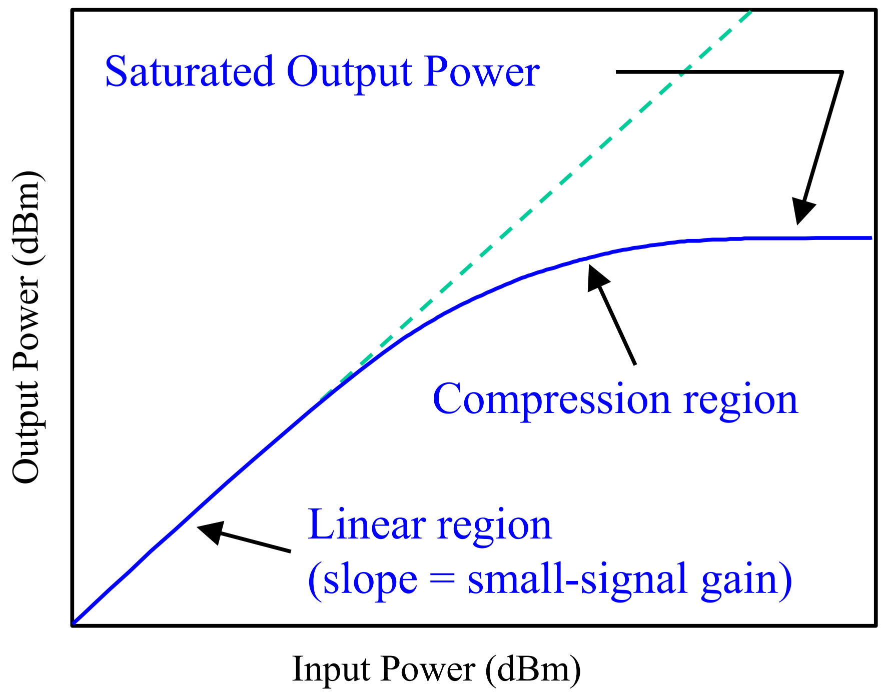
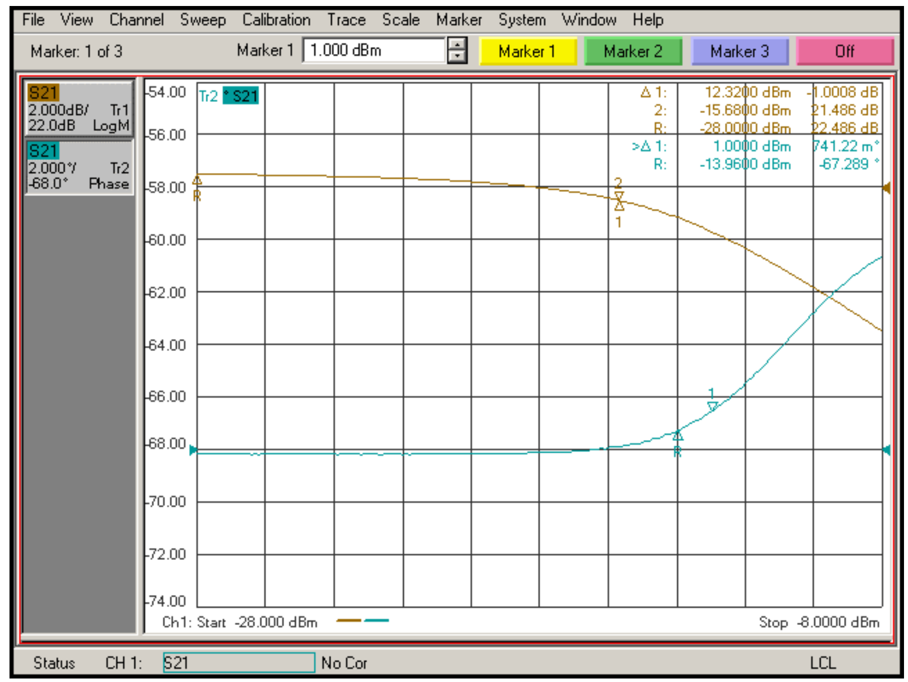
Nonlinear Testing With One Source – Power Sweeps

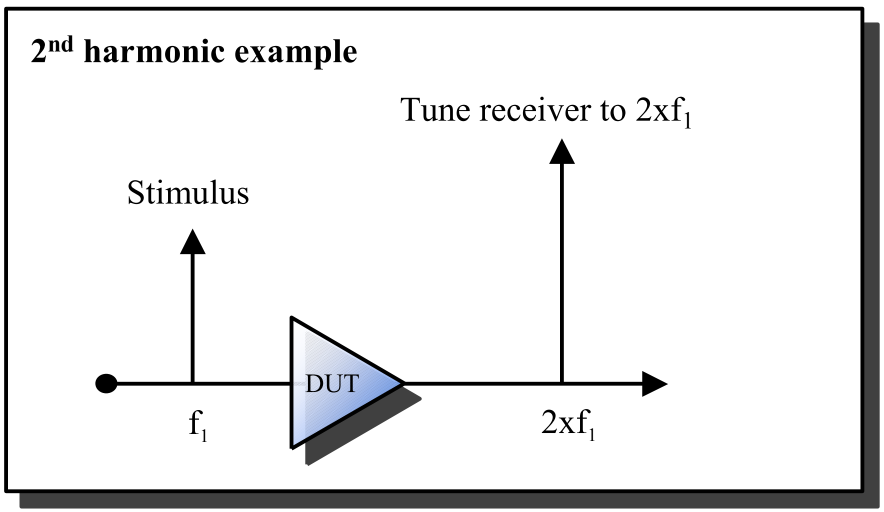
- Sweep power at a fixed frequency (CW)
- Measure gain compression and phase compression (AM-to-PM conversion)

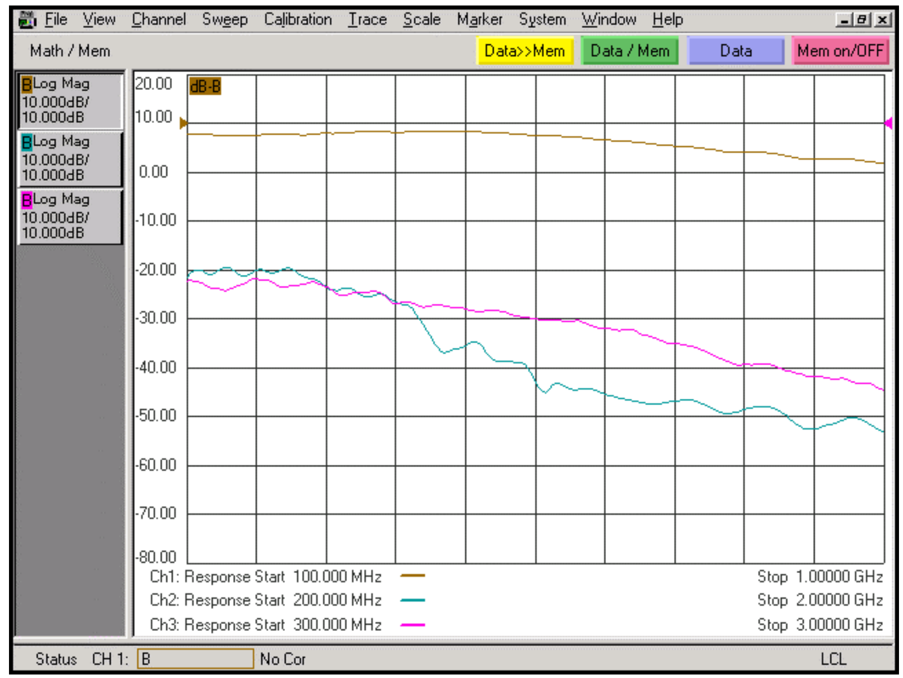




Nonlinear Testing With One Source – Harmonics

- Sweep fundamental frequency
- Measure harmonics generated by DUT
- VNA must be able to tune receivers independent of stimulus (frequency-offset mode)





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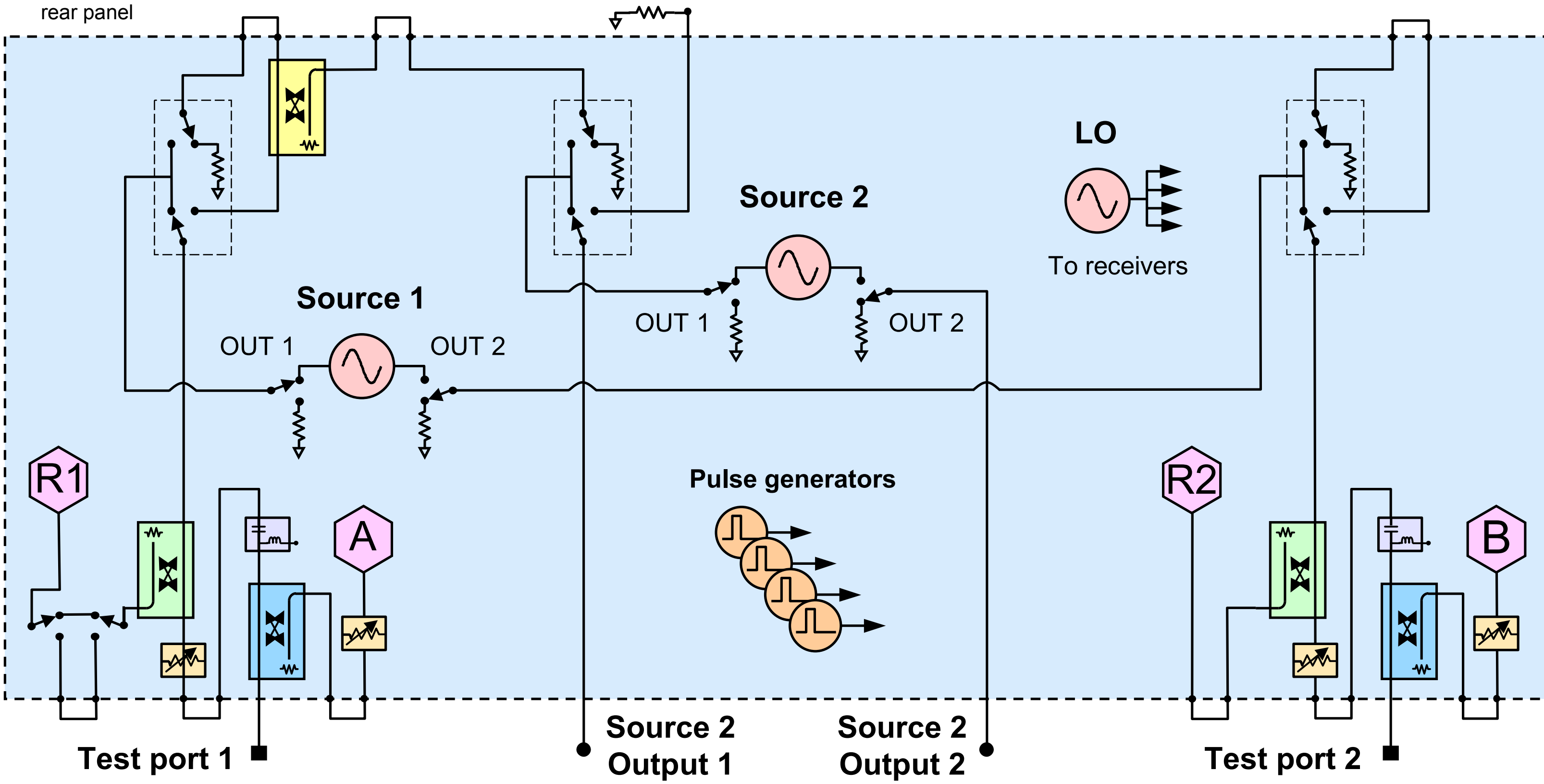
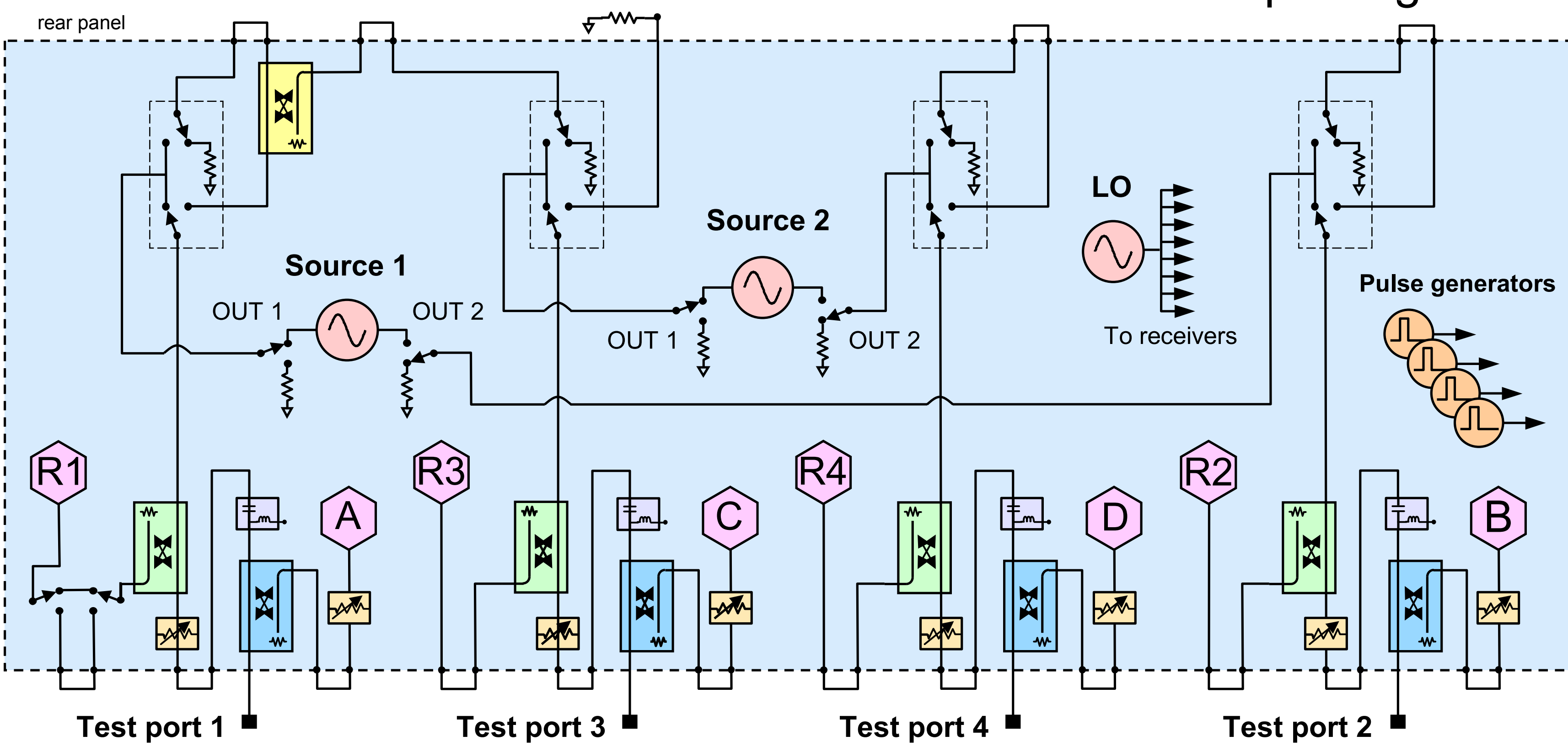
Modern Two-Port VNA Architecture

- Second internal source
- Internal signal combiner
- Flexible signal routing
- Internal modulators and pulse generators

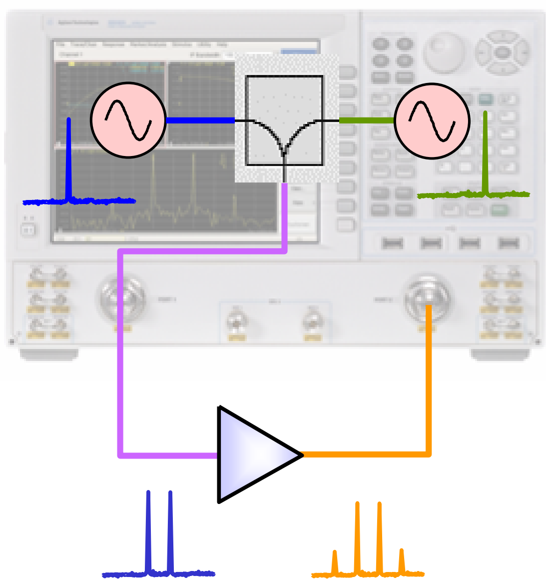


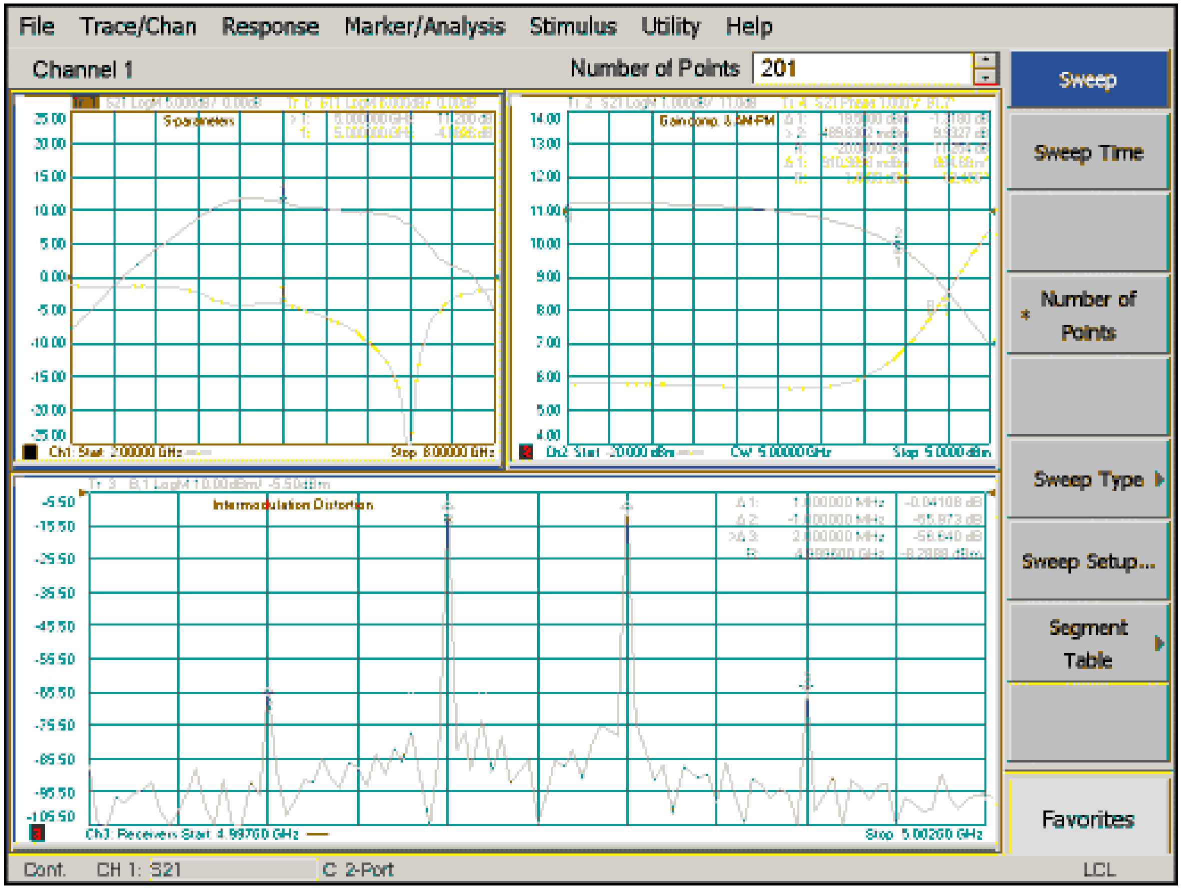
Modern Four-Port VNA Architecture

- Second internal source
- Internal signal combiner
- Flexible signal routing
- Internal modulators and pulse generators



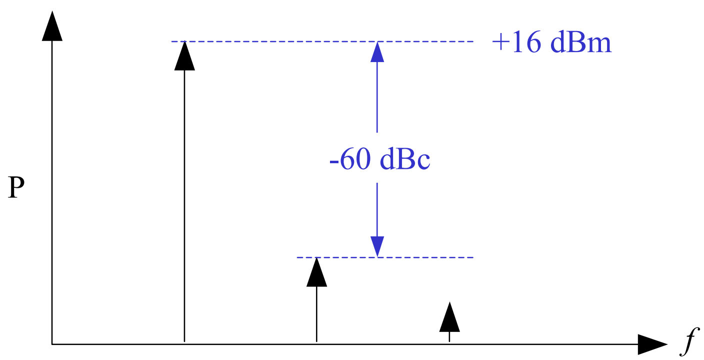
Easily Switch Between One- and Two-Source Tests

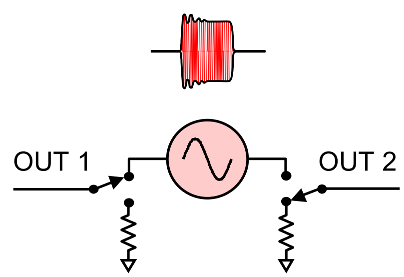


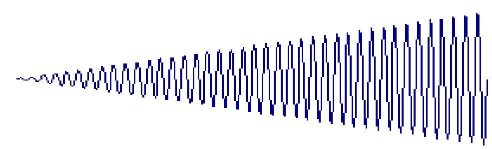


Desirable Source Attributes

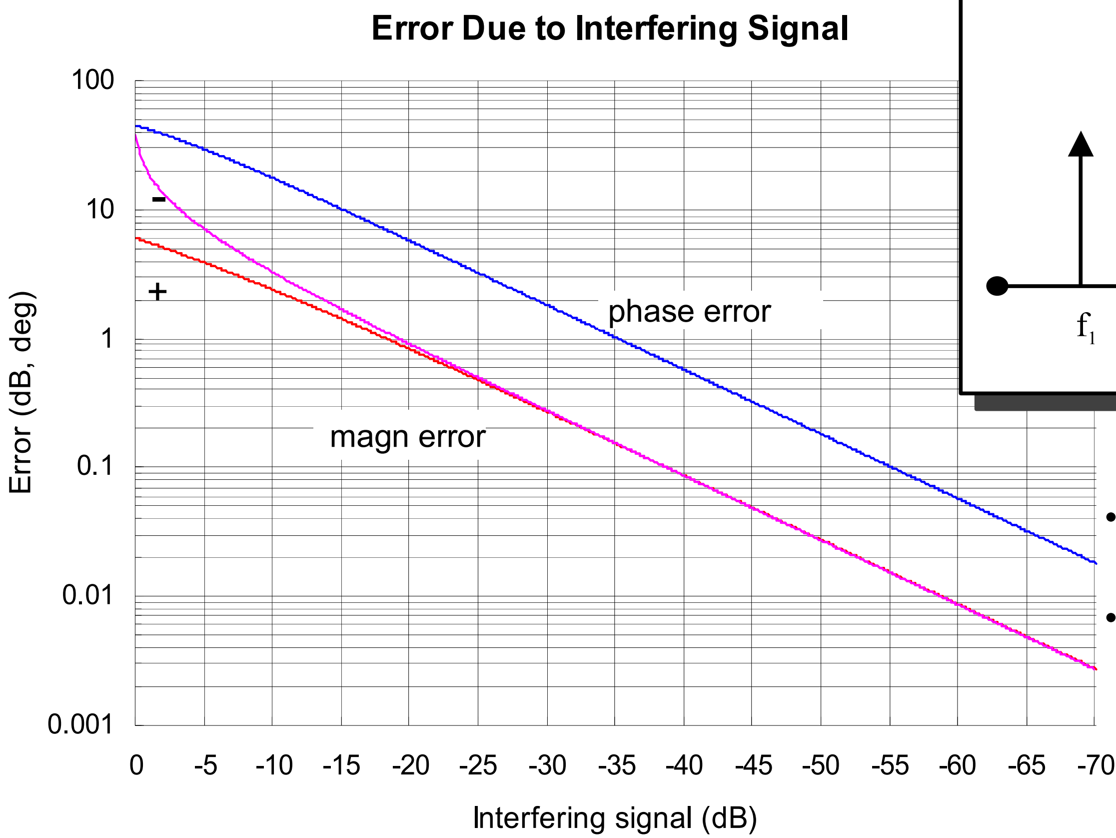
- **High port power** to drive amplifiers into compression and to ensure measurable distortion products
- **High port power** for driving mixer LO ports
- **Low source harmonics** for more accurate harmonic and IMD measurements
- **Wide power-sweep range** to cover linear-to-nonlinear transition
- Built-in **pulse modulators** for simple pulsed S-parameter setups

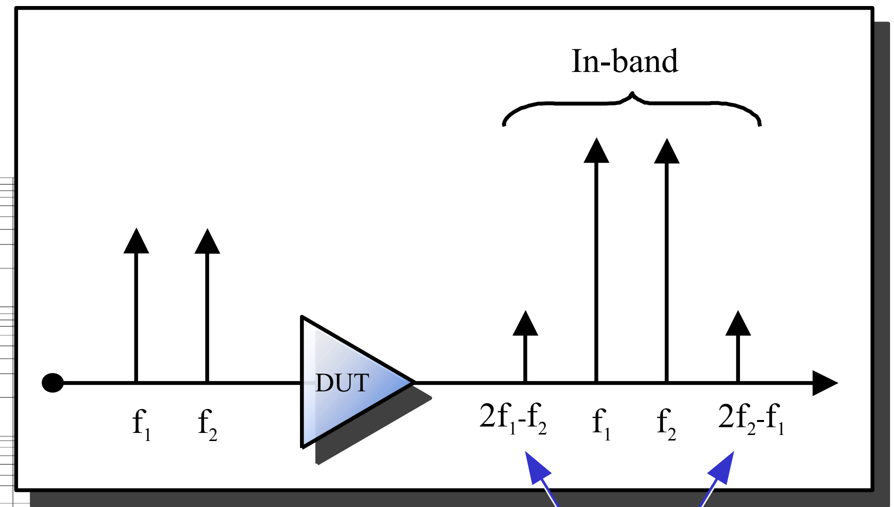






Benefit of Low Source Harmonics for IMD Tests

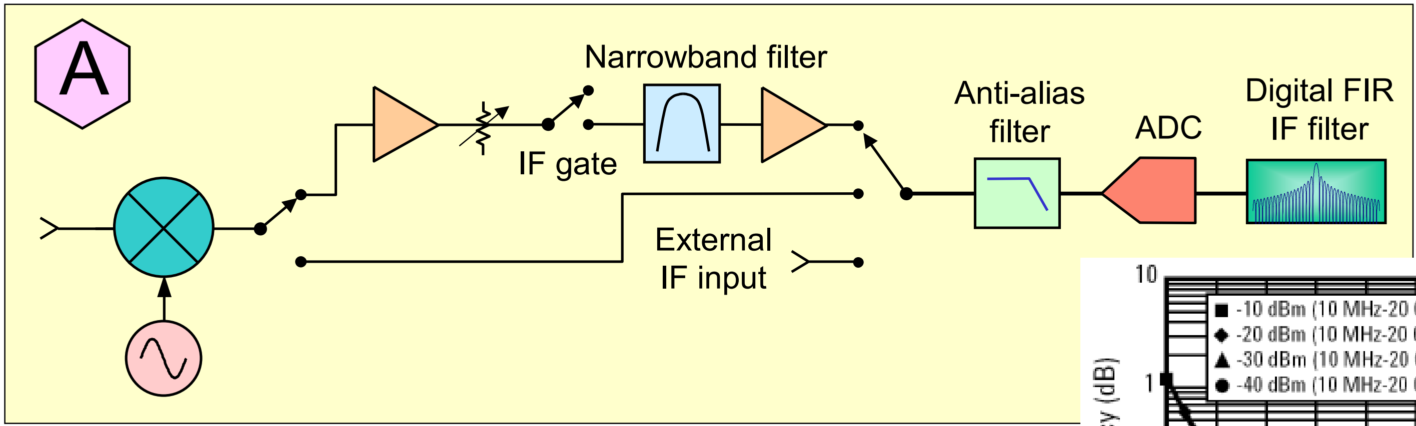


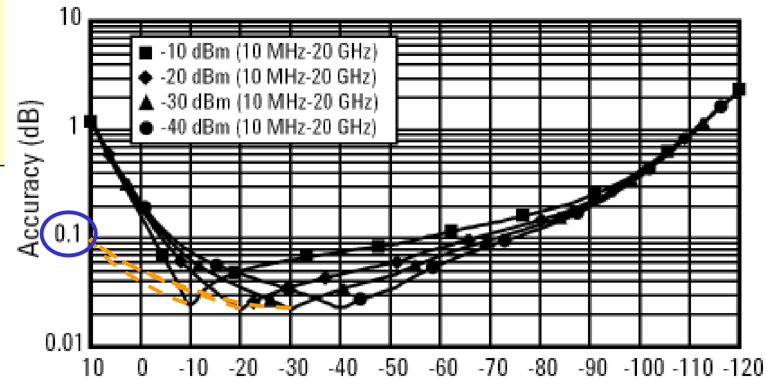


- Source harmonics will interfere with device-generated intermodulation products
- Quantify error by applying f_1+2f_2 or $2f_1+f_2$ at input to DUT where power of $2f_1$ or $2f_2$ is same as source 2nd harmonic power level

Desirable Receiver Characteristics

- Excellent linearity with a high compression point
- Narrowband IF path for improved IMD and pulsed measurements
- Internal IF gates for narrowband pulsed measurement
- External IF inputs for antenna-system remote-mixing situations





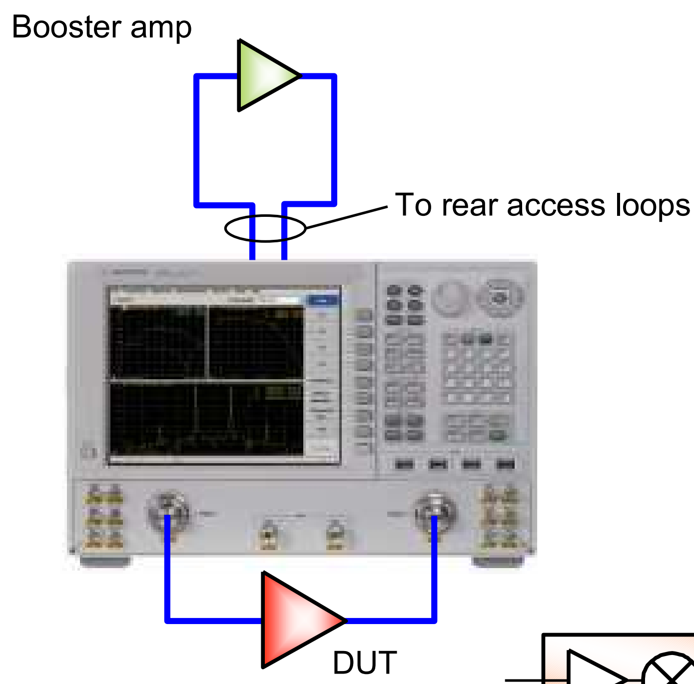
PNA-X Provides Industry-Leading Performance

N5242A PNA-X Performance

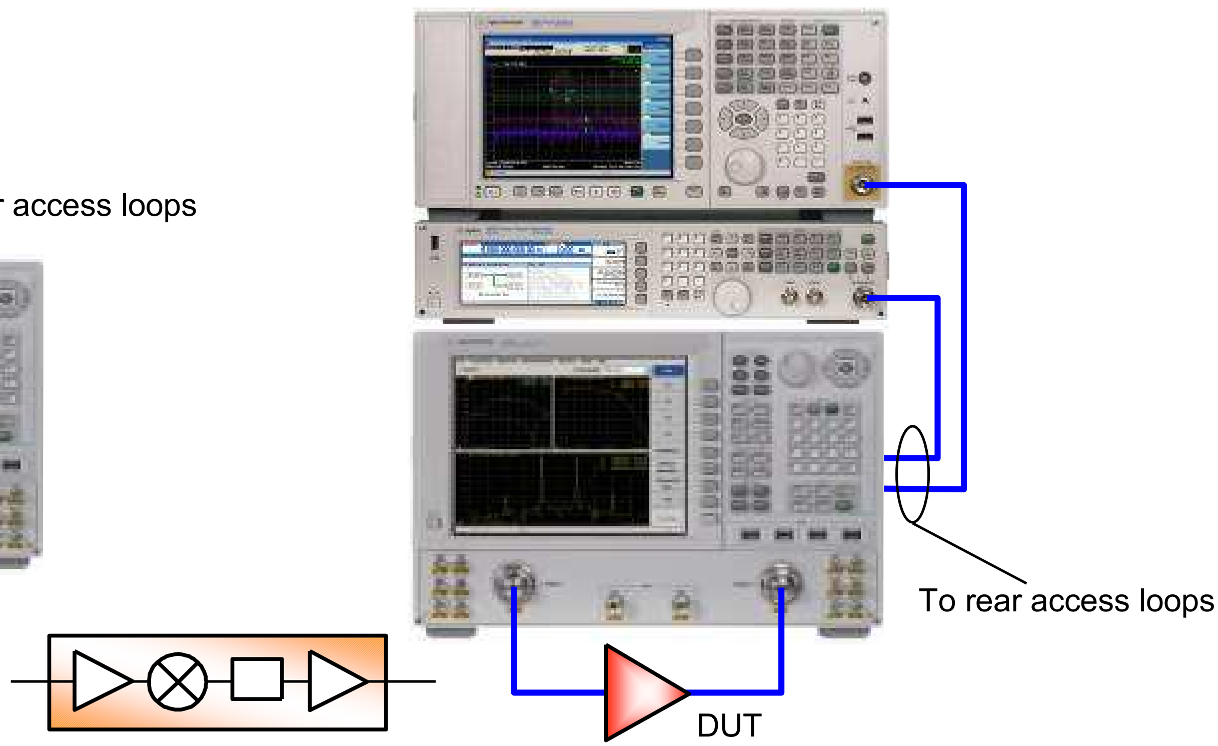
• Frequency Range	10 MHz to 26.5 GHz
• IF Bandwidths	1 Hz to 600 kHz
• Dynamic Range	130 dB at 24 GHz
• Trace Noise (1 kHz IF BW)	0.0006 dB at 22.5 GHz
• Output Power	+16 dBm at 24 GHz
• Source Harmonics	-60 dBc at 24 GHz
• 0.1 dB Receiver Compression	+12 dBm at 20 GHz
• Power Sweep Range (ALC)	40 dB at 24 GHz

Additional Access Loops Expand Range of Measurements

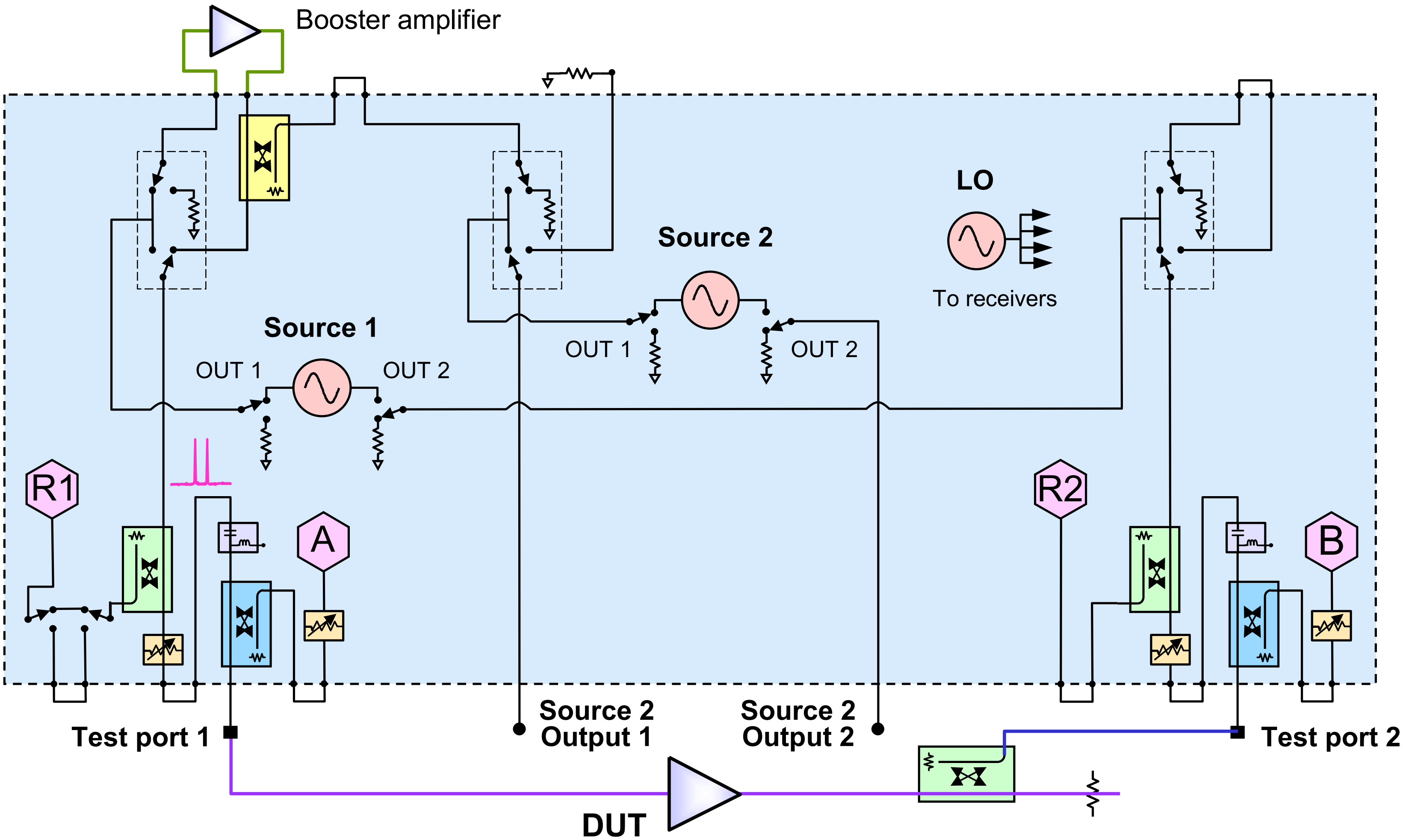
Example 1: switch between normal path and high-power path



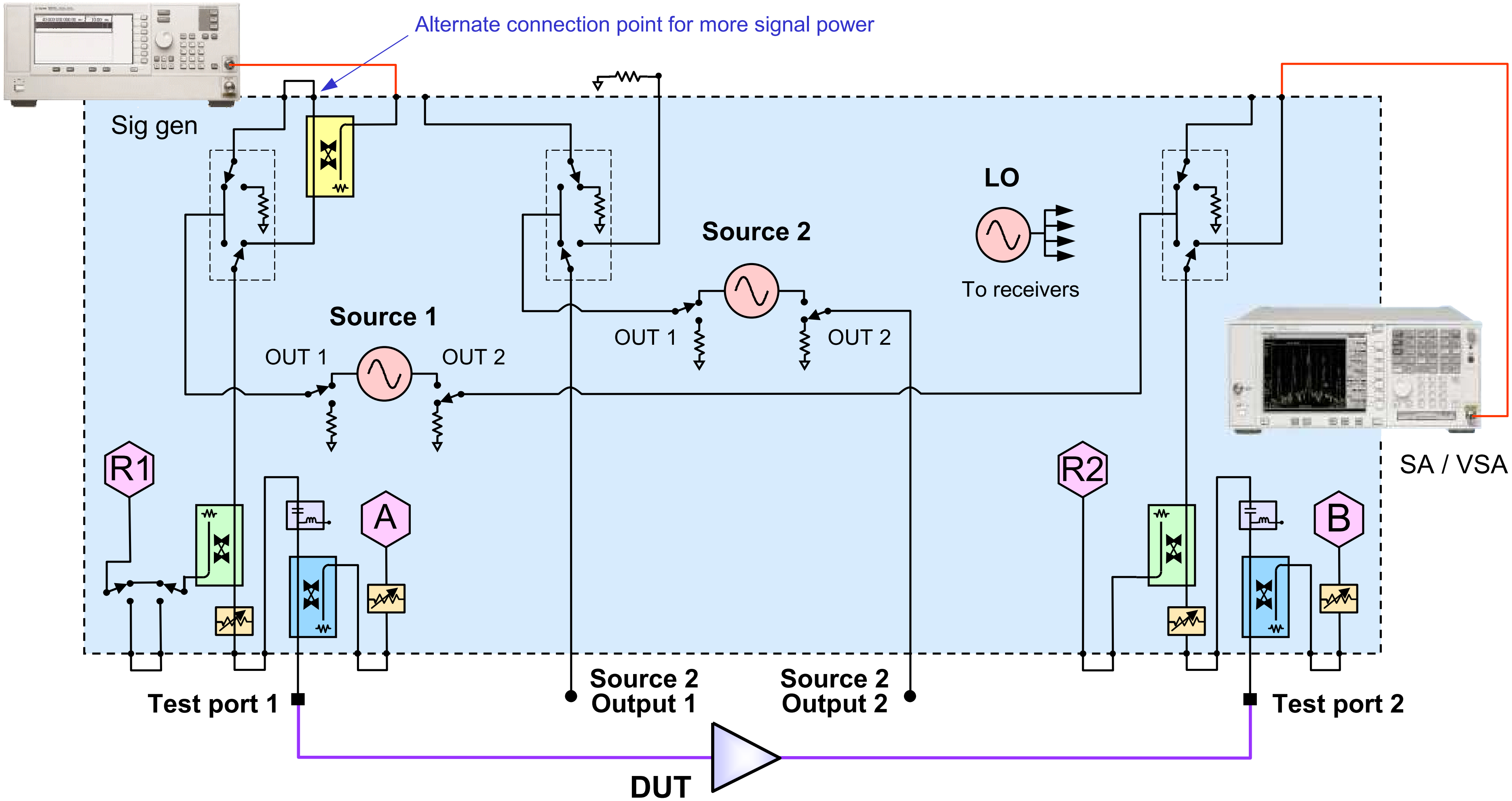
Example 2: switch between network analyzer and external source and SA/VSA



Two-Port PNA-X High-Power Amplifier Measurements

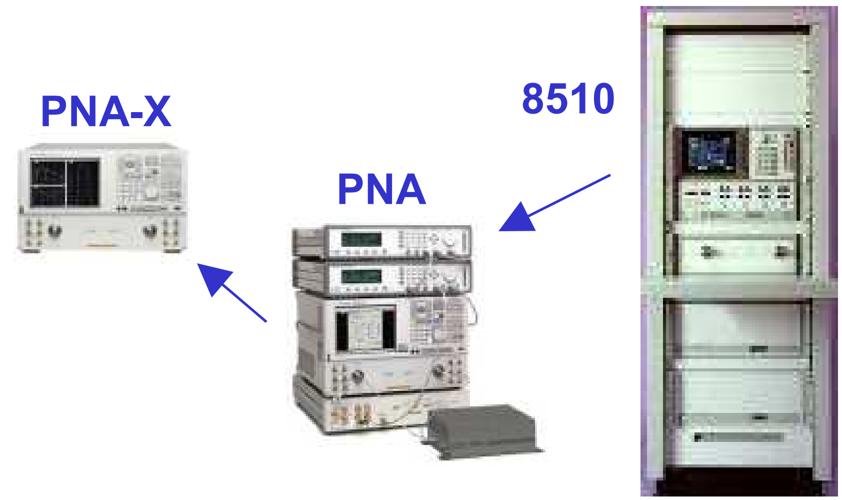


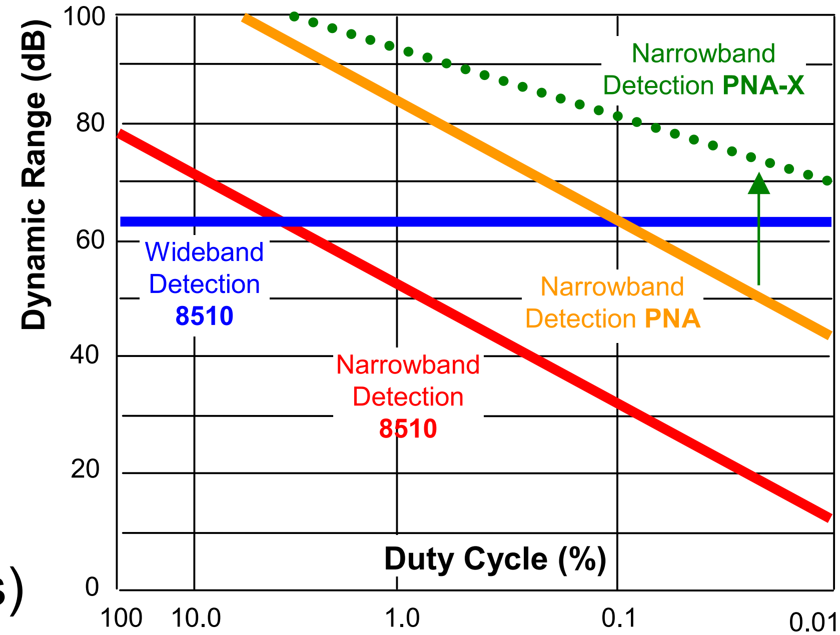
Single Connection, Multiple Measurements



Pulsed S-parameters

- **Ease of Setup**
  - Internal pulse modulators (one or two)
  - Internal pulse generators (four)
  - Very fast pulse-profile measurements (20-30x improvement over PNA)
- **Wide- or narrow-band detection**
  - Wideband down to 2 us (< 1 us soon)
  - Narrowband down to 33 ns
- **Dynamic range improvements for narrowband detection**
  - Crystal-filter path with increased gain
  - Patented software-gating technique (especially helpful for small duty cycles)





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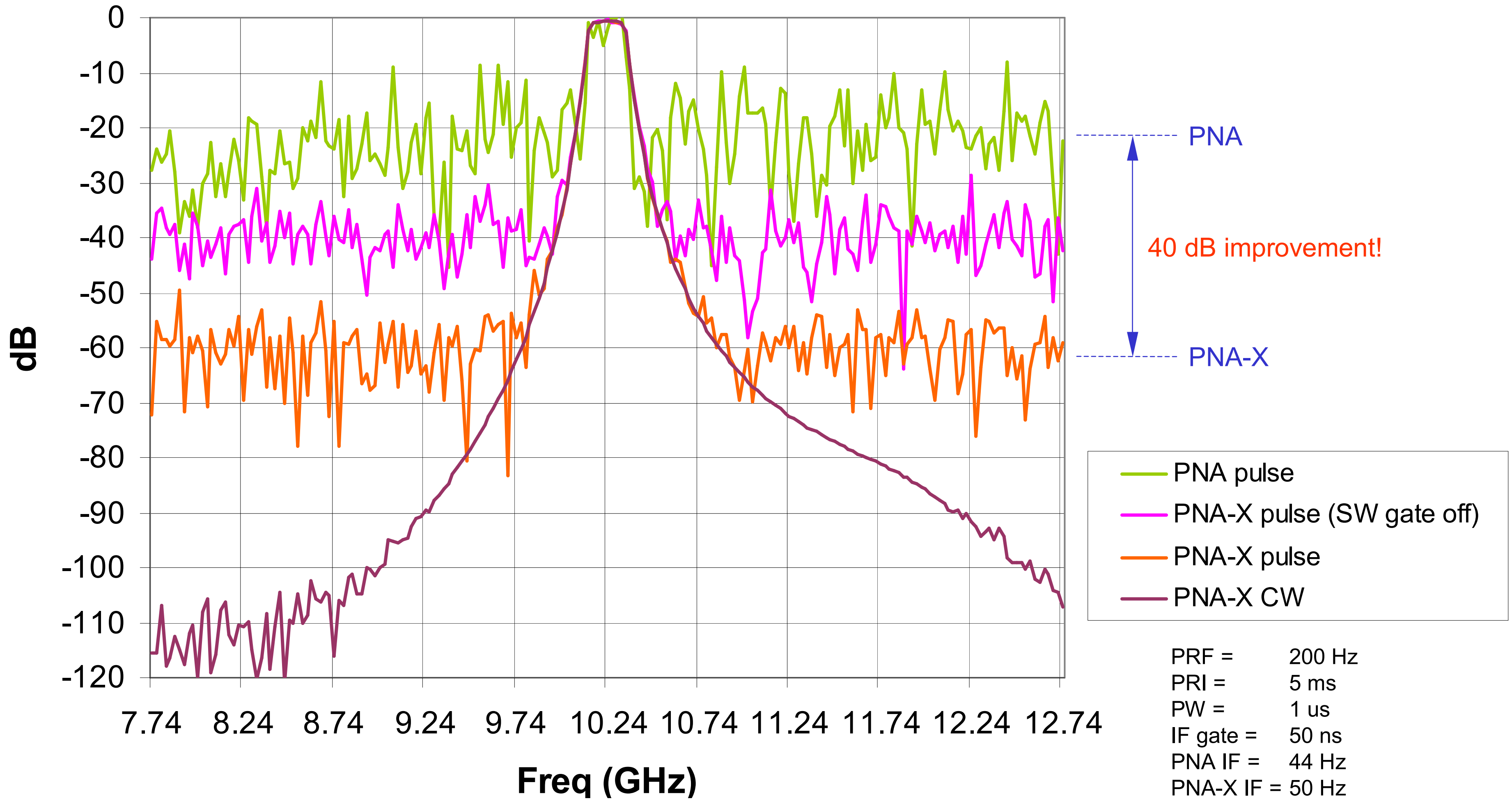
Narrowband Example with Low Duty Cycle (.001%)



PRF =	200 Hz
PRI =	5 ms
PW =	1 us
IF gate =	50 ns
PNA IF =	44 Hz
PNA-X IF =	50 Hz

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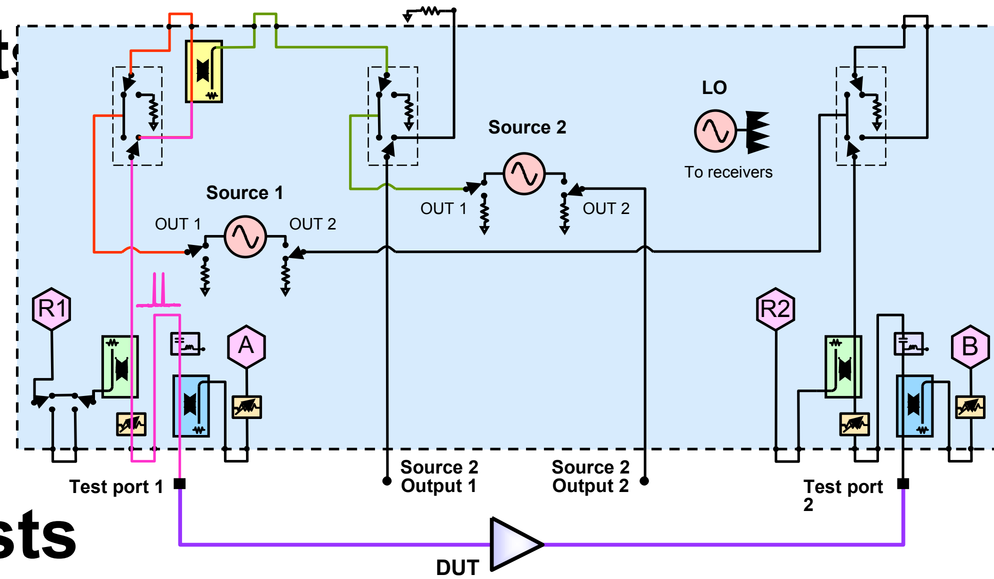
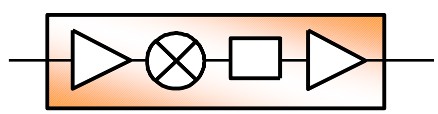
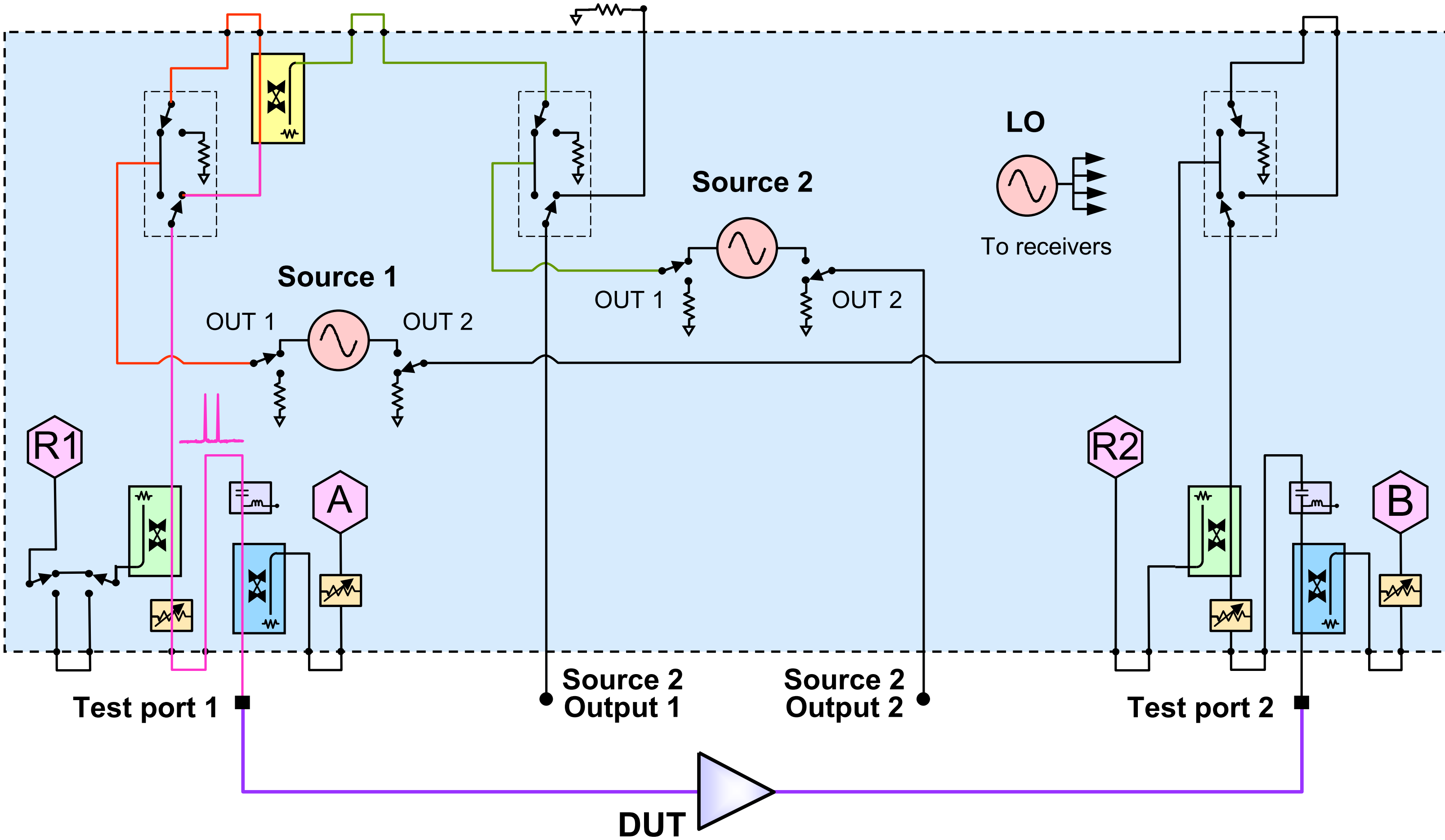
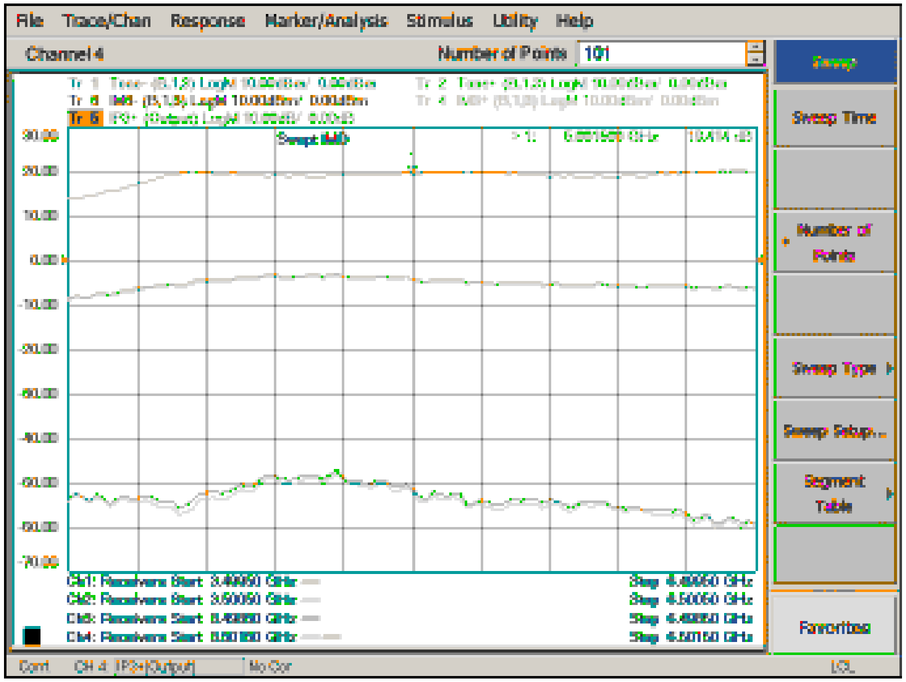




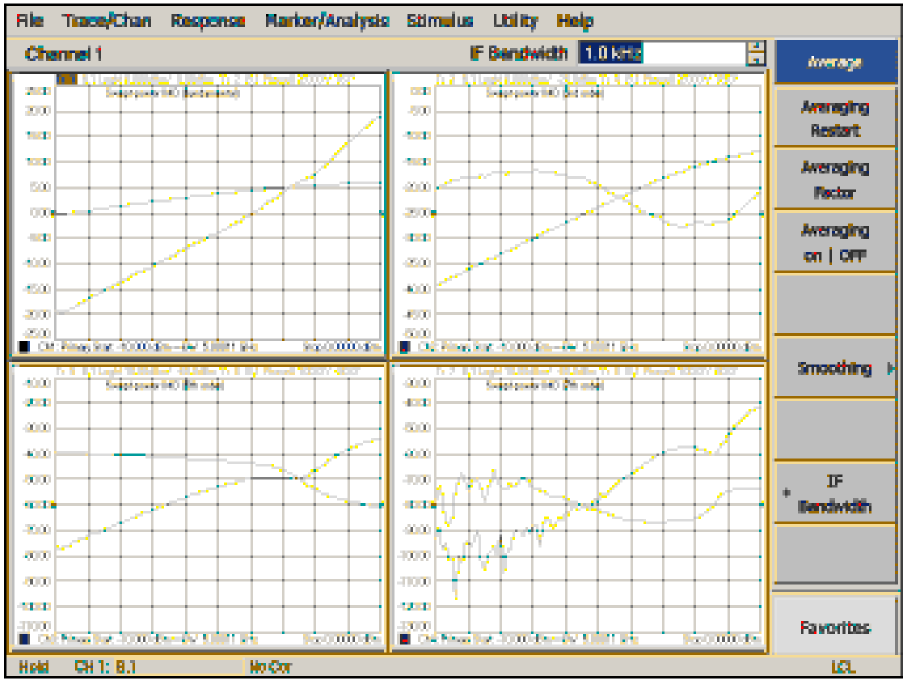
Two-Port PNA-X Two-Tone IMD Measurements



IMD Examples

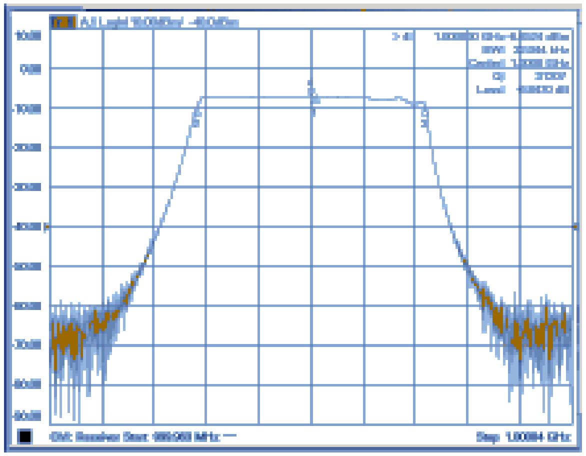


Swept-frequency IMD

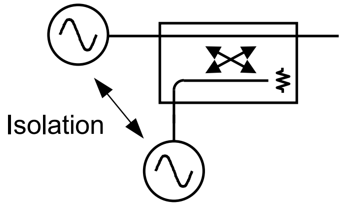


Swept-power IMD

Optimizing IMD Measurements



- Use narrowband (crystal-filtered) IF path
- Set IF bandwidth as narrow as possible (limited by measurement speed)
- Set attenuation in receiver path to optimize noise floor and receiver IMD
- Avoid source spurs
  - single tone spurs generated by synthesis process
  - avoid multiples of 10 MHz by 3 to 10 times the IF bandwidth
- Avoid source cross modulation (due to ALC loop interaction)
  - use combiner with good isolation between sources
  - use open-loop leveling



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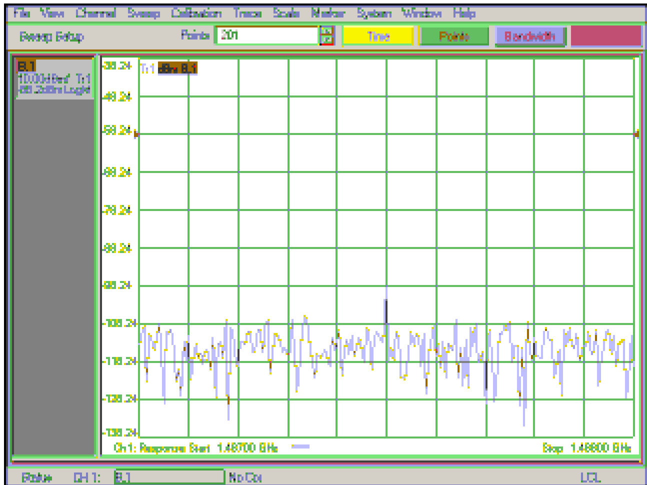
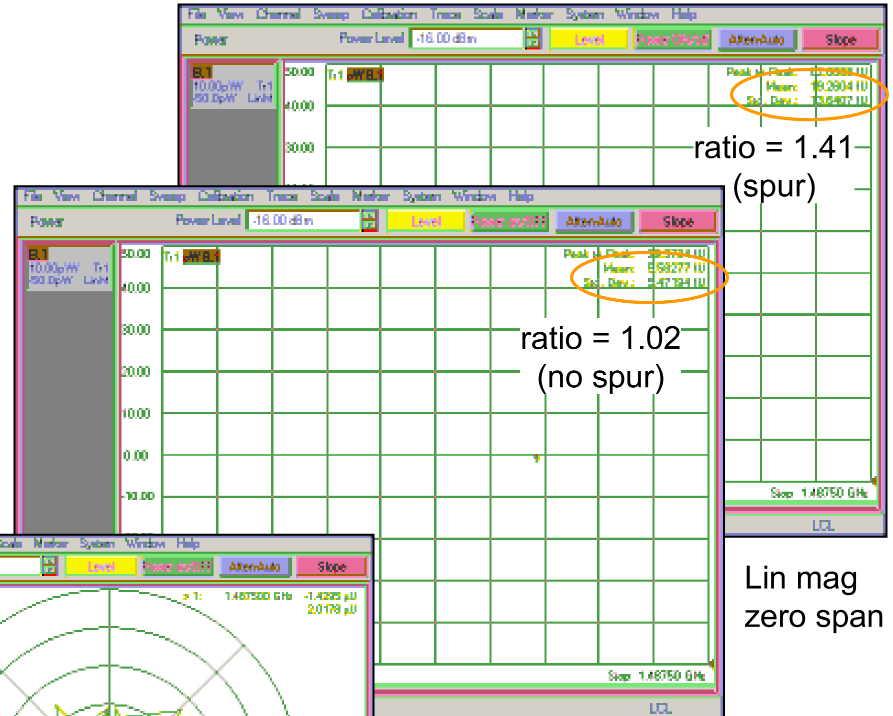
Looking for Source Spurs

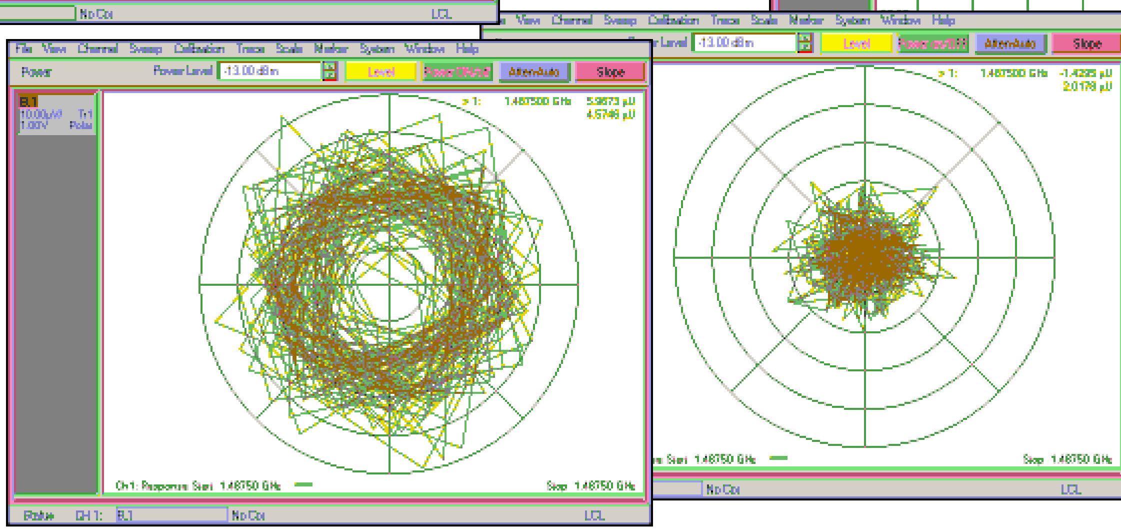


Log mag
non-zero span



Lin mag
zero span

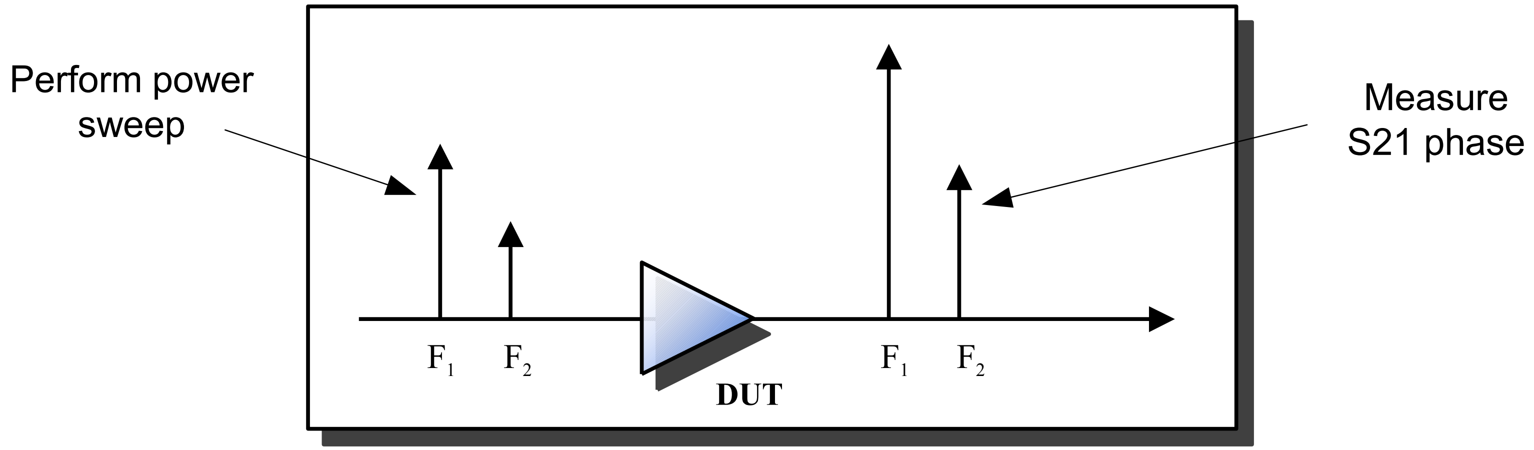
Mean/(Std. Dev.) ≥ 1.25
indicates a spur (for 201 points)



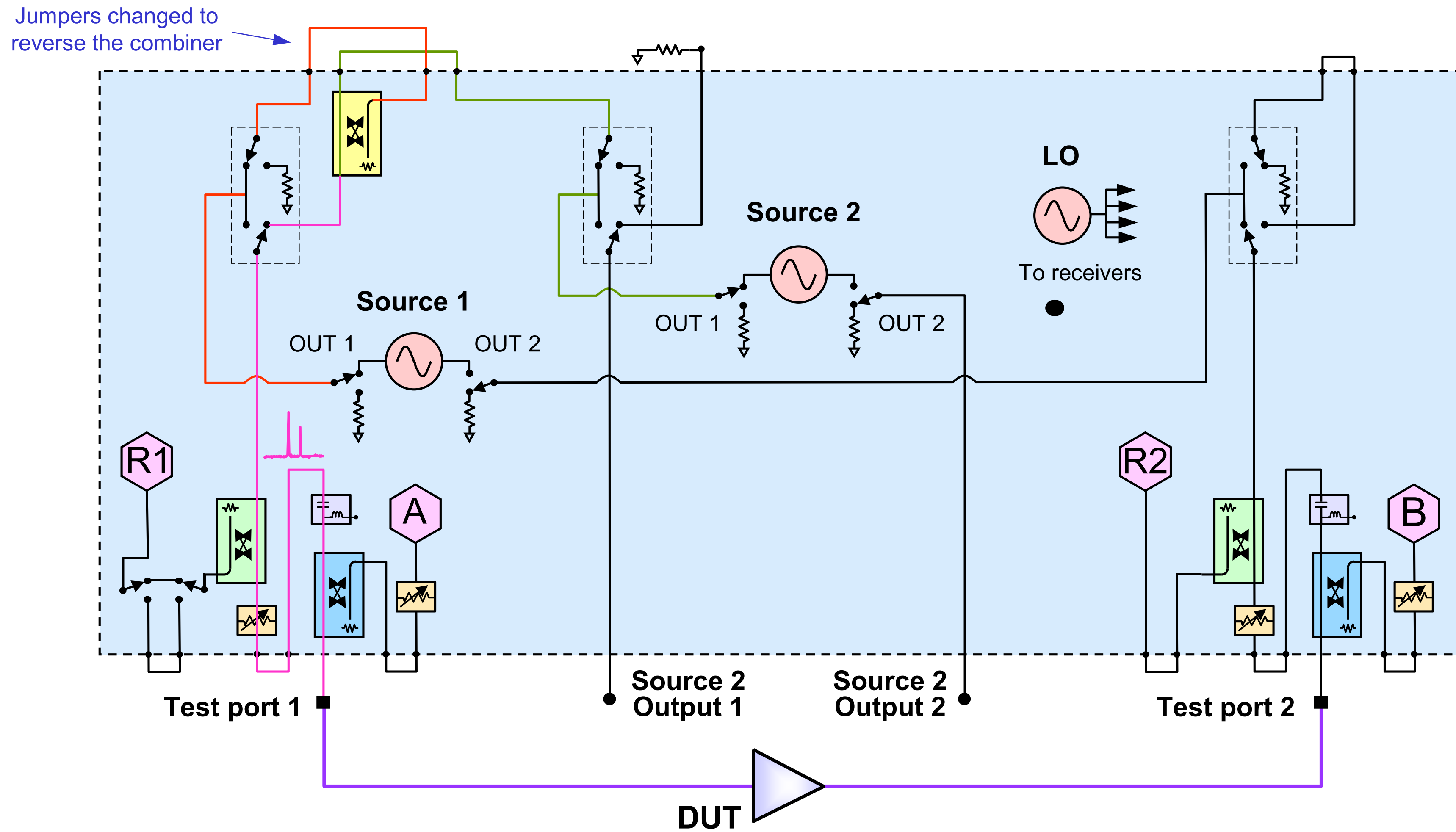
Polar
zero span

Phase Versus Drive

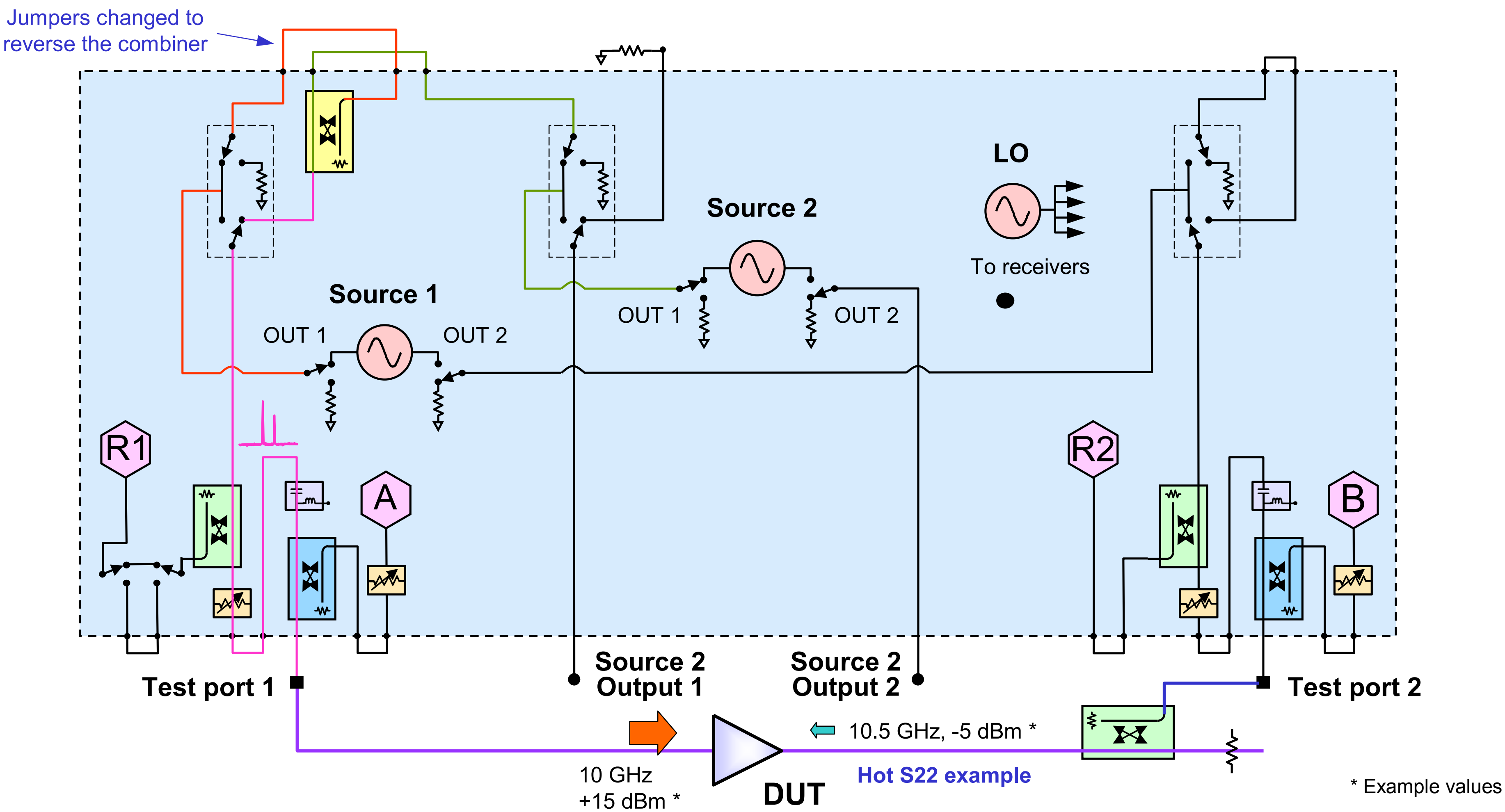
- Measure phase change on fixed signal F_2 (low power) induced by amplitude change on signal F_1 (high power)
- Combine signals with same hardware setup as for measuring IMD
- Perform a power sweep with F_1
- Tune receivers to F_2 and measure S21 phase
- Calculate delta phase divided by delta amplitude (e.g., deg/dB)



Two-Port PNA-X Phase Versus Drive

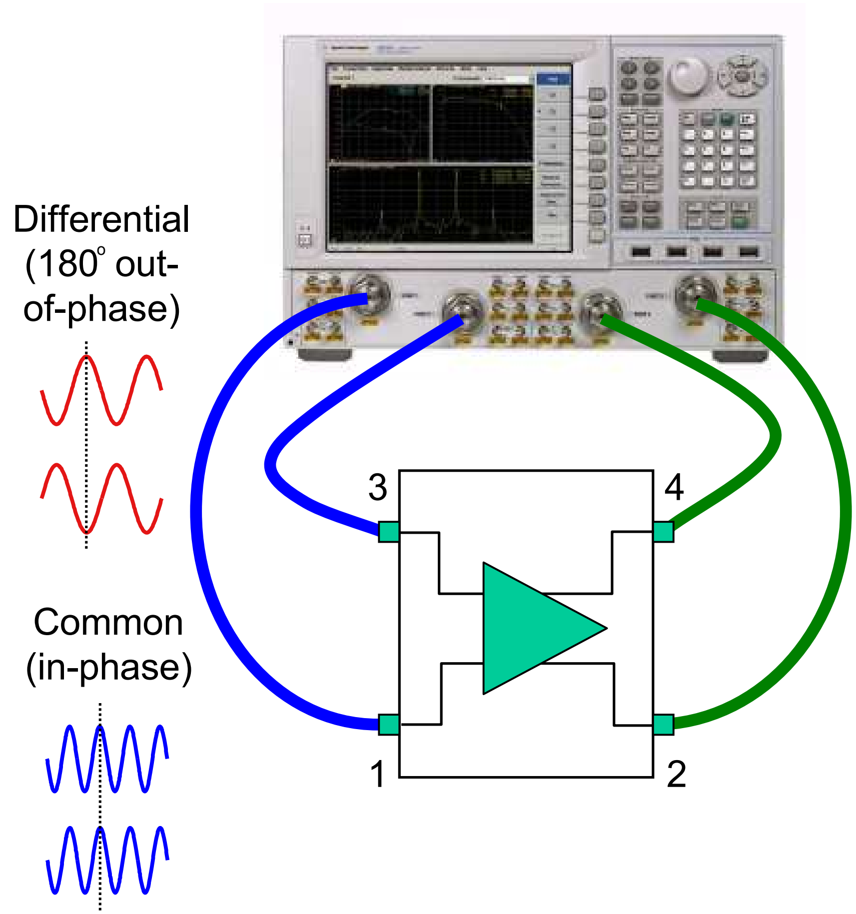


Two-Port PNA-X Hot S-Parameters



True-Mode Stimulus

- Accurately characterize balanced amplifiers in nonlinear region of operation
- Apply true-differential or true-common-mode stimulus (forward and reverse direction)
- Apply arbitrary phase offset (CW only)
- Measure differential-mode, common-mode, and cross-mode S-parameters
- Correct amplitude/phase imbalance due to mismatch with single-ended 4-port calibration



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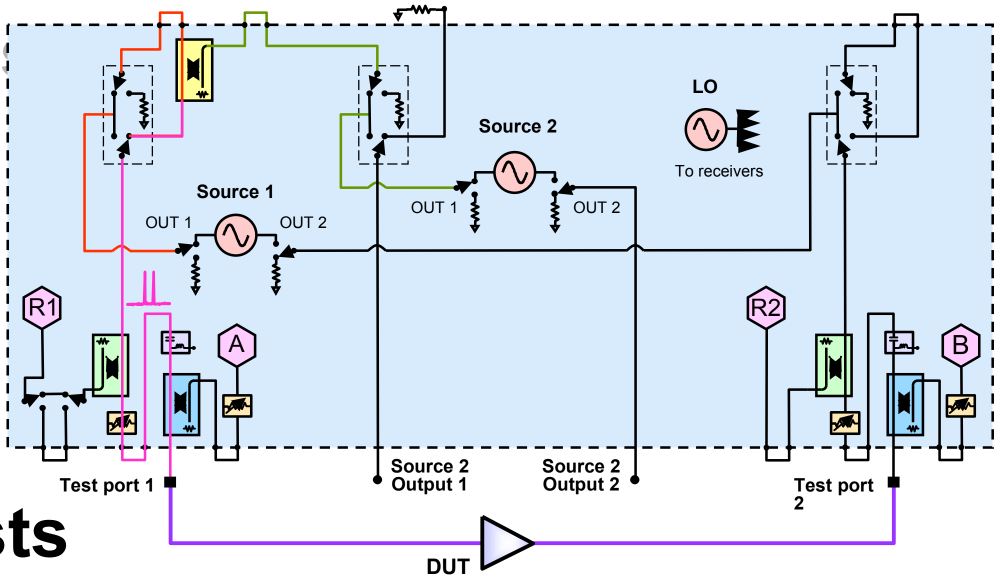
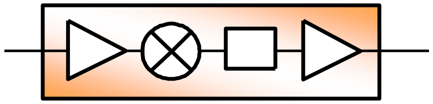
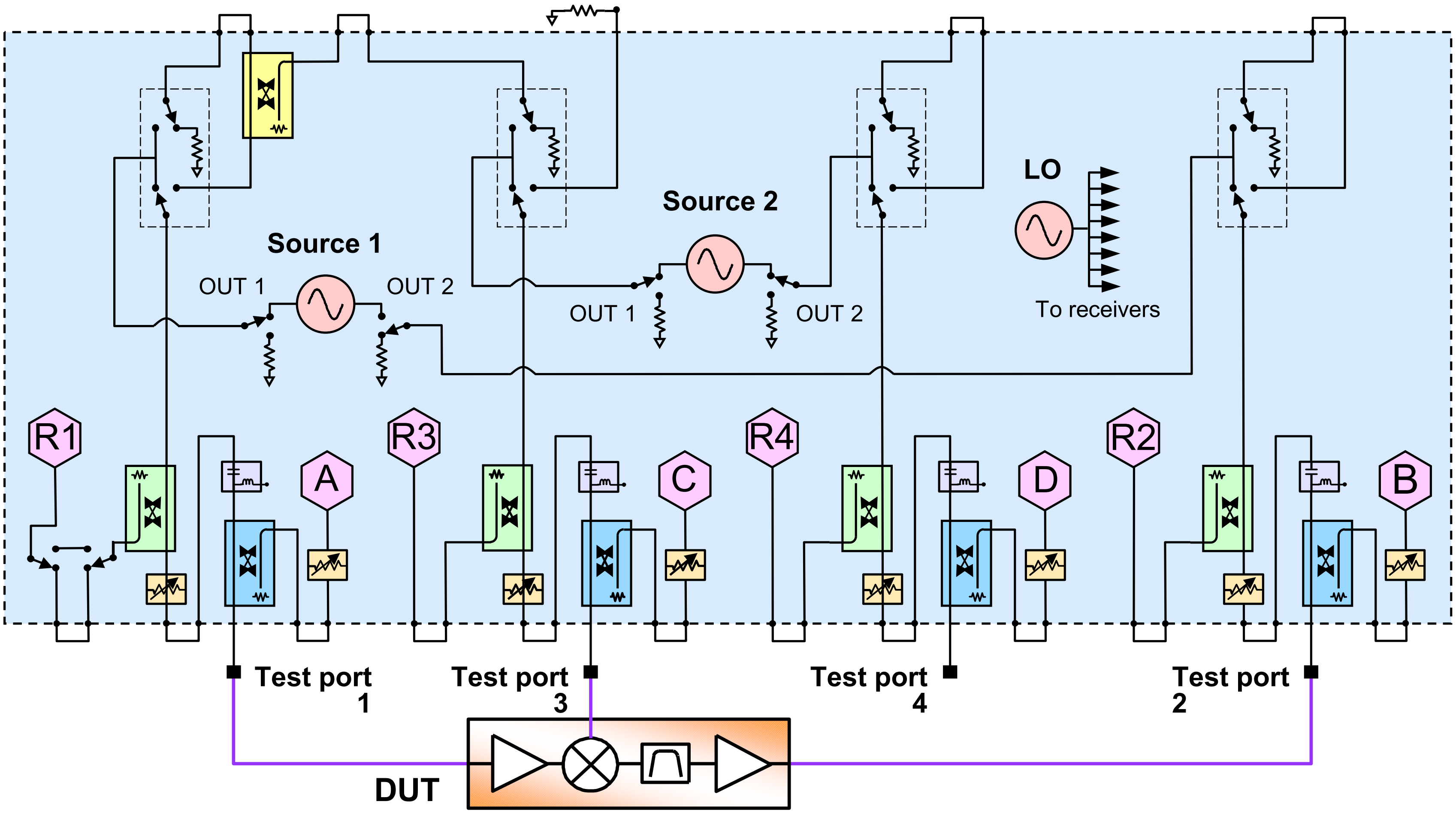
- **Mixer and Converter Tests**
- **Summary**

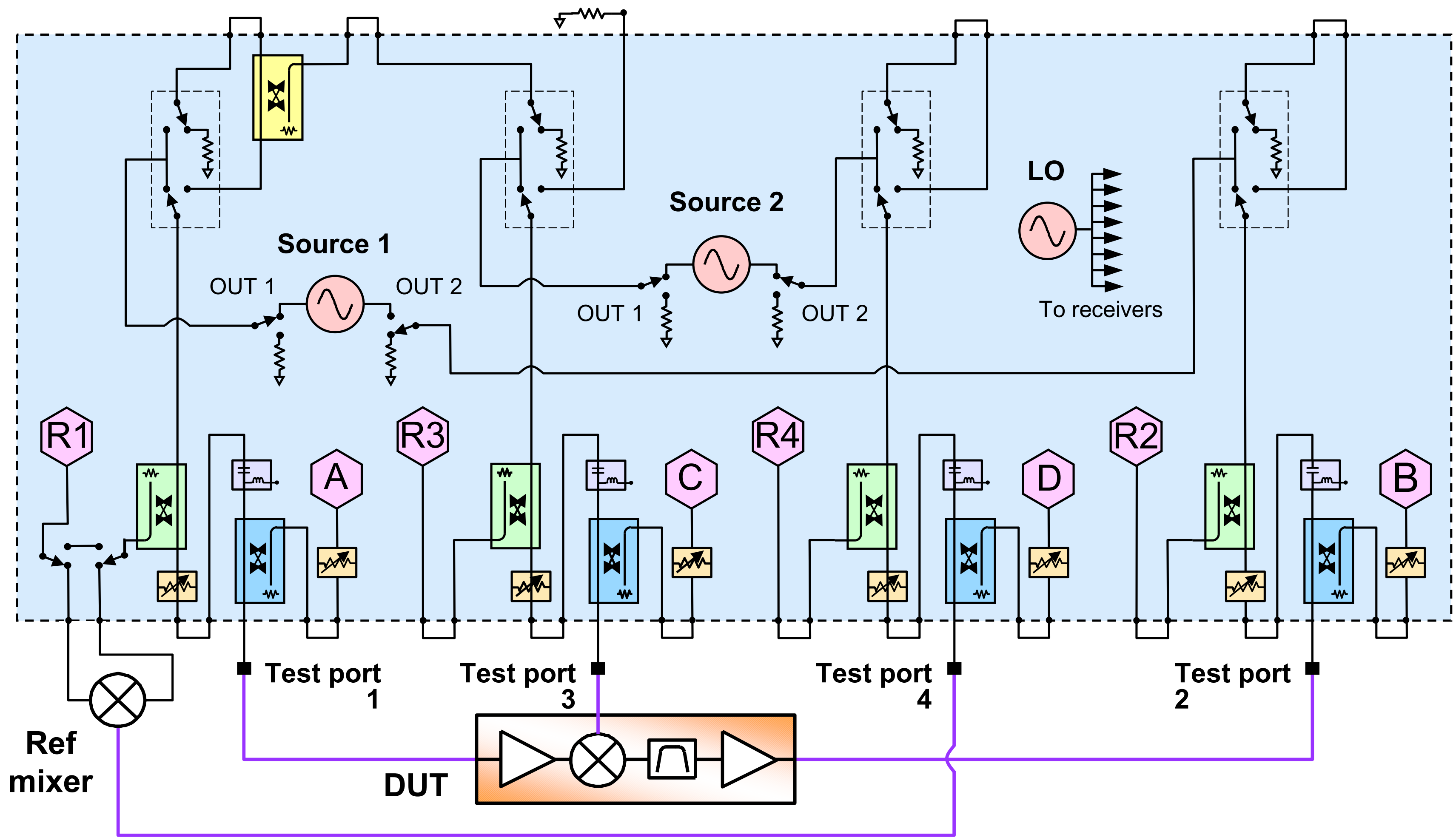




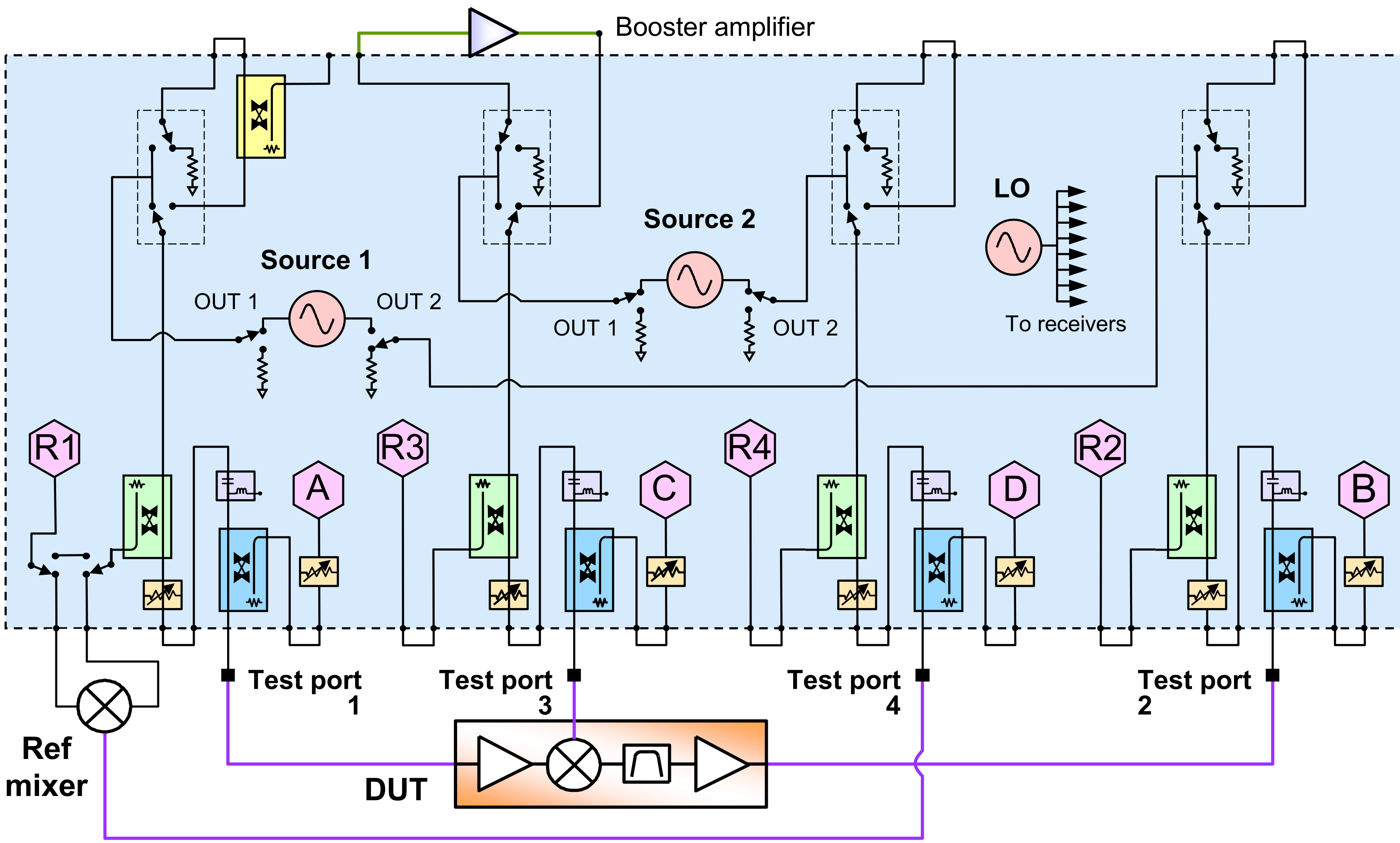
Four-Port PNA-X Scalar Mixer/Converter Measurements



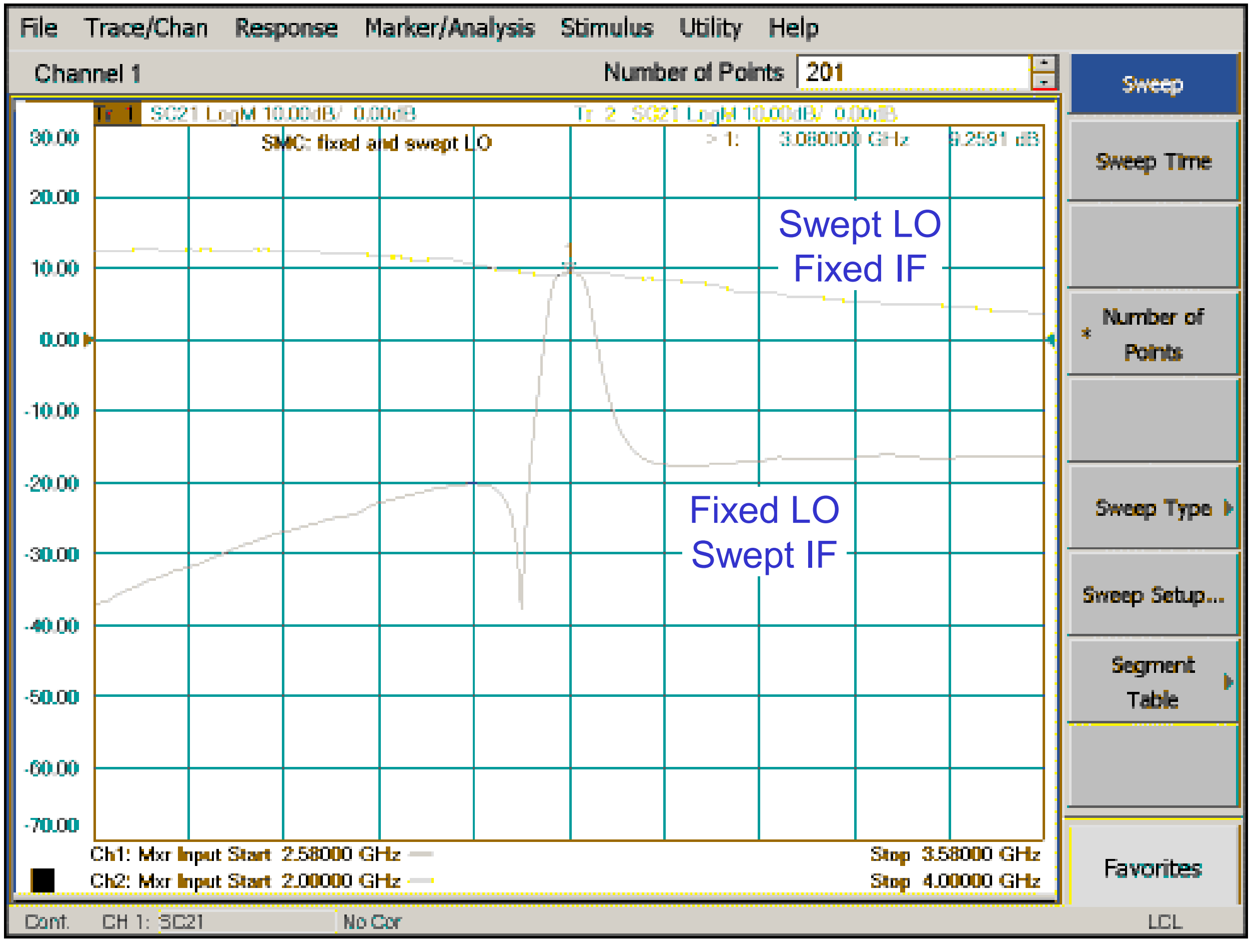
Four-Port PNA-X Vector Mixer/Converter Measurements



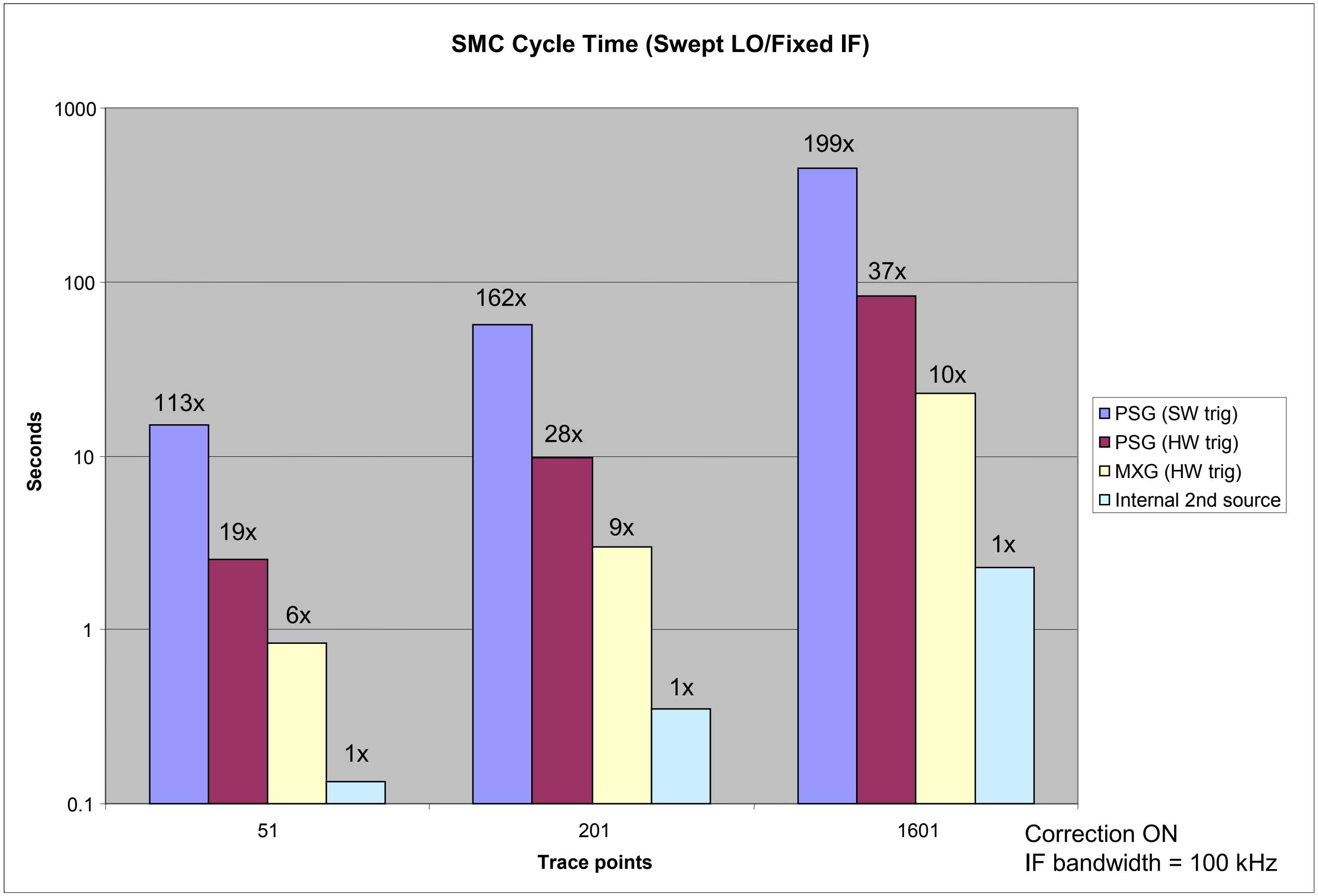
Vector Mixer/Converter Measurements – High LO Power



Example of Fixed and Swept LO Measurements



Speed Improvements with Internal Second Source

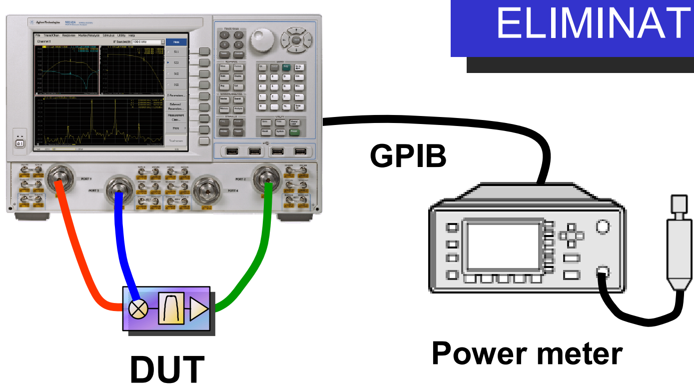


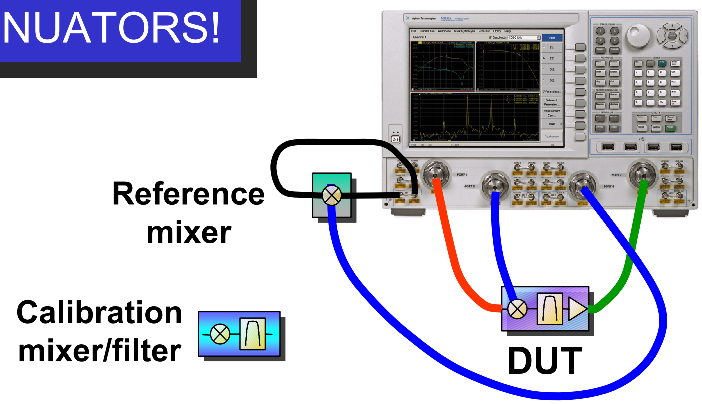
Advanced Calibration Techniques for Mixers/Converters

Conversion loss and match

- Simple setup with no external signal source
- Match correction ELIMINATES ATTENUATORS!

Conversion loss, delay, and match





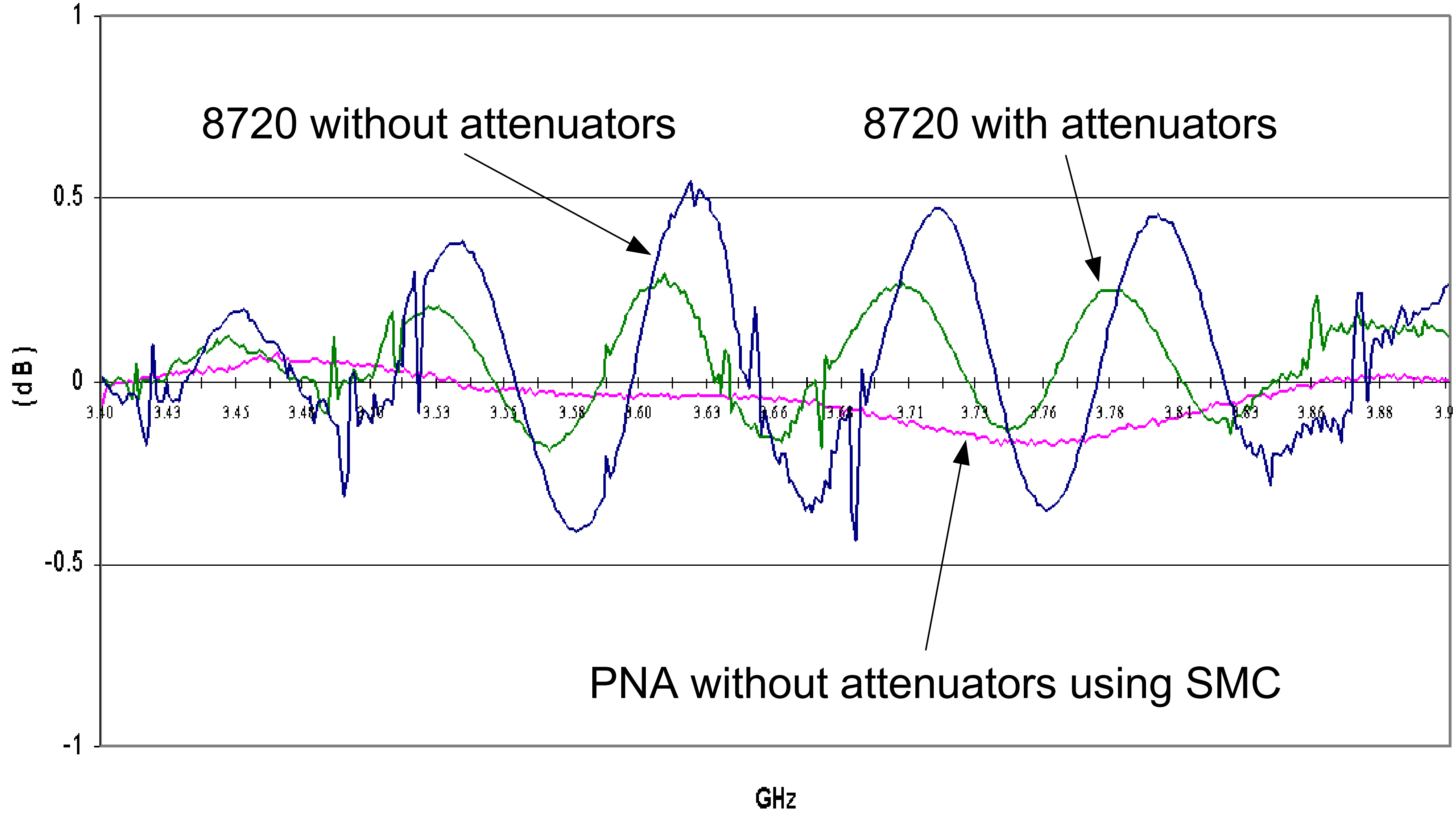
Scalar Mixer Calibration (SMC)

- Highest accuracy conversion-loss measurements with simple setup and cal
- Removes mismatch errors during calibration and measurements by combining one-port and power-meter calibrations

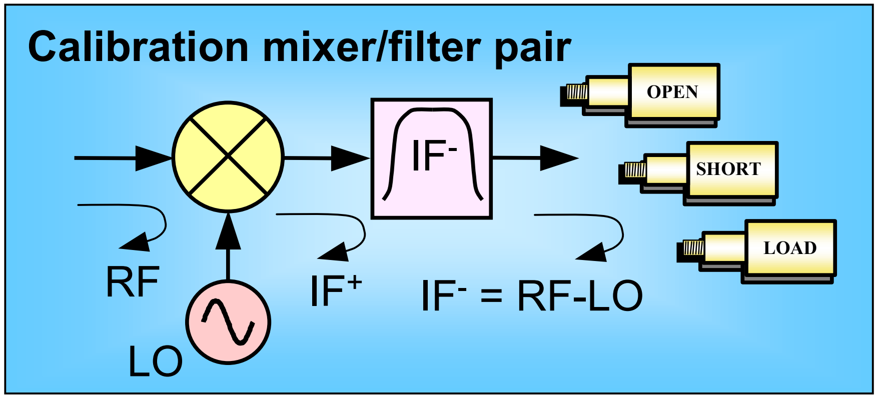
Vector Mixer Calibration (VMC)

- Most accurate measurements of phase and absolute group delay
- Removes magnitude and phase errors for transmission and reflection measurements by calibrating with characterized through mixer

Example Conversion Loss Measurements

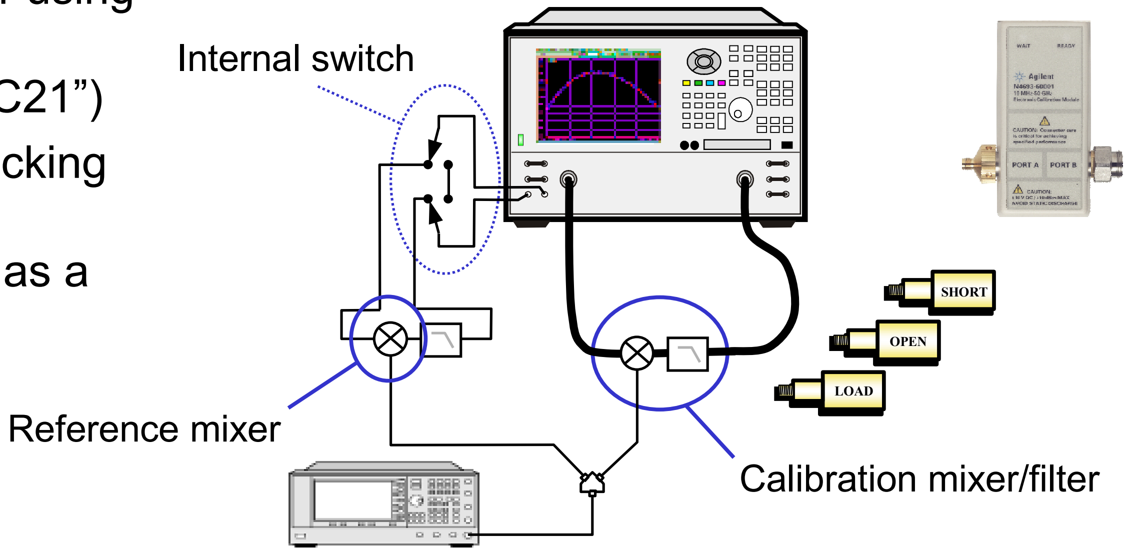


Agilent's Patented Vector Mixer Calibration Technique

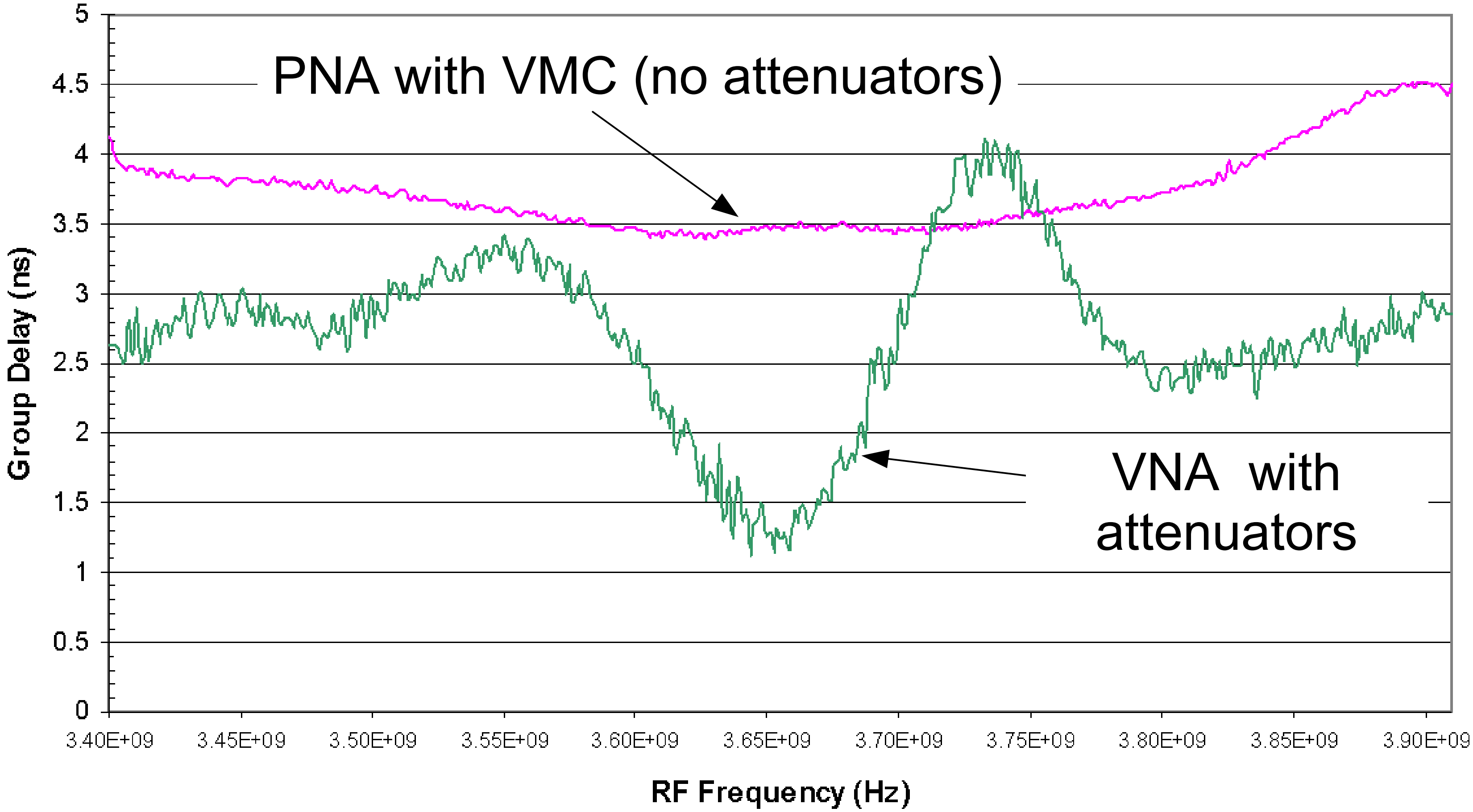


Three step calibration:

- **Step 1**: measure one-port error terms at input and output frequencies
- **Step 2**: completely characterize a calibration mixer/filter pair using reflection measurements (acquire S11, S22, and “C21”)
- **Step 3**: calibrate transmission tracking term of test system using characterized mixer/filter as a through standard

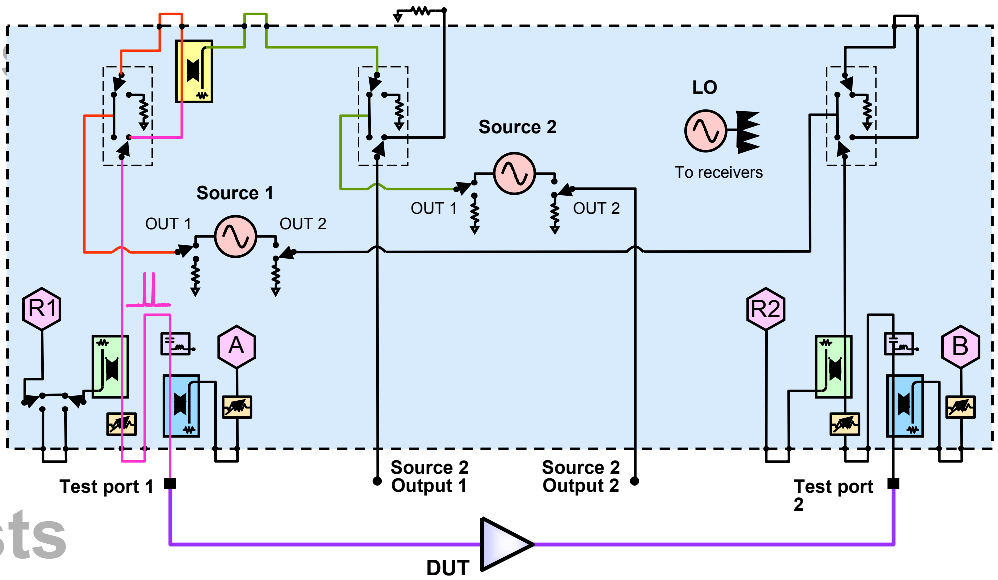


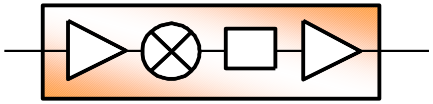
Example Group Delay Measurements



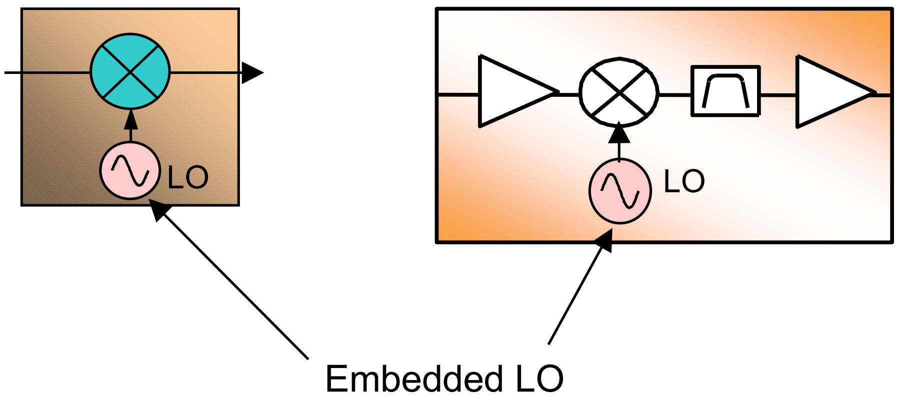
Agenda

- Overview of Component Testing Using a VNA
- Modern VNA Architectures
- Nonlinear Amplifier Tests
  - Intermodulation distortion
  - Phase versus drive
  - Hot S22
  - True-mode stimulus
  - Single connection, multiple measurements
- Mixer and Converter Tests
- **Applications**
- **Summary**





Frequency Converters w/Embedded LO
S.W Option = 084



Embedded LO Option 084:

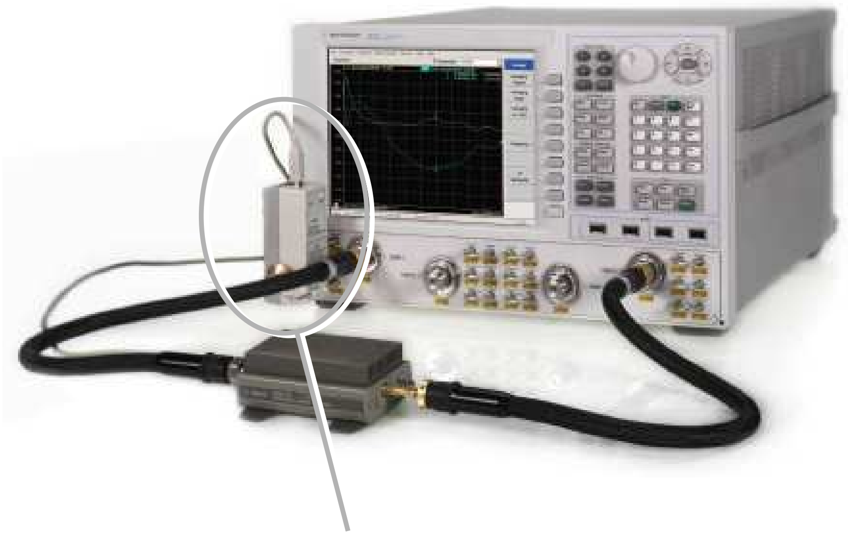
1. Allows measurement of relative phase and absolute group delay **without** accessing to embedded LO source.

2. Is an extension of the Vector Mixer Calibration (VMC, opt. 083).
   - PNA requires option 014, 080, 081, UNL and 083.
   - PNA-X requires option 080, 083.

Embedded LO Option 084 is NOT:

1. Fixed output frequency.
2. DUT LO frequency > 10MHz of reference mixer LO frequency.

Introducing the N5242A Option 029



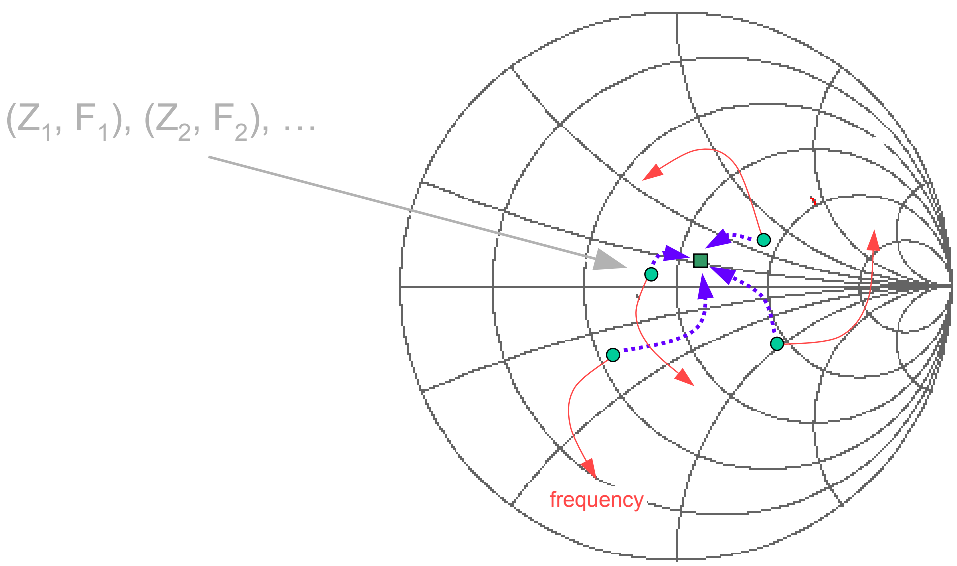
Agilent's unique noise-figure-calibration technique uses an ECal module as an impedance tuner to remove the effects of imperfect system source match

Source-corrected noise figure option **extends single-connection multiple-measurement capability of the PNA-X**

- Measure key amplifier parameters up to 26.5 GHz with a **single connection** (e.g. S-parameters, noise figure, compression, IMD, harmonics)
- Achieve the **highest measurement accuracy** of any solution on the market

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 (NF_{50}) can be calculated
- Each impedance state is measured versus frequency



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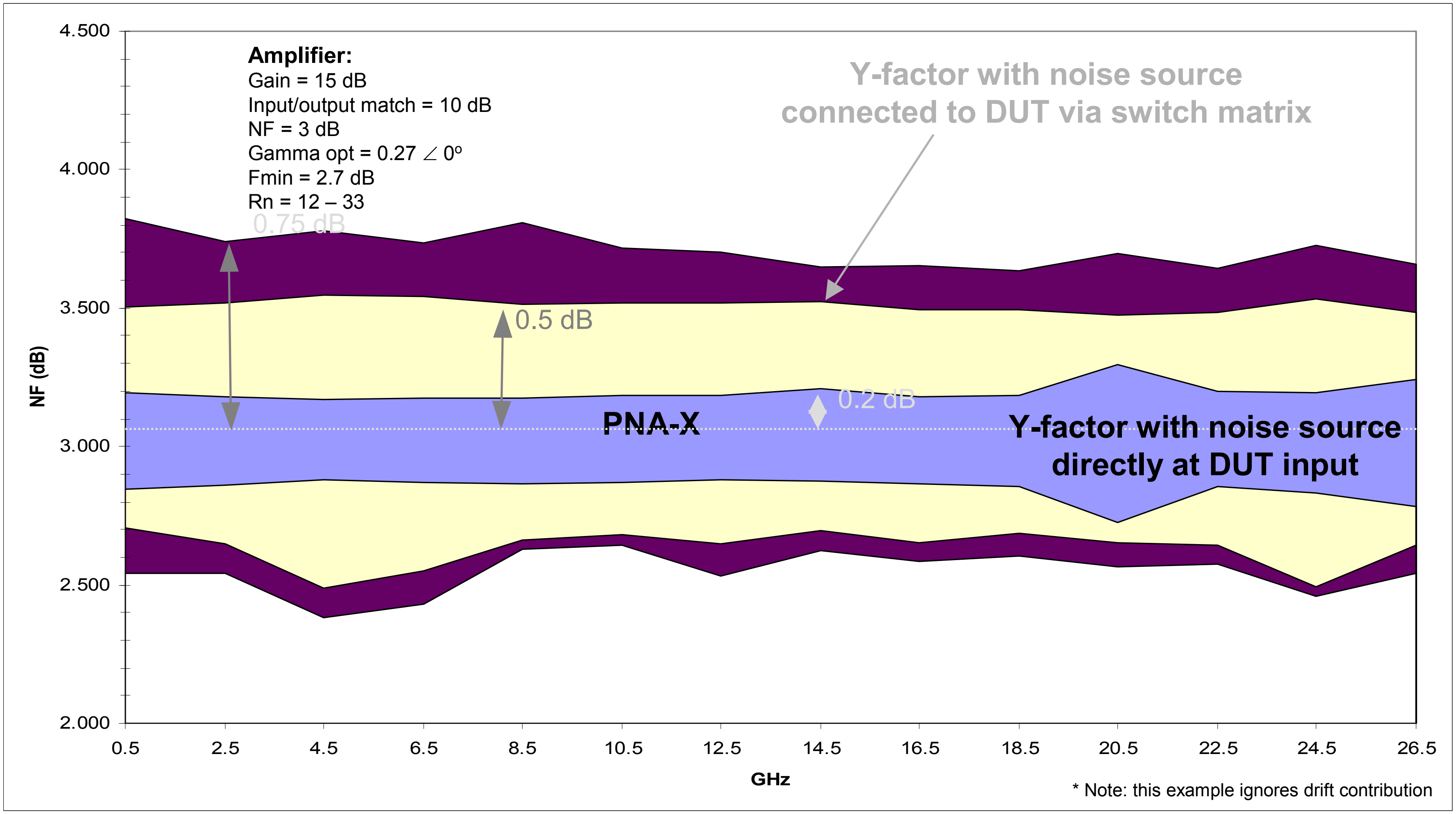
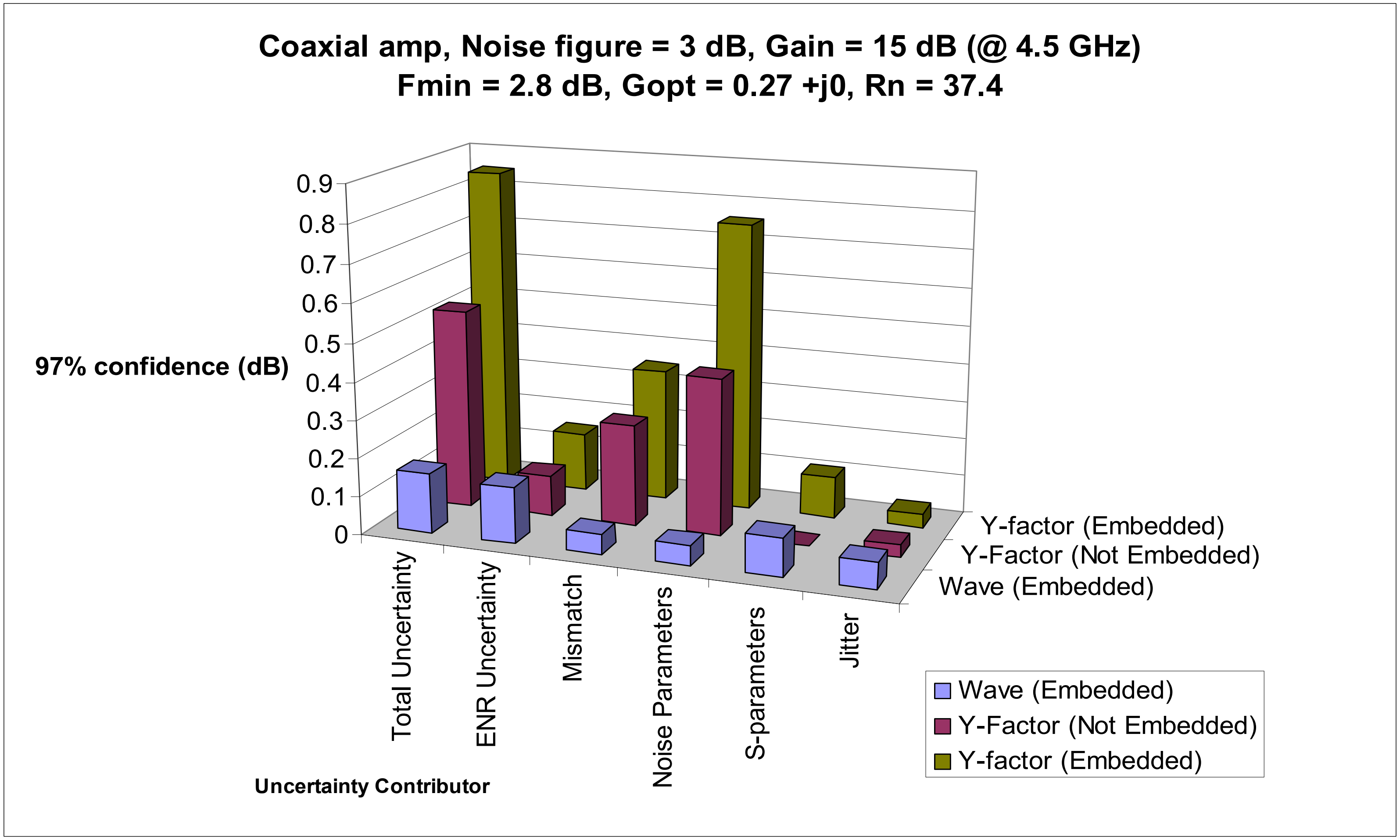
Noise Figure Uncertainty Example (ATE Setup)



Uncertainty Breakdown (ATE Setup)

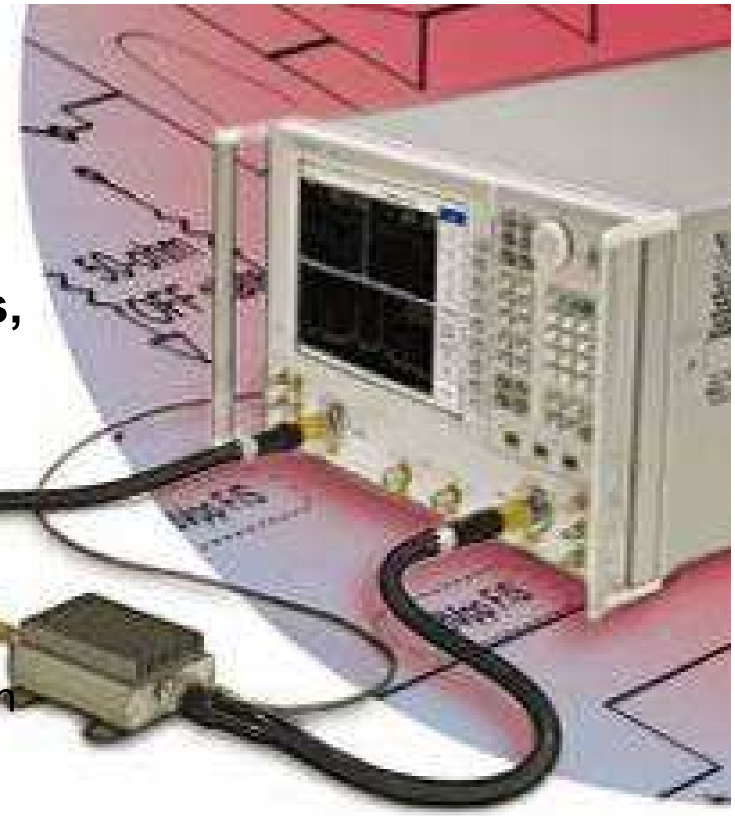


Comparing Accuracy of Two Methods

- Noise parameter effect present for both methods
- Y-factor
  - Noise source directly to DUT: **good** source match
  - Noise source in ATE or probe situation: **poor** source match

- Cold source
  - Without source correction: **poor** source match
  - With source correction: **excellent** effective source match

N5242A Option 086 (GCA)
Gain Compression Application



GCA builds upon PNA-X's strength in single-connection active-device measurements, providing gain compression data fast and accurately,
at multiple frequencies, with a simple setup.

Measure a key amplifier spec multiple times faster compared to current methods, with GCA's SMART sweep.

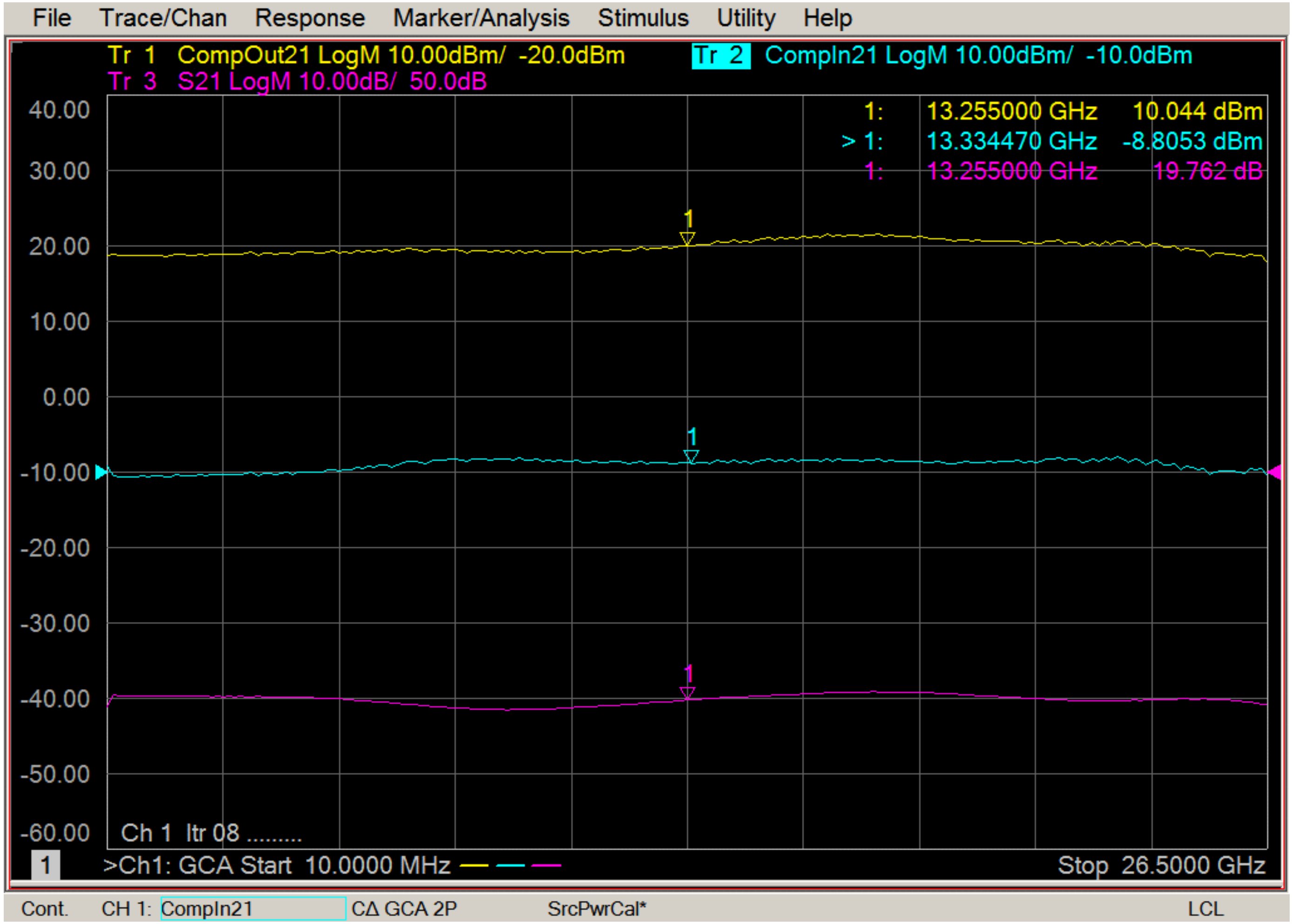
✓Achieve the highest measurement accuracy of any solution in the market with mismatch correction.

✓Frequency converters not supported at intro. Future enhancement.

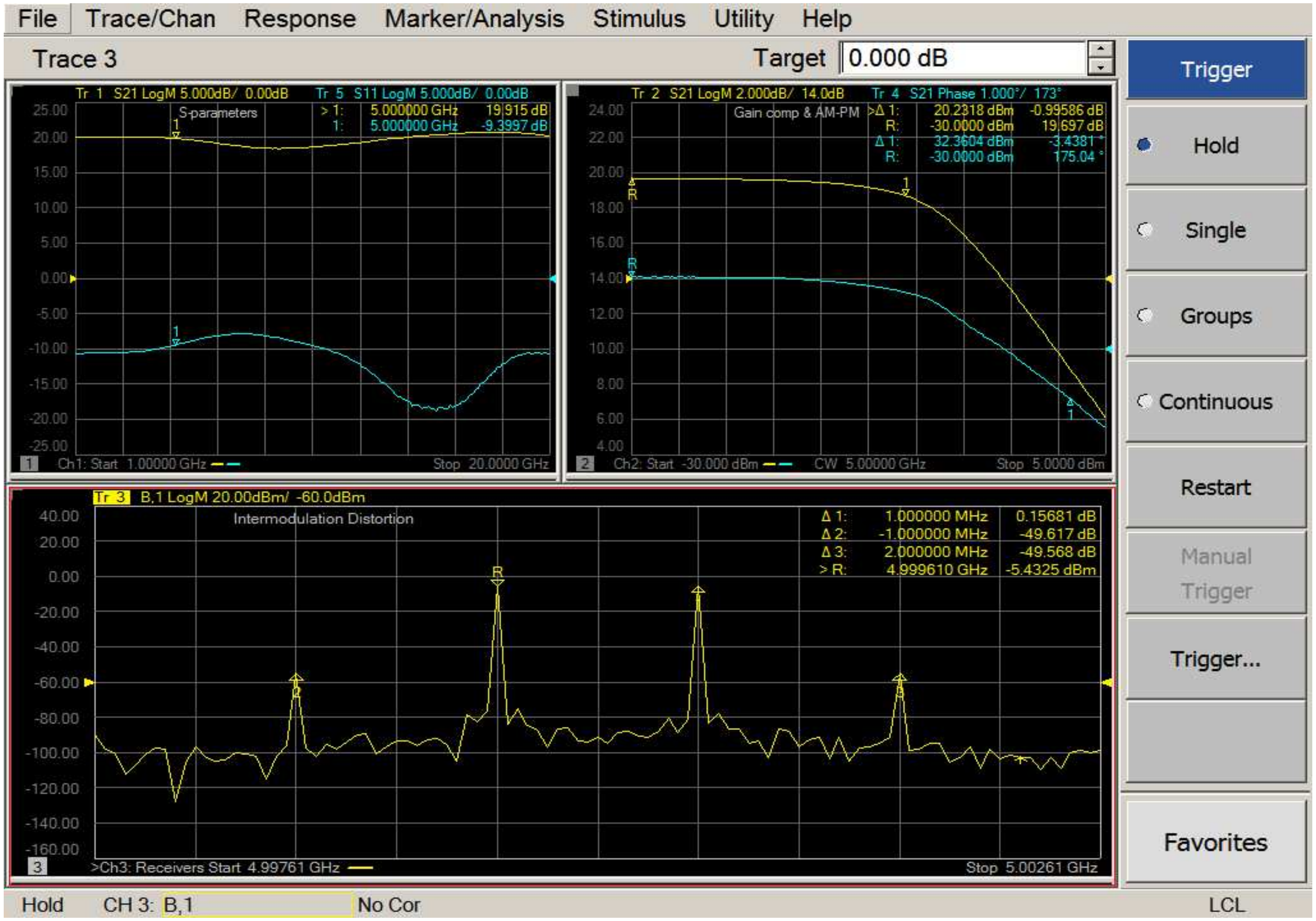
free trial license

A firmware upgrade for existing PNA-Xs.
Free 14-day trial license for PNA-X owners to try out Option 086.

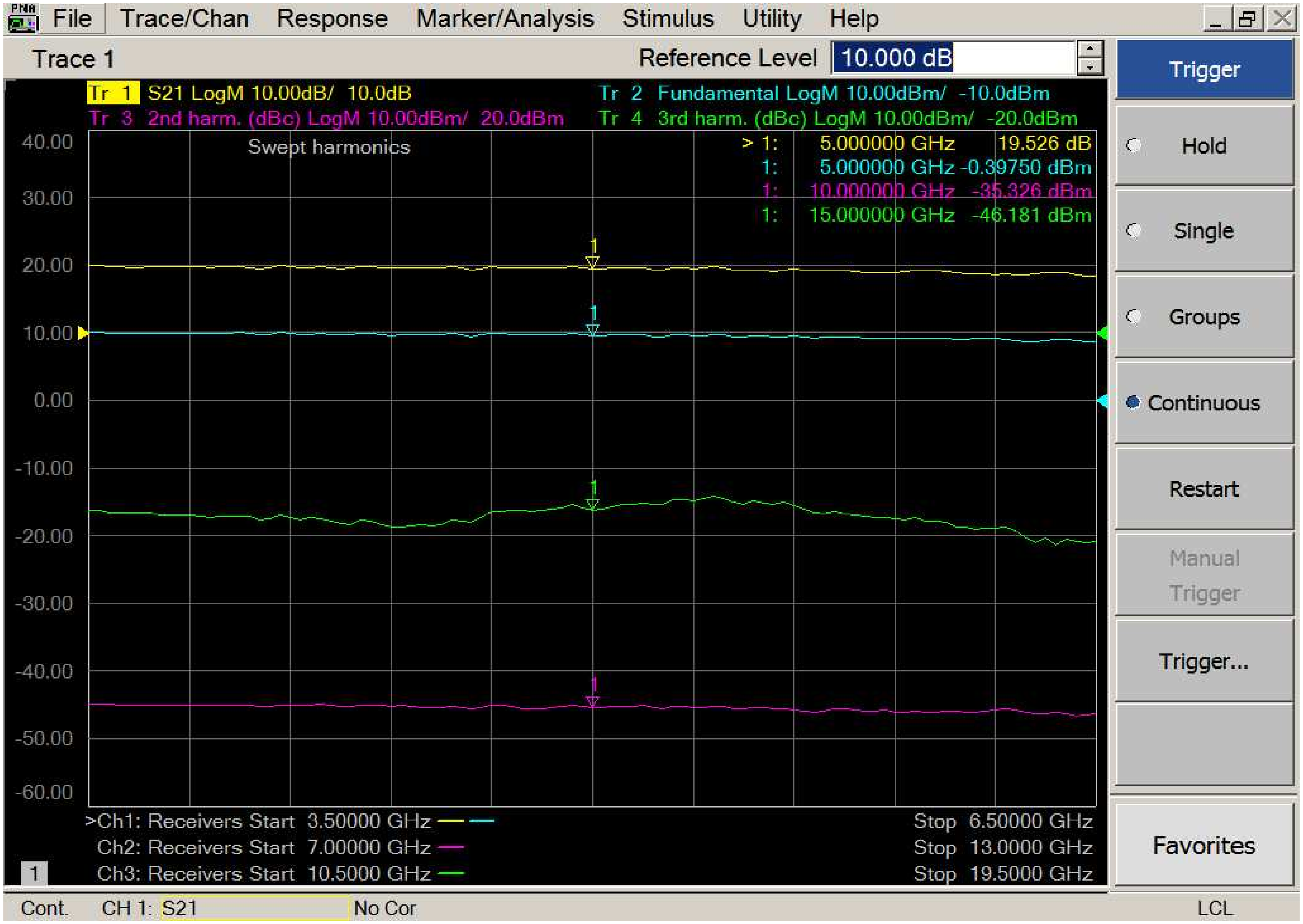
Nonlinear Testing GCA – Power Sweeps



Easily Switch Between One- and Two-Source Tests



Swept Harm



Agilent Technologies

Swept Third

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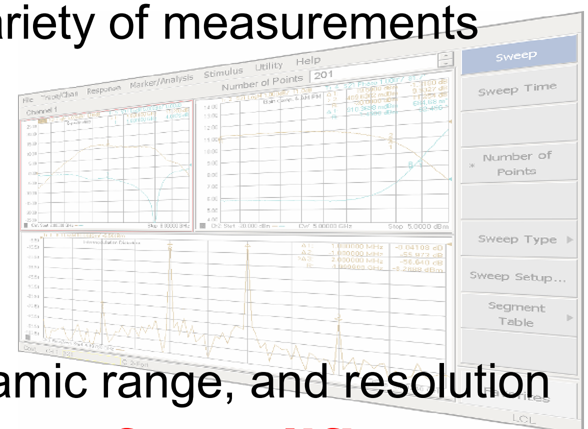
Summary

Modern VNA architectures provide:

- **Two internal signal sources with high output power and low harmonics**
  - Simplifies measurements of IMD, phase vs. drive, hot S22 and more
  - Provides convenient and fast LO signal for mixer and converters
- **Flexible signal routing**
  - Combine sources with internal signal combiner for variety of measurements
  - Add signal-conditioning hardware and external test equipment via front and rear-panel RF access loops
- **Complete set of pulsed S-parameter hardware**
  - Modulators, pulse generators, IF gates, wide and narrowband IF filters
  - Detection choices offer tradeoff between speed, dynamic range, and resolution



Characterize linear and nonlinear behavior of amplifiers, mixers and converters with simple test setups and fast test times