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Summary & analysis of the critical power amplifier design tool - Linearity loadpull characterization

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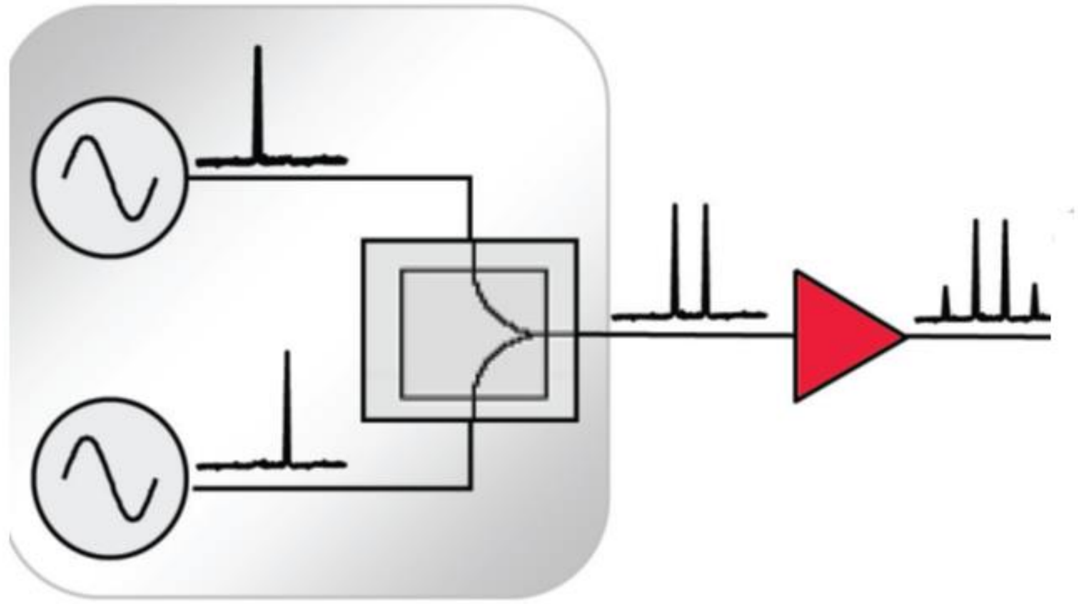
Outline

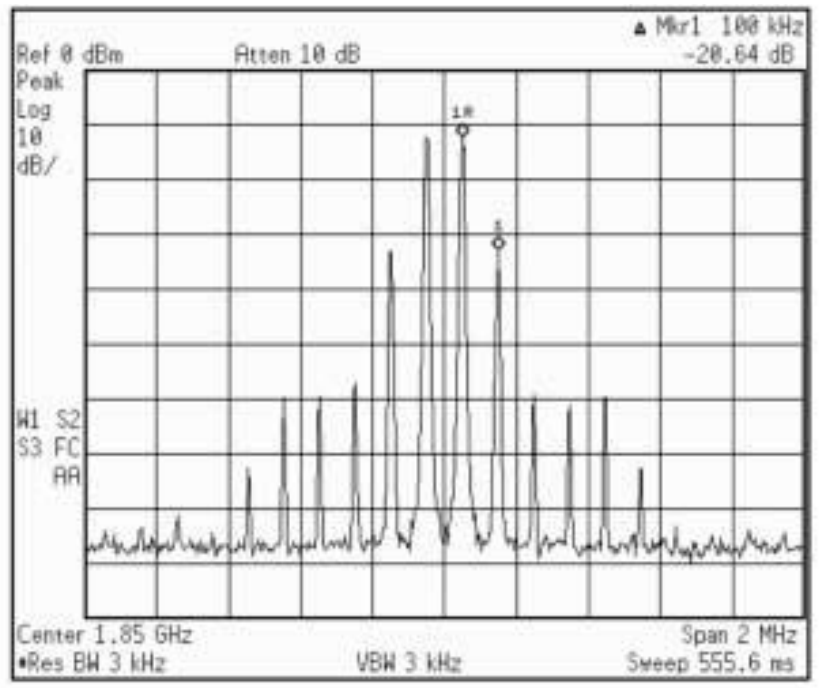
- *Non-50 Ohm Linearity measurement history*
- *The challenge of 2 tone test on unmatched device*
- *A novel 2 tone measurement solution → **MT2000**!*
- *Beyond active loadpull*
- *System Offering*

Non-50 Ohm Linearity measurement history

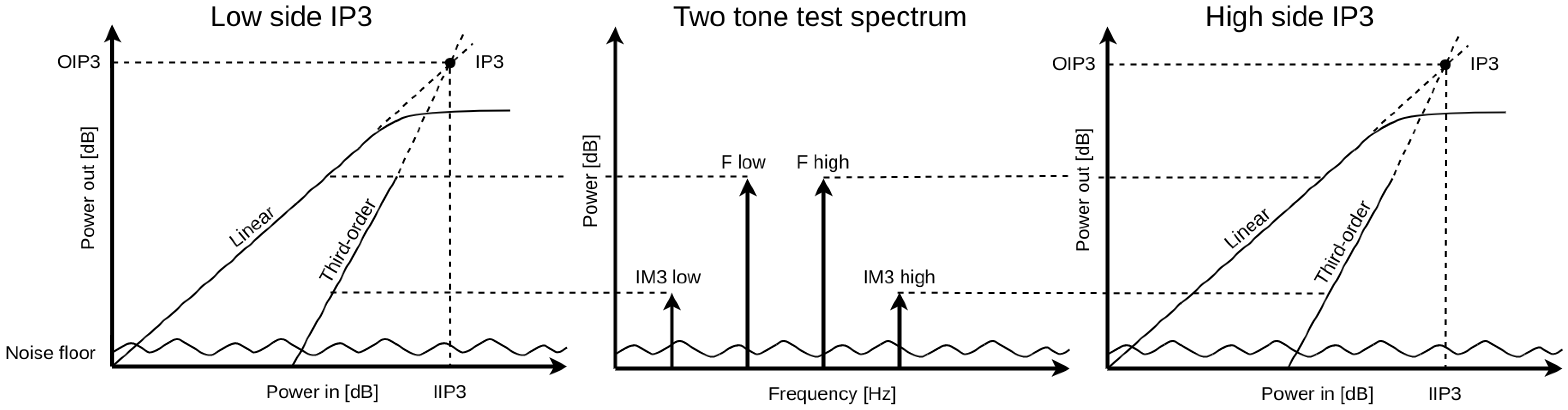
Introduction

Intermodulation distortion (IMD) is a measure of the nonlinearity of an amplifier and sometime even passive components.



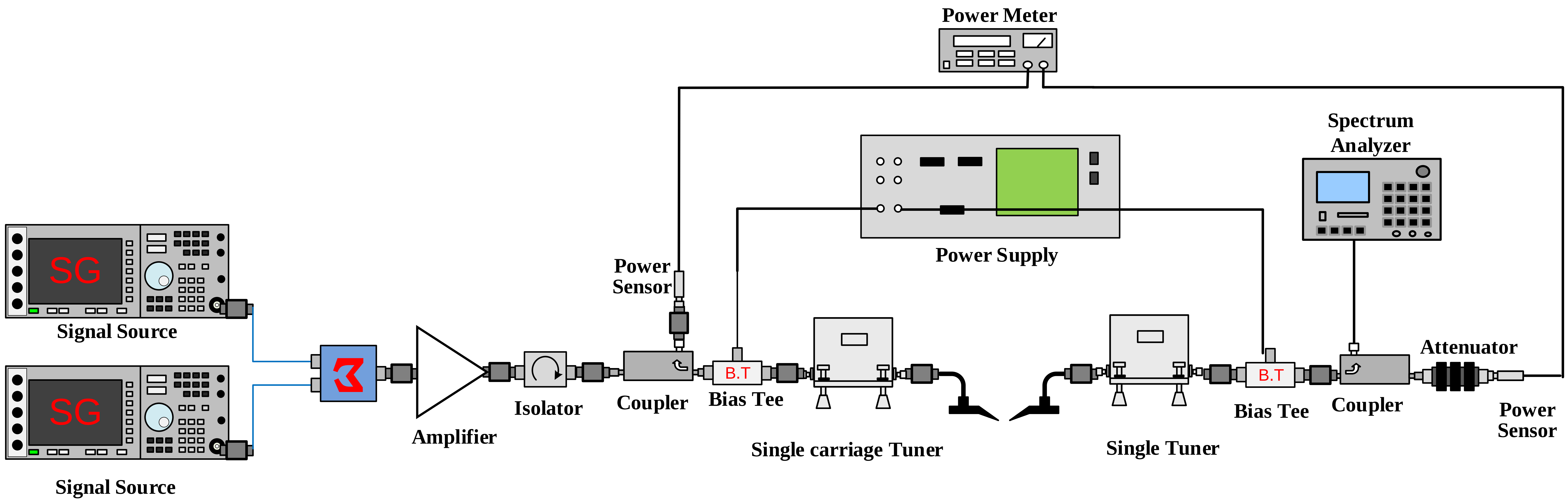


The third-order intercept point (IP3) or the third-order intercept (TOI), often used interchangeably, are figures of merit for intermodulation distortion.



$$\boxed{IP3\ (dBm) = P\,(f_1) + (P\,(f_2) - P\,(2f_1 - f_2))\,/\,2}$$

Traditional 2 tone/ACPR measurement

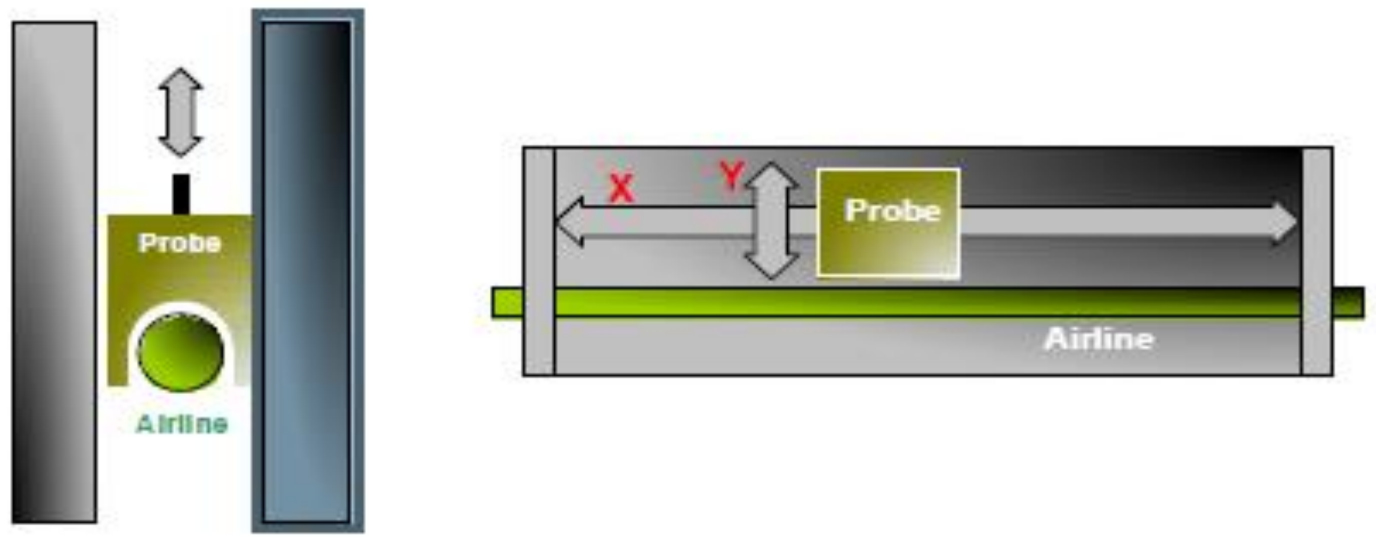


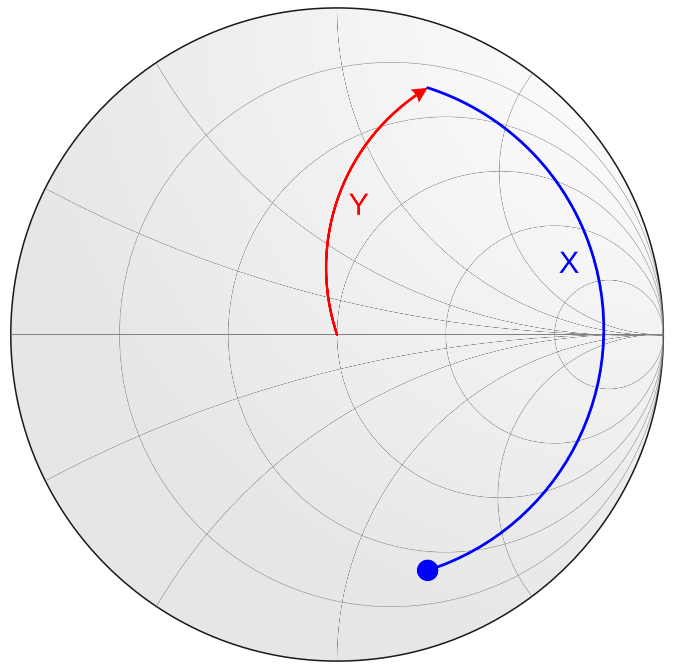
Calibration routine

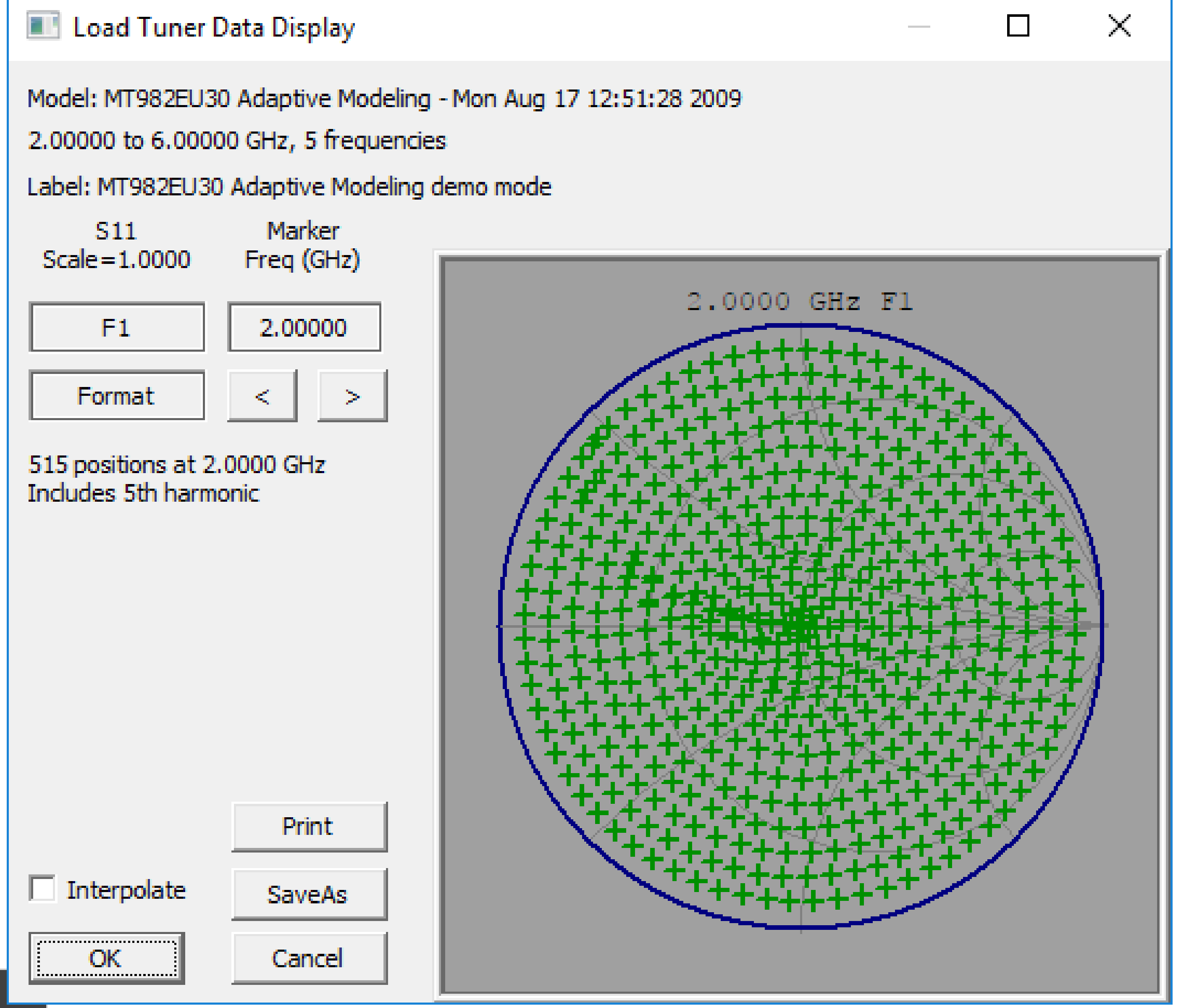
Traditional loadpull for 2 tone measurement

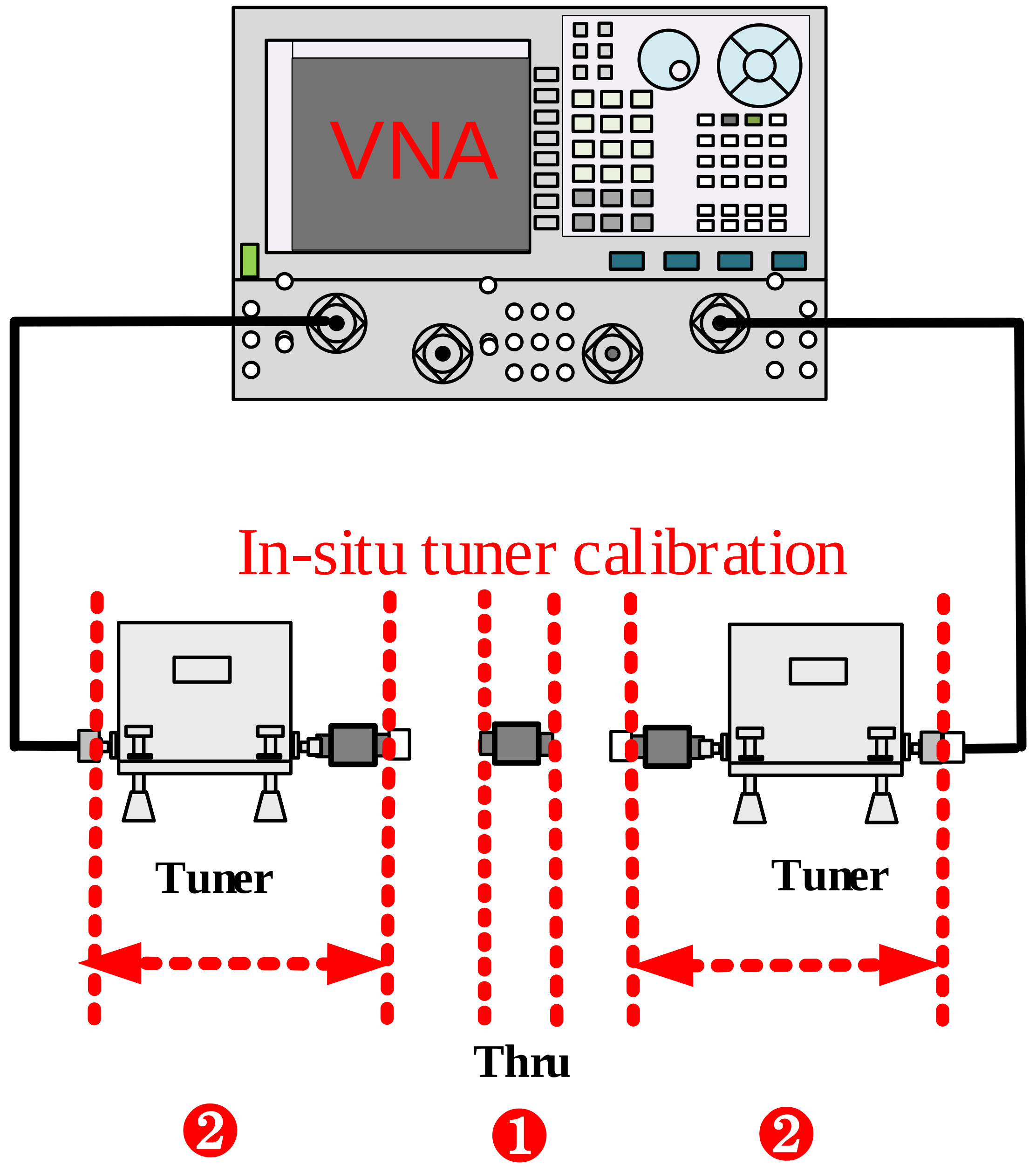
1. *Non 50 Ohm characterization -> tuner calibration*
2. *Hardware connection -> manual setting of spectrum analyzer and synchronization, 10MHz synchronization*
3. *Power calibration -> sweep each tone space and each power level, generate a data base table*
4. *Measurement -> recall the table, sweep step by step*

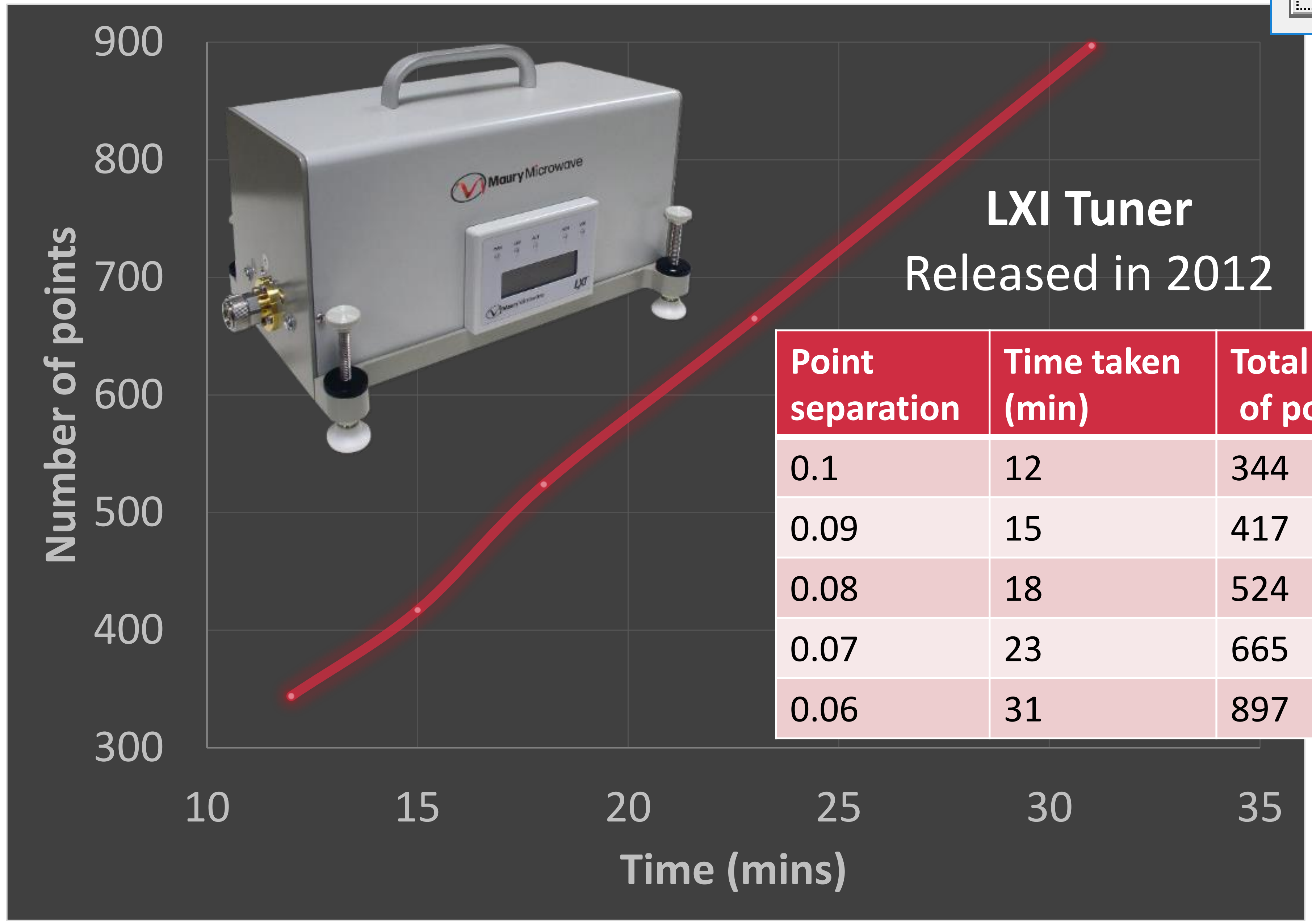
Tuner calibration









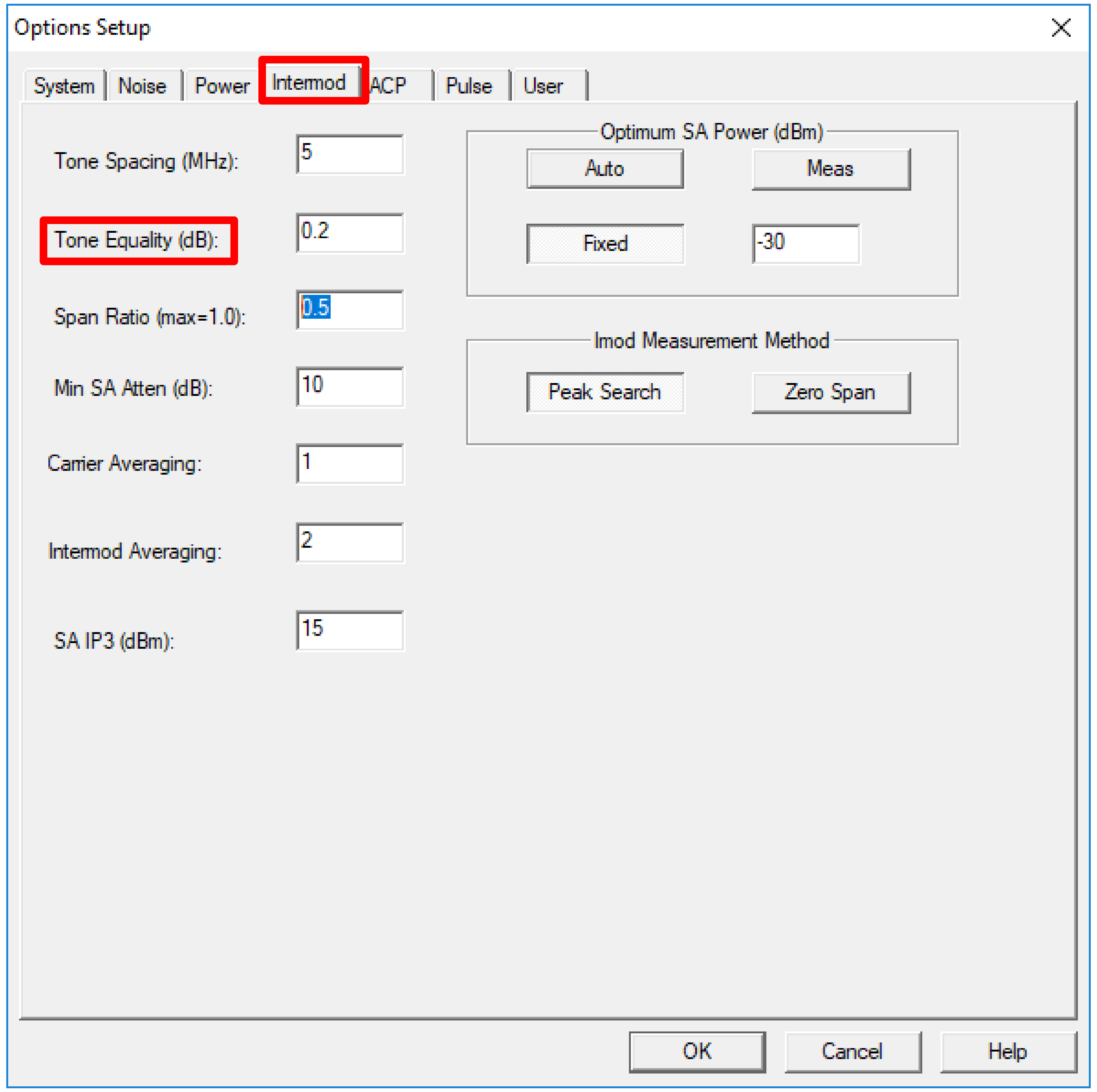


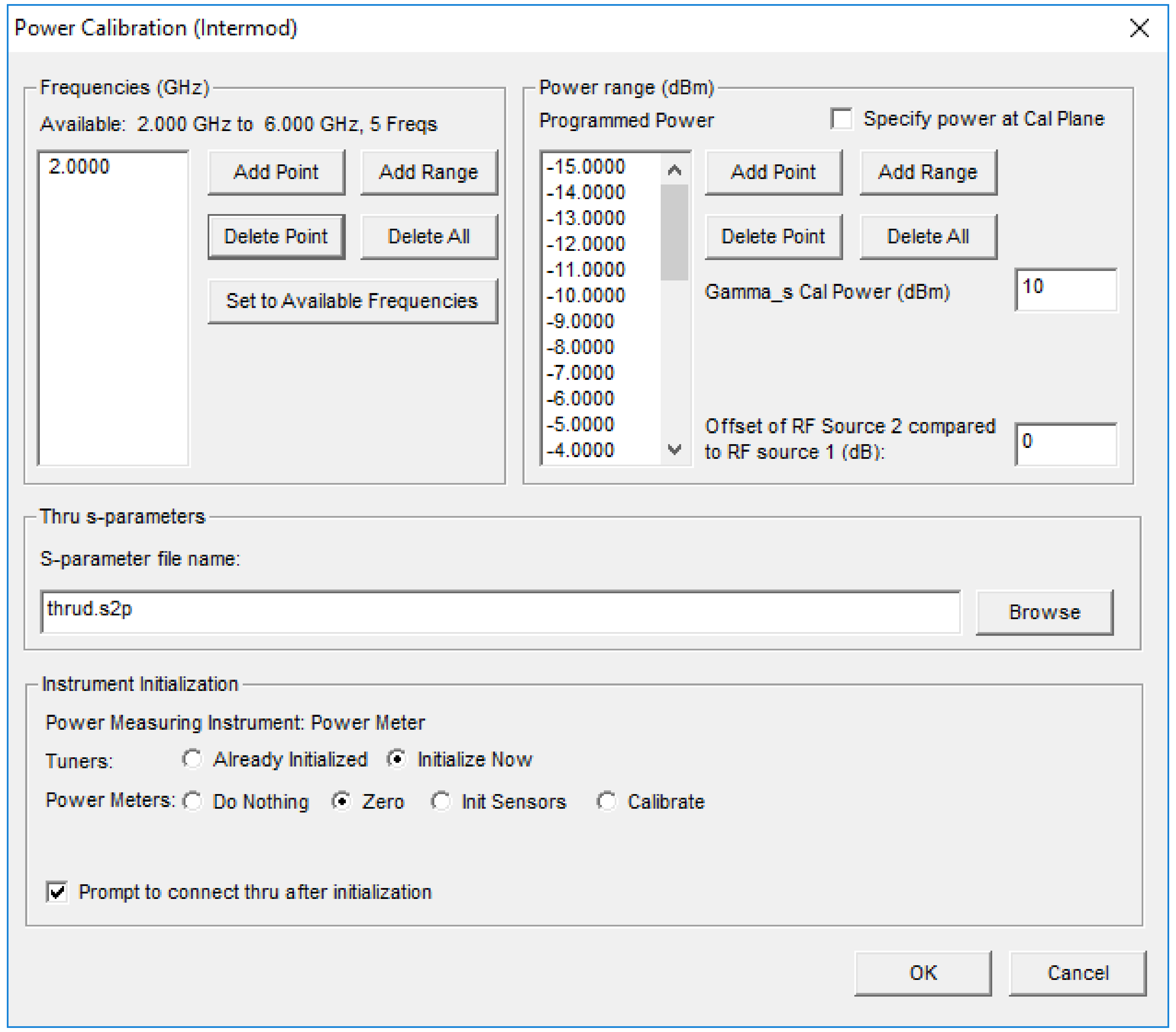
Point separation	Time taken (min)	Total number of points
0.1	12	344
0.09	15	417
0.08	18	524
0.07	23	665
0.06	31	897

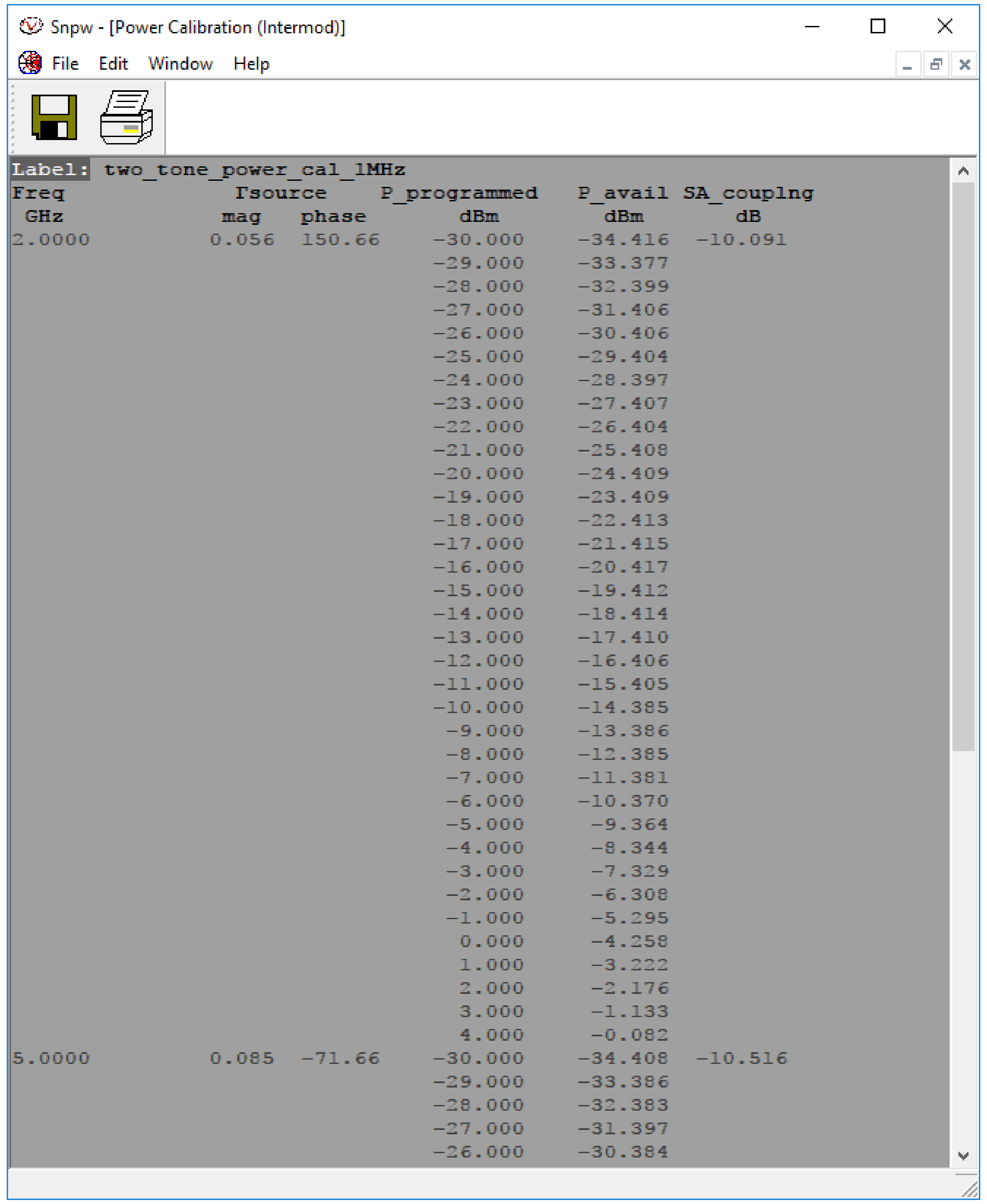
XT Tuner
Released in 2018
XT98xxxx Tuner
Internal microprocessor
Improved accuracy and mechanical speed

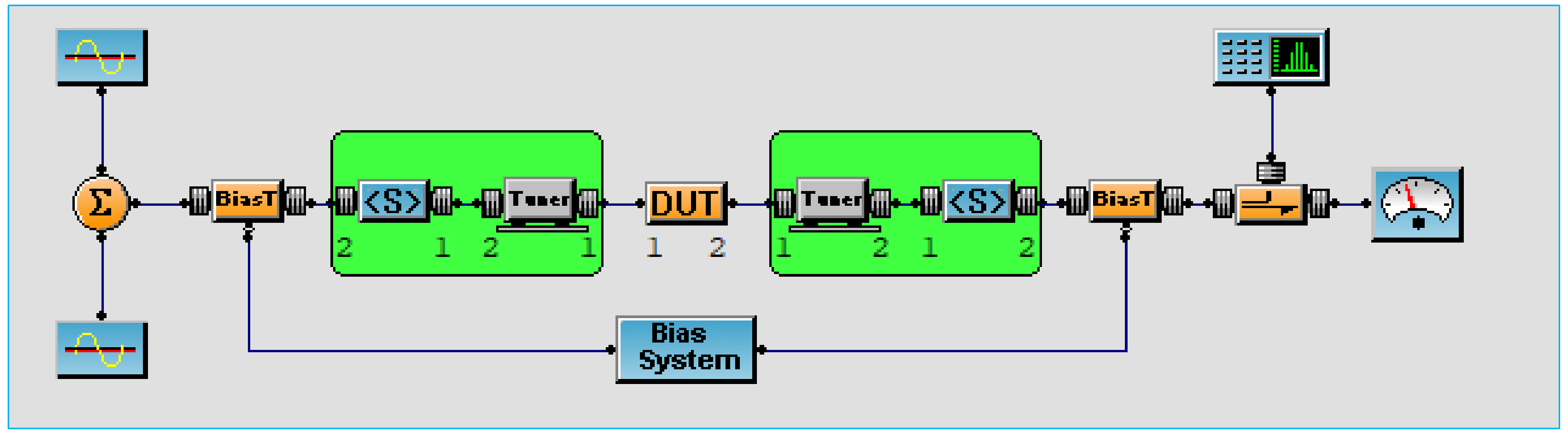
Tuner calibration, critical and inevitable step, but TEDIOUS!

Power calibration with tone balancing









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pros and cons

Traditional loadpull based on power meter is the only choice in last century

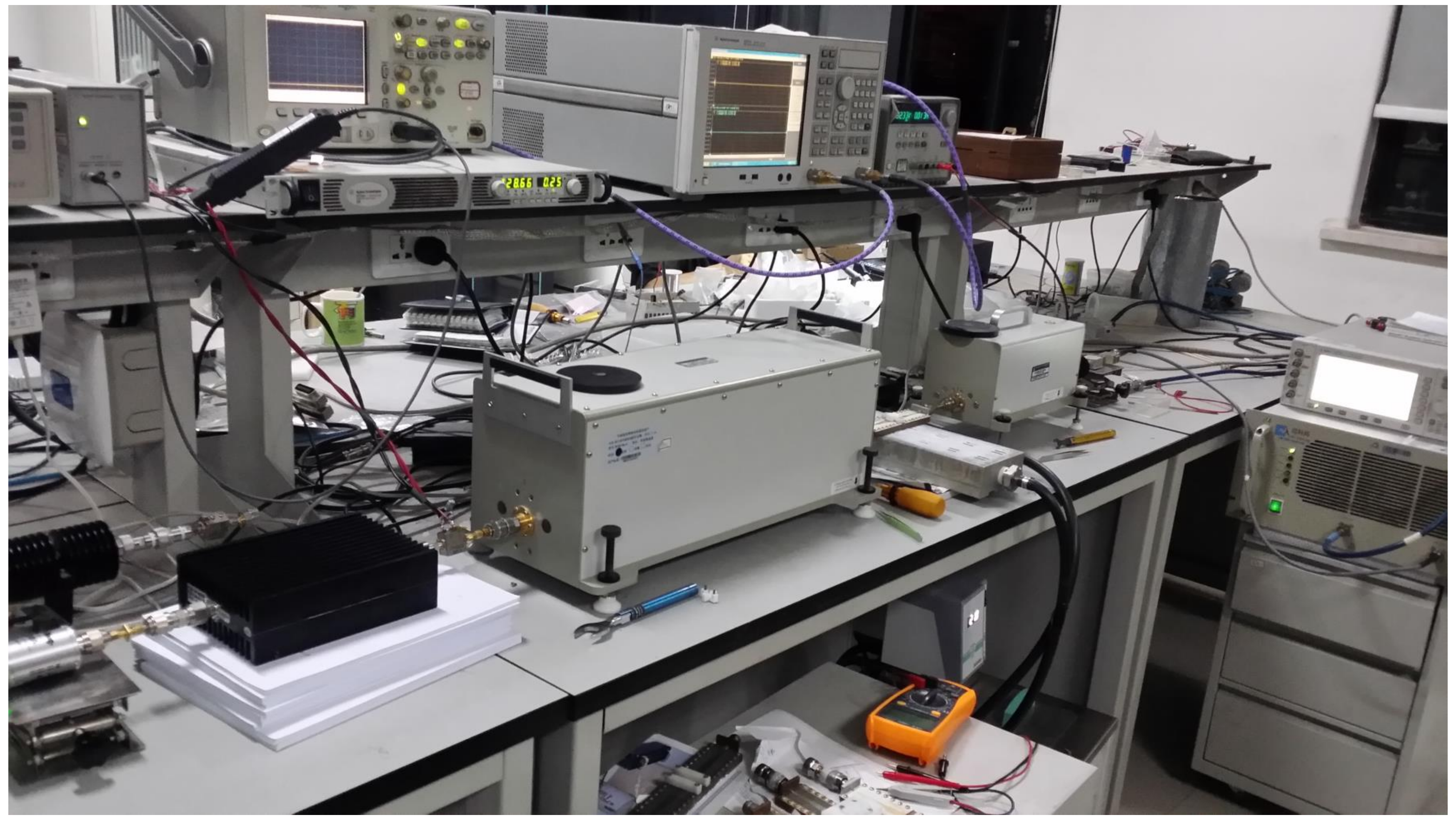
- *Tedious tuner calibration*

  Rely on de-embedding all the way
- *Elaborate setting/verification of system*

  For accurate and relatively fast measurement
- *Exact power cal.*

  Table should be created before measurement, if driving amplifier changed, the table should be updated again.
- *Not cheap and complexed to setup*

  Spectrum analyzer should be connected
- *Operator should be experience enough*



- *Cheap at the first glance, but unfortunately NOT in long term view*

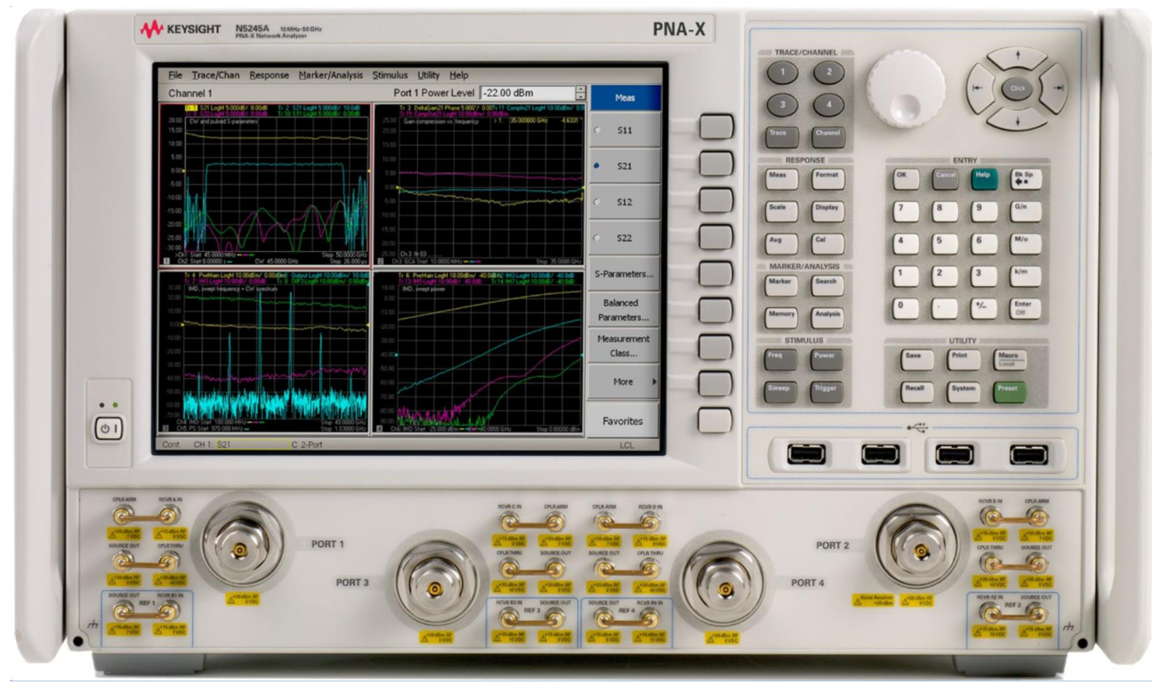
VNA's advanced features for simple 2 tones test

IMD measurement challenges

– Two signal generators, a spectrum analyzer, and an external combiner are most commonly used, requiring manual setup of all instruments and accessories

– Test times are slow when swept-frequency or swept-power IMD is measured

– Instruments and test setups often cause significant measurement errors due to source-generated harmonics, cross-modulation, and phase noise, plus receiver compression and noise floor



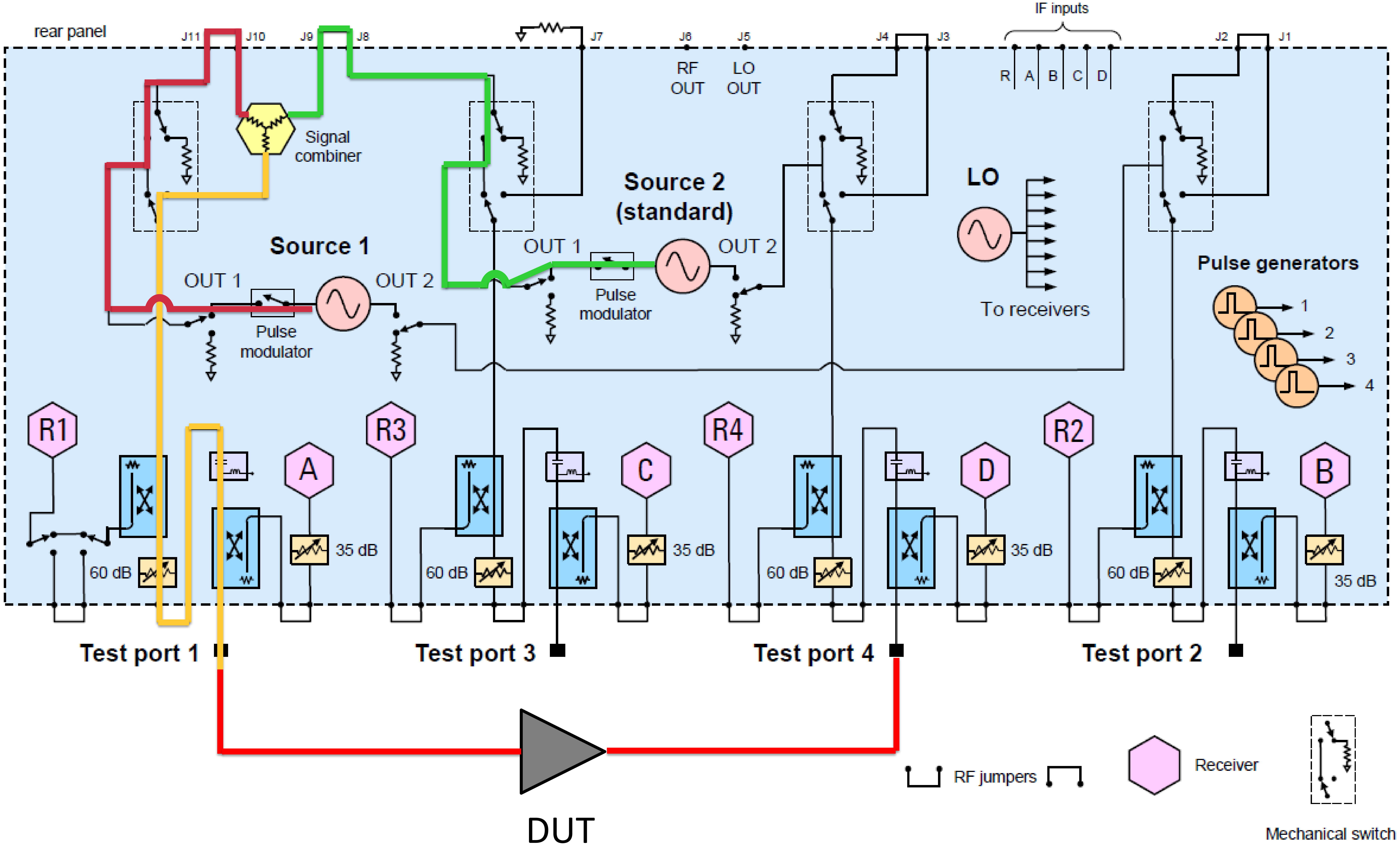
Frequency Offset Mode (Option 080)

- Sets different frequency range for the source and receivers.
- Can be used for harmonics or intermodulation distortion (IMD) measurements with the VNA.

Combiner (Option 423)

- Sets different frequency range for the source and receivers.
- Can be used for harmonics or intermodulation distortion (IMD) measurements with the VNA.

block diagram of 4 port PNAX with combiner for 2 tones



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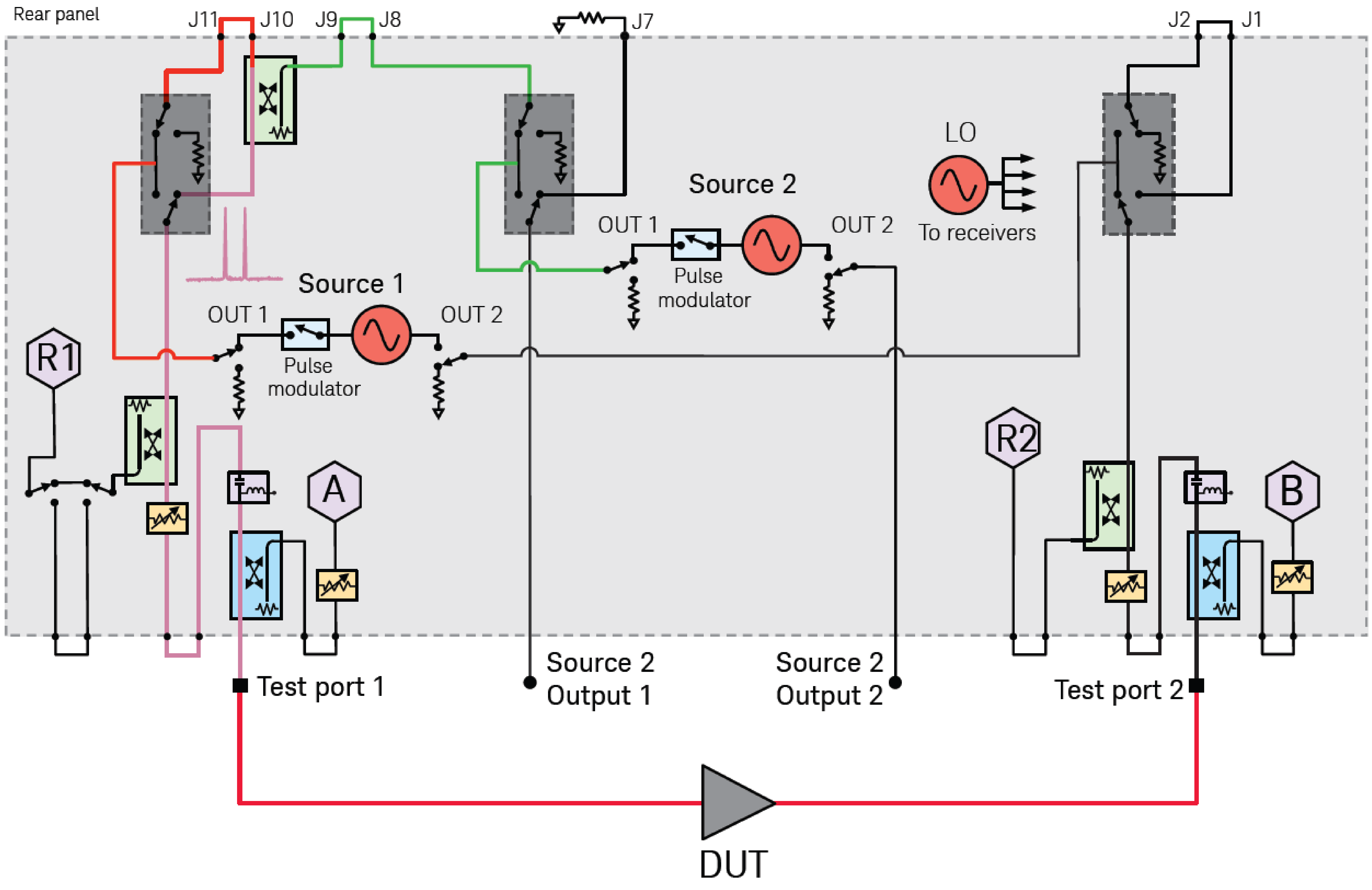
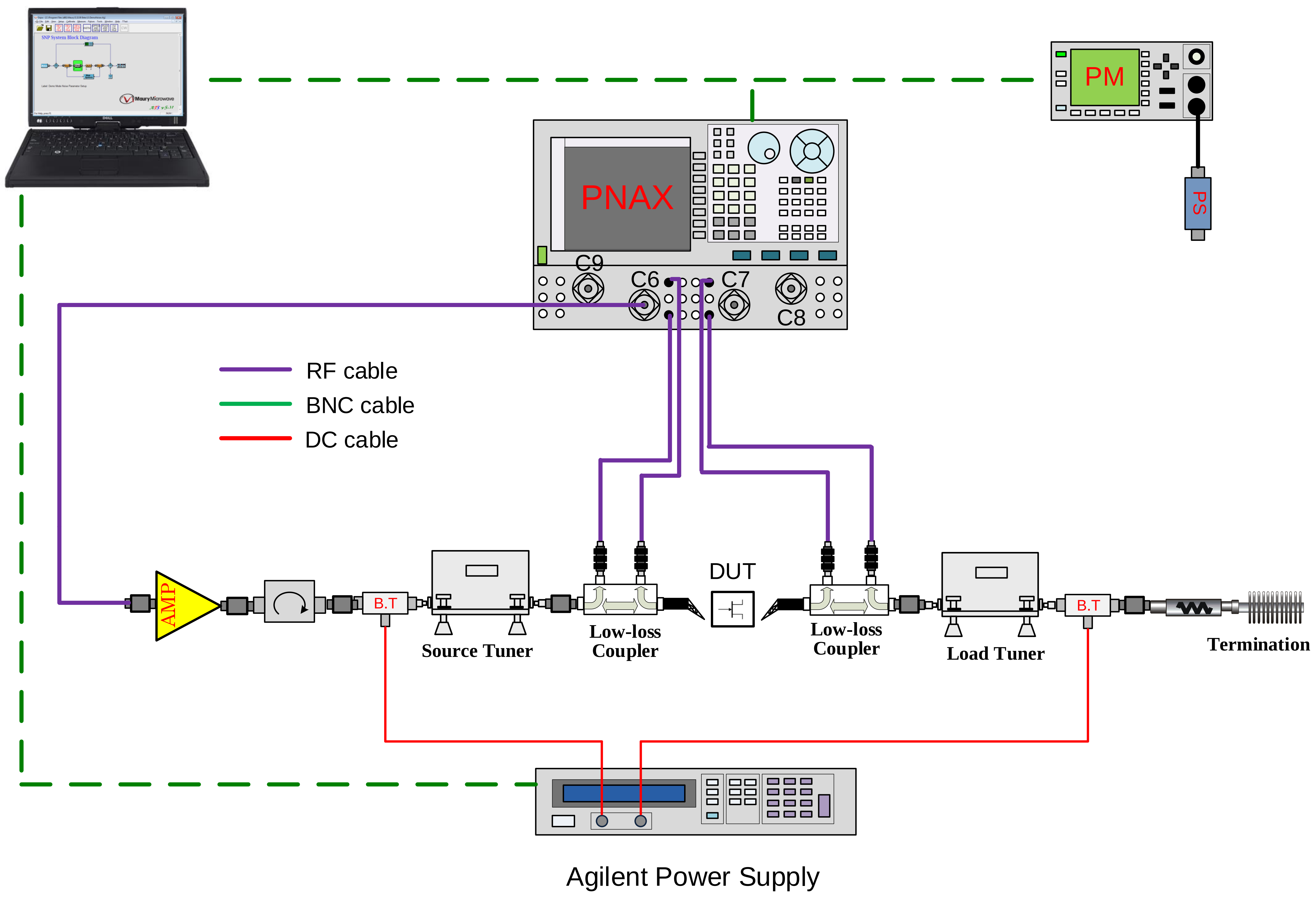
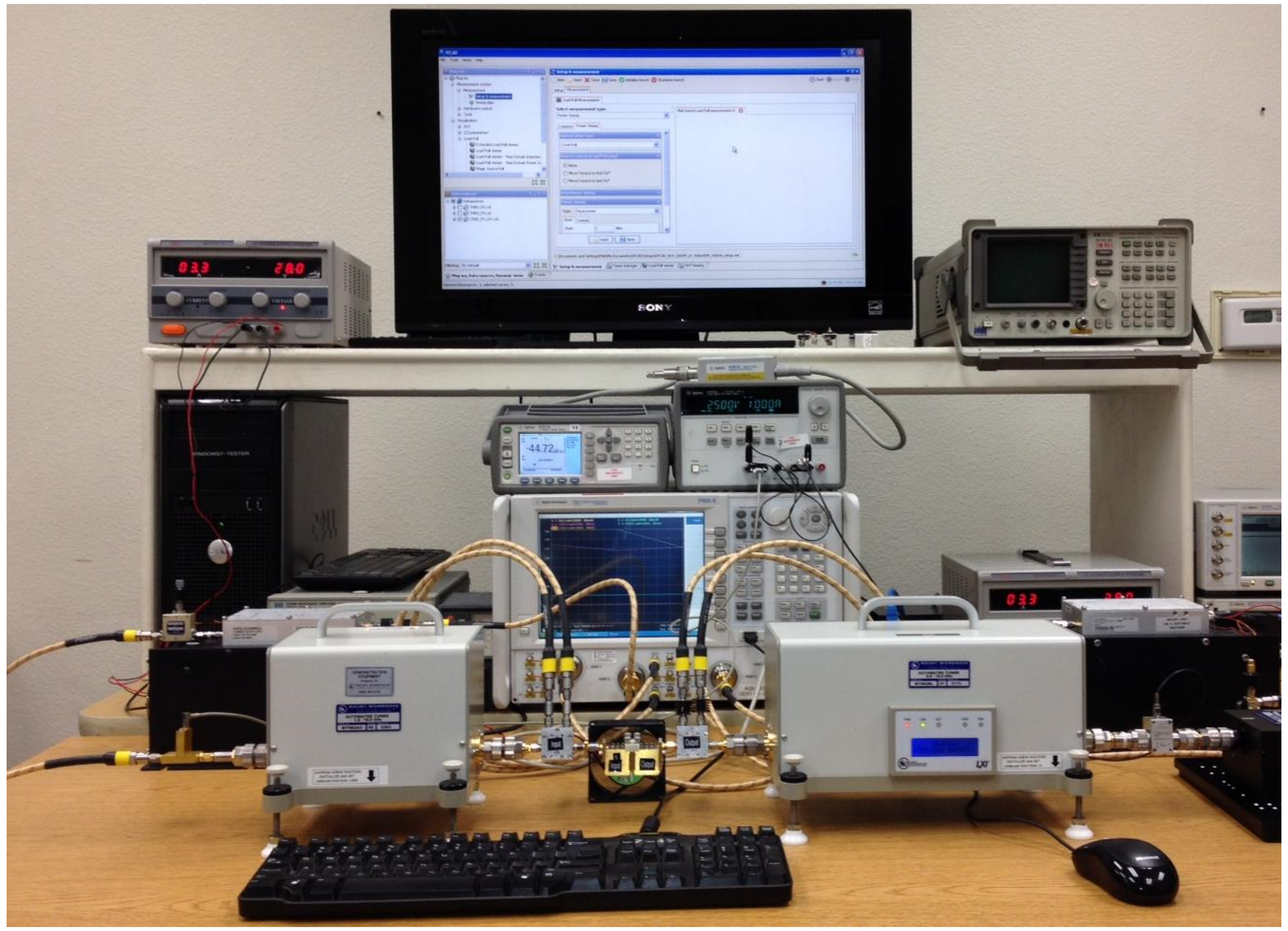
Block diagram of 2 port PNA with coupler for 2 tones



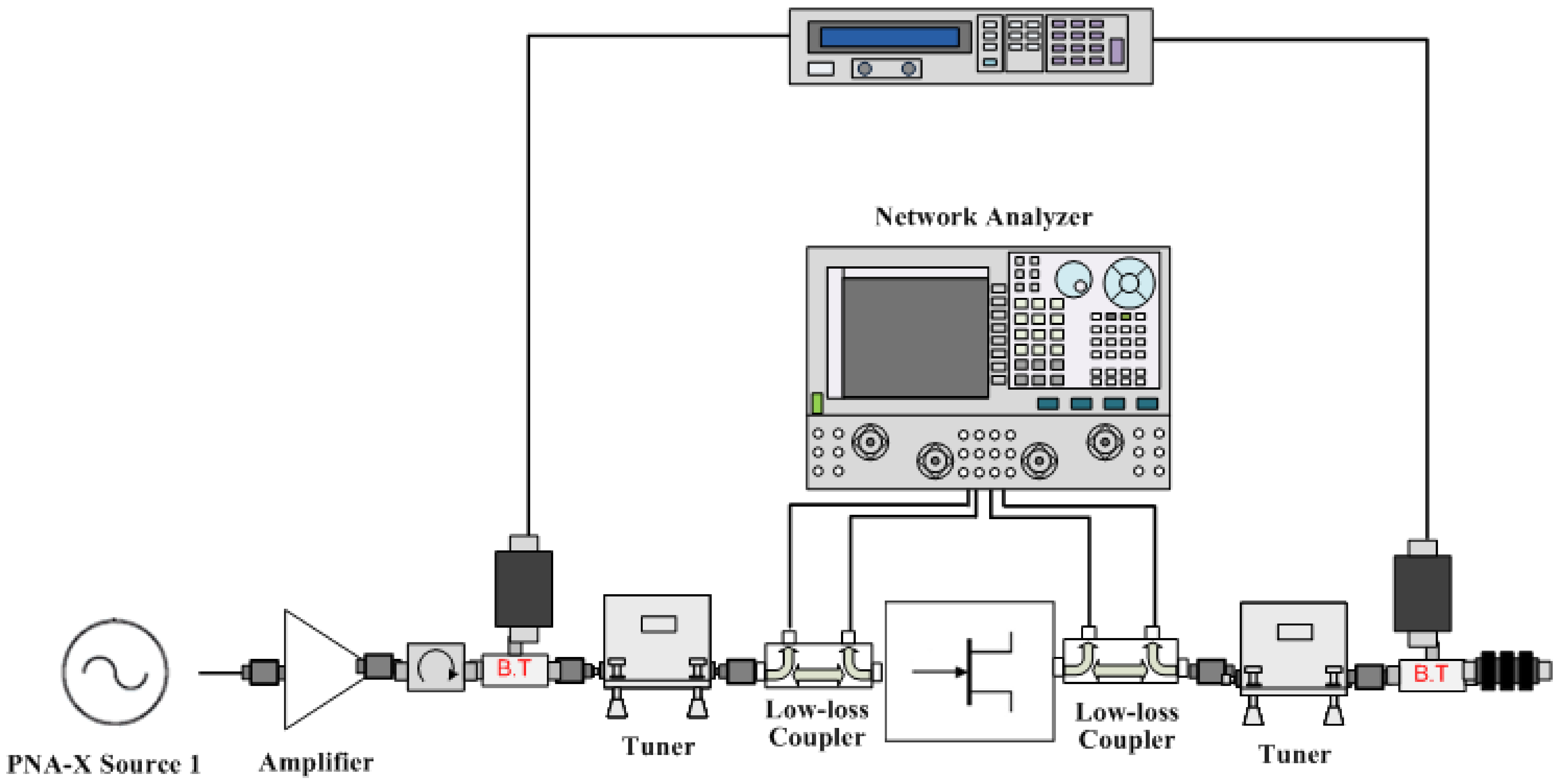
Better loadpull structure based on VNA advanced architecture

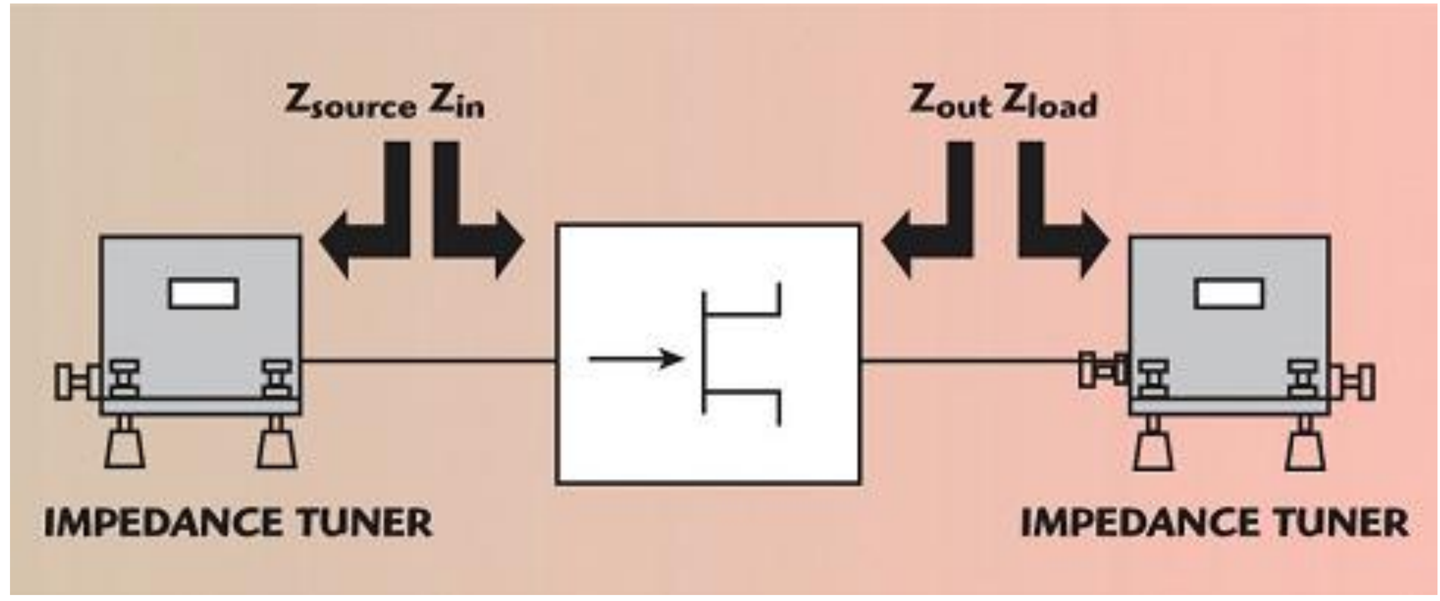


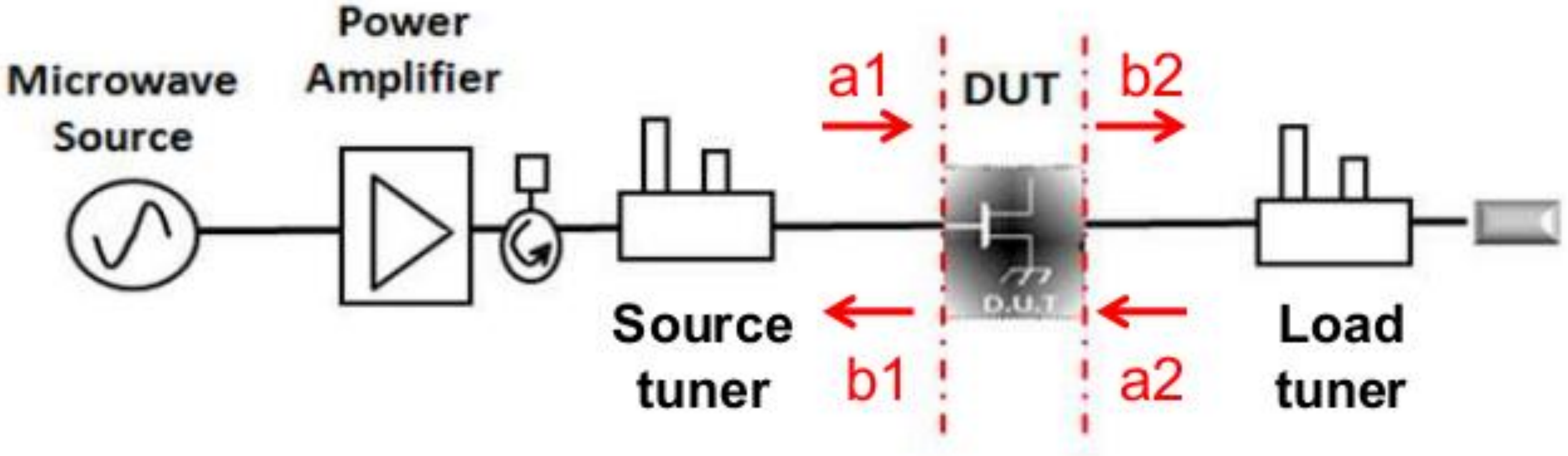


➤ ***VNA based loadpull /*** ➤ ***Vector Veceiver loadpull /*** ➤ ***Real Time loadpull***

Better loadpull structure based on VNA advanced architecture







$$\Gamma_{in} = \frac{b_1}{a_1}$$

$$\Gamma_{load} = \frac{a_2}{b_2}$$

$$P_{out} = \frac{1}{2}\left(|b_2|^2 - |a_2|^2\right)$$

$$P_{in,del} = \frac{1}{2}\left(|a_1|^2 - |b_1|^2\right)$$

$$P_{in,available} = P_{in,del} \Bigg/ \left(1 - \left|\frac{Z_{in} - Z_s^*}{Z_{in} + Z_s^*}\right|^2\right)$$

$$G_p = \frac{P_{out}}{P_{in,del}} = \frac{|b_2|^2 * \left(1 - |\Gamma_{load}|^2\right)}{|a_1|^2 * \left(1 - |\Gamma_{in}|^2\right)}$$

$$PAE = \frac{P_{out} - P_{in,del}}{P_{DC}}$$

Calibration routine of VNA based LP

- *Tuner calibration*

-> much lower density needed compared with traditional one.

- *Receiver vector calibration*

-> fast, no sensitive to source and load match.

- *Receiver power calibration*

-> absolute power cal. of receiver by power meter

Pros and cons

- *Integrated and fast solution*

frequency offset measurement mode for IMD3, Spectrum analyzer is not necessary

- *Reduced tuner calibration time*

real time measure mode of receiver

- *Fast tone balance leveling real-time*

power calibration is not necessary

- *Change driving PA without calibration*

8 terms model doesn’t rely on source/load match, not necessarily do raw power calibration again even change driving PA

- *PNAX should be occupied always by system*
- *PA linearity is prerequisite for accurate device linearity measurement*

The challenge of 2 tone test on unmatched device

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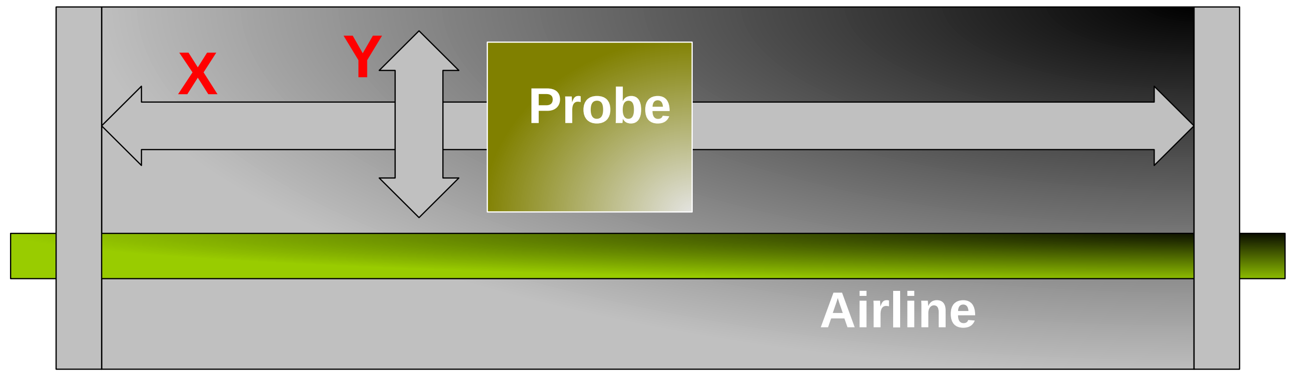
Challenge in the non 50Ohm linearity measurement

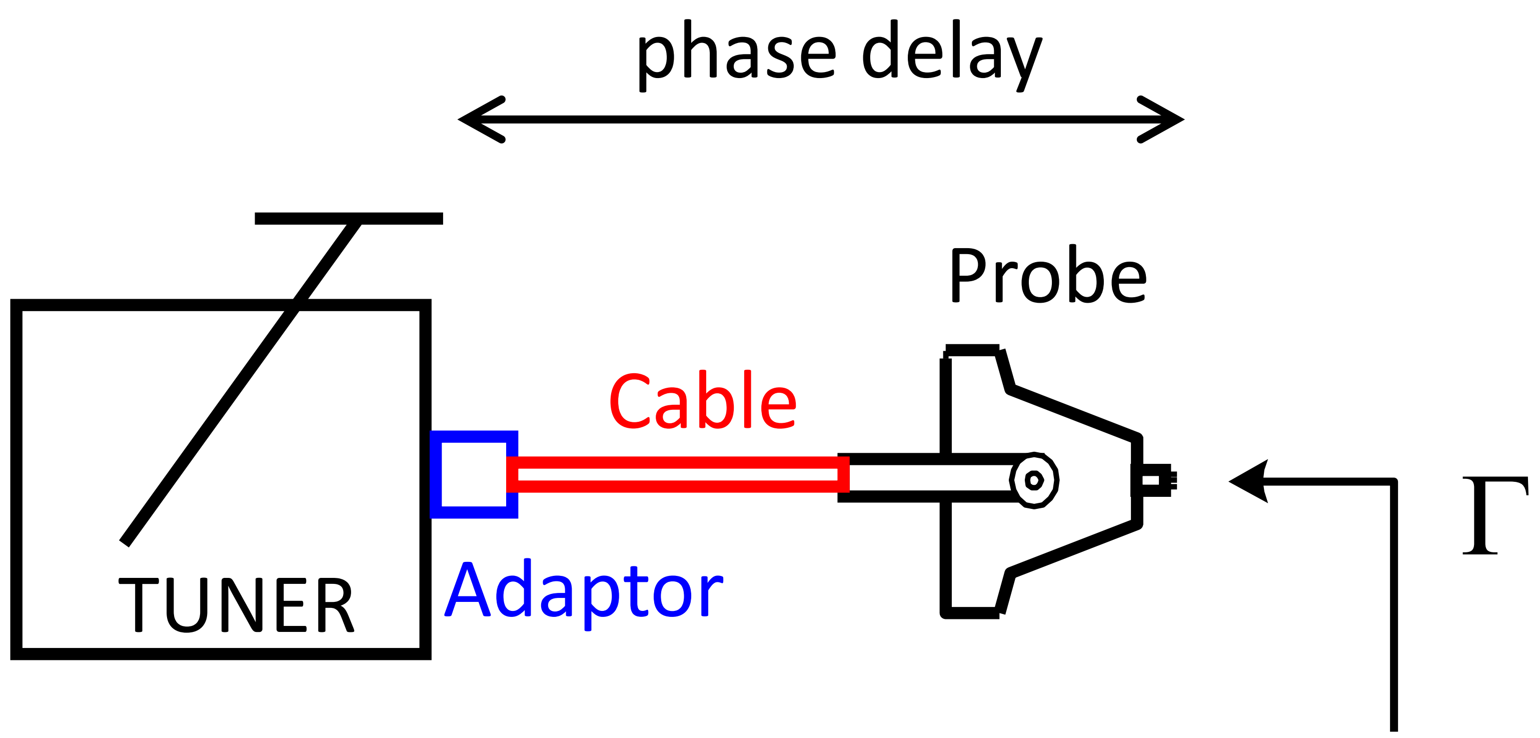
Modulation	Freq. range	Bandwidth (single channel)	Total Bandwidth (1 Channel + ACLR)
W-CDMA	800 MHz –3.5 GHz	5 MHz	15 MHz
Multi-carrierW-CDMA	800 MHz –3.5 GHz	15 MHz	25 MHz
LTE	600 MHz –6 GHz	20 MHz	60 MHz
802.11a/b/g	2.4 GHz	20 MHz	60 MHz
802.11n	2.4 GHz, 5 GHz	40 MHz	**160 MHz**
LTE-A	800 MHz –3.5 GHz	100 MHz	**300 MHz**
802.11ac	5 GHz	160 MHz	**480 MHz**
5G	600 MHz –6 GHz	100 MHz	**300 MHz**
5G	28 GHz	~1 GHz	
5G	38 GHz	~1 GHz	

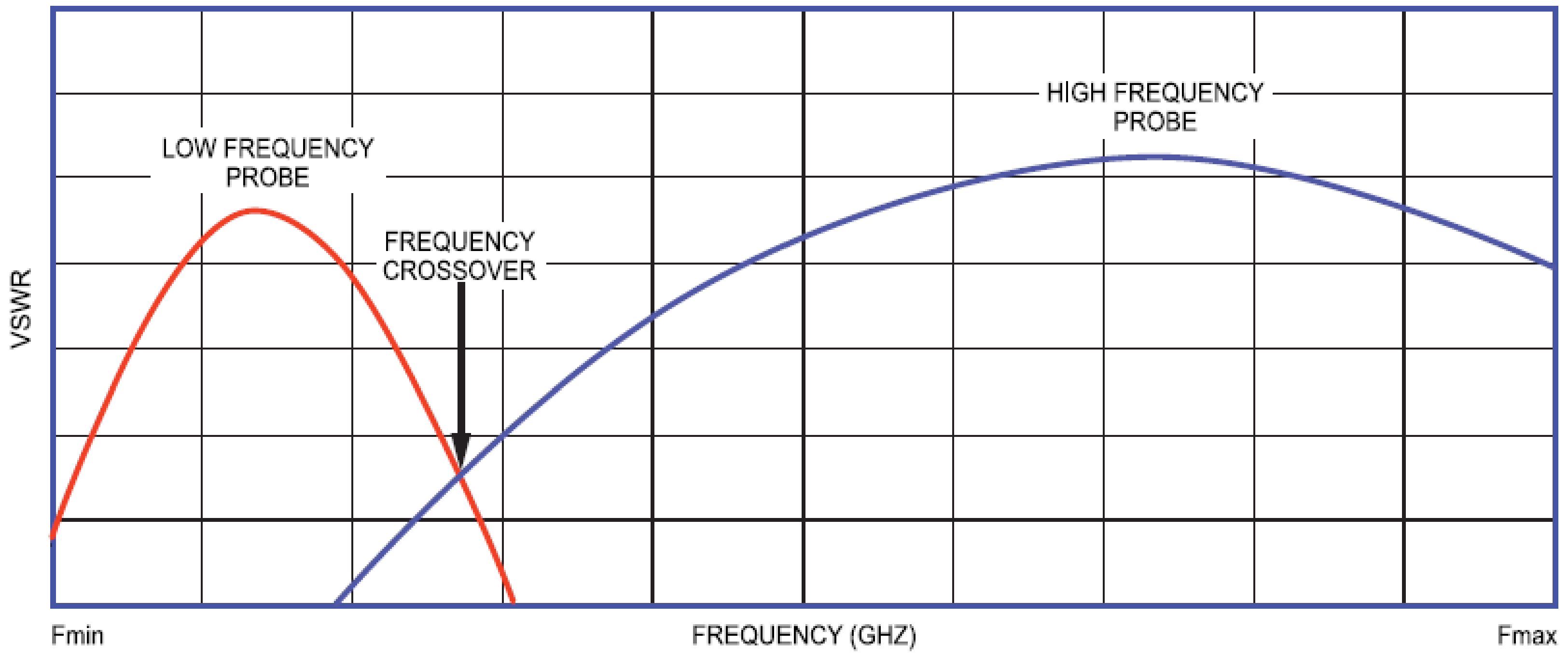
Bandwidth is more than 40 MHz in 4G times, it will be much wider in the coming 5G times, what are the challenges for linearity non-50 load pull test for PA?

What we found in real envionment

Phase shift issue





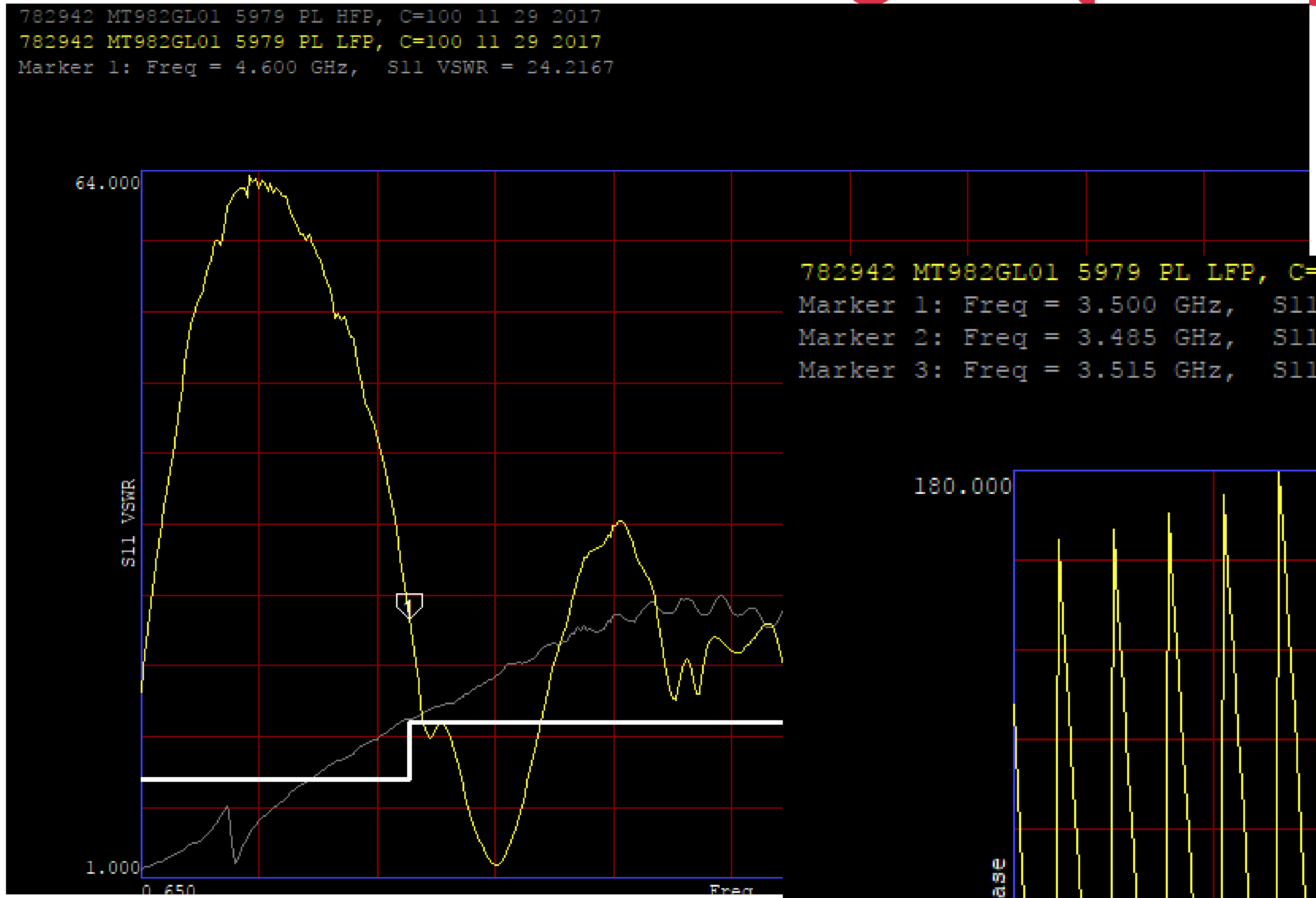


VSWR versus Frequency of a two-probe slide-screw tuner.

For passive tuner, where there is distance of probe to DUT, there will be phase shift, longer the distance, greater the phase shift

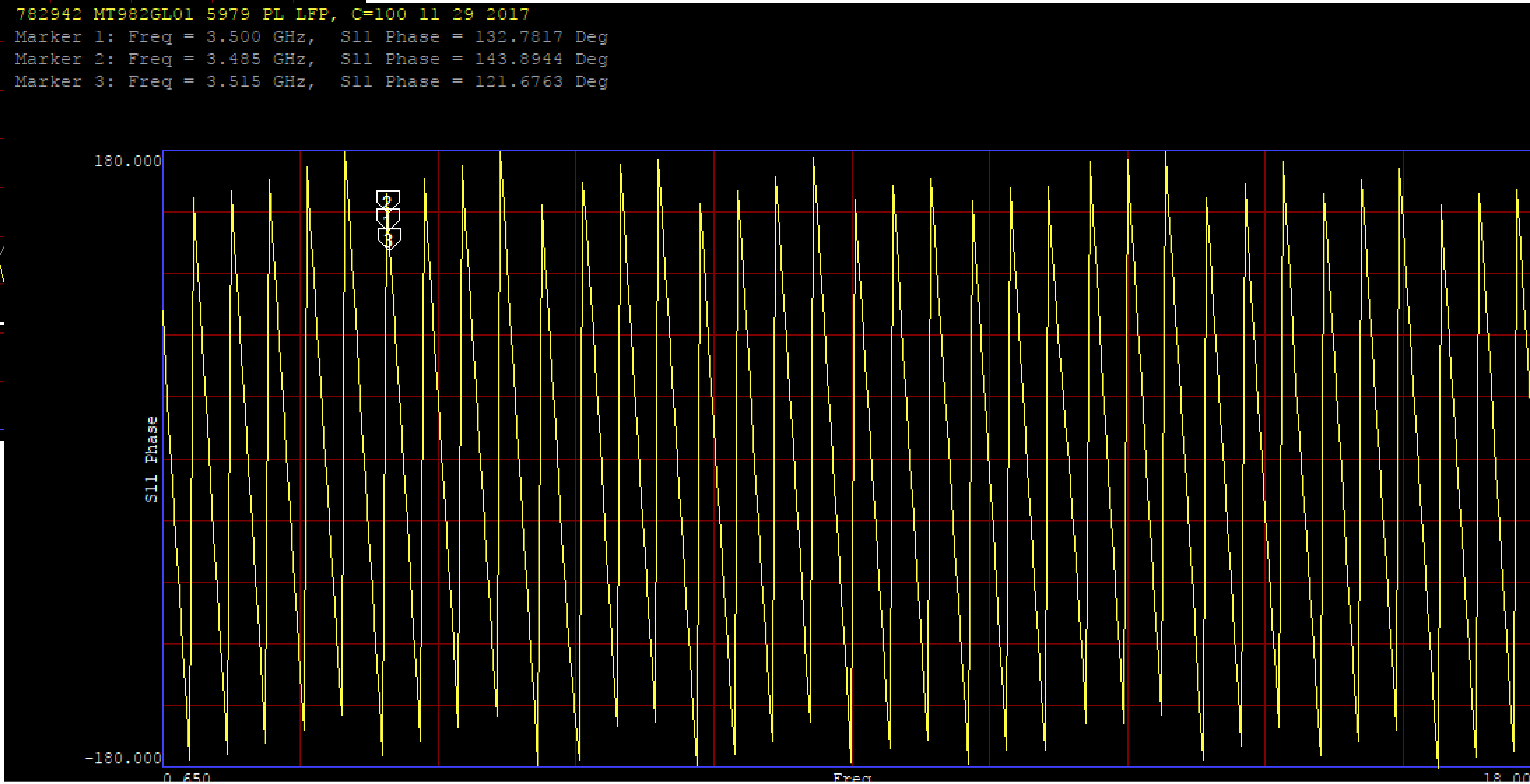
The great phase shift is not permitted in the real matching network

Tuner matching frequency response of a typical position



Model: MT982GL01,0.65-18GHz, crossover freq.: 4.6GHz

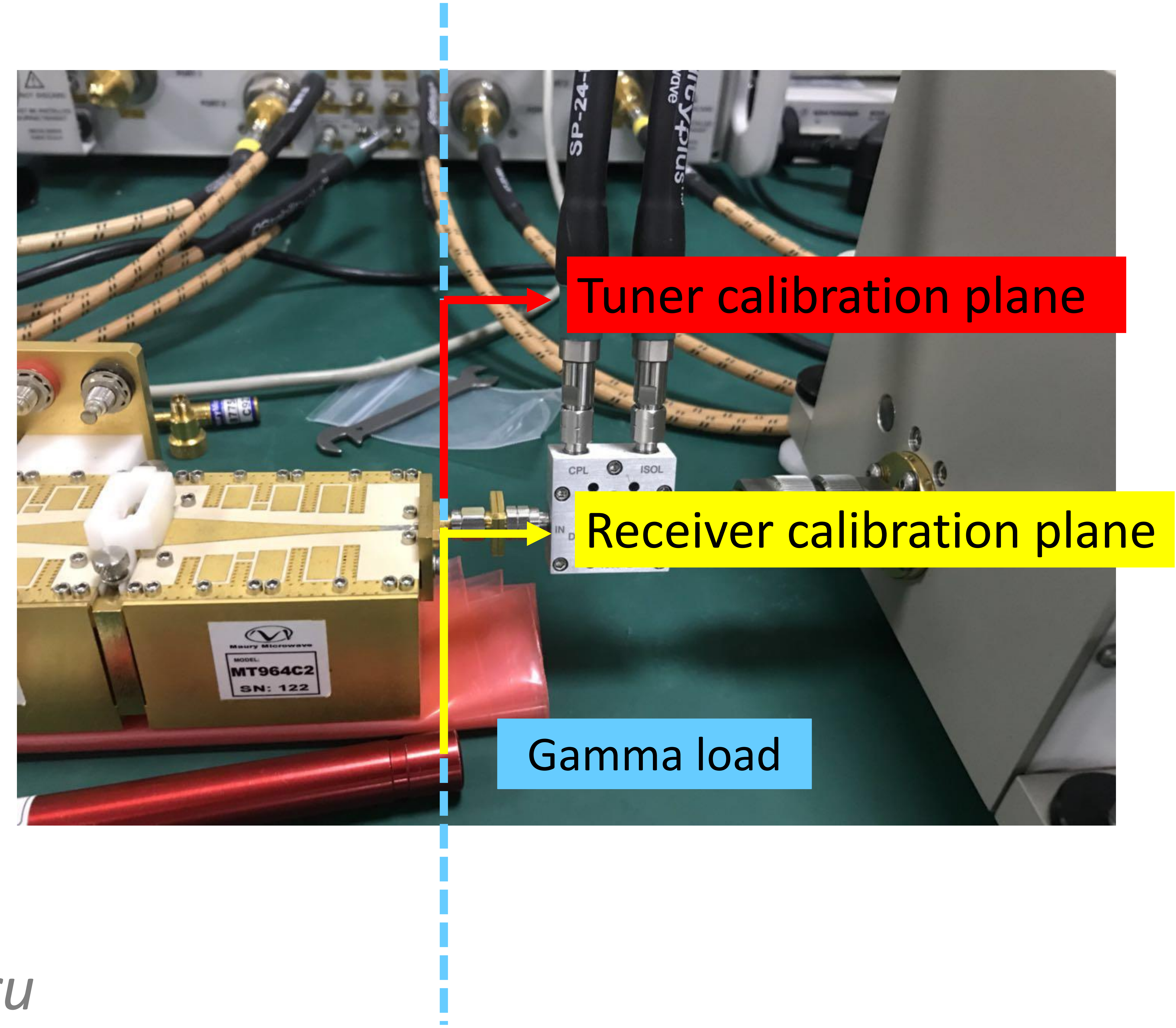
Position: carriage , probe1, probe2: (100, 0, 5000)



*Tuner is a **very narrow** freq. response device which is not optimum for wideband measurement*

Narrow response issue

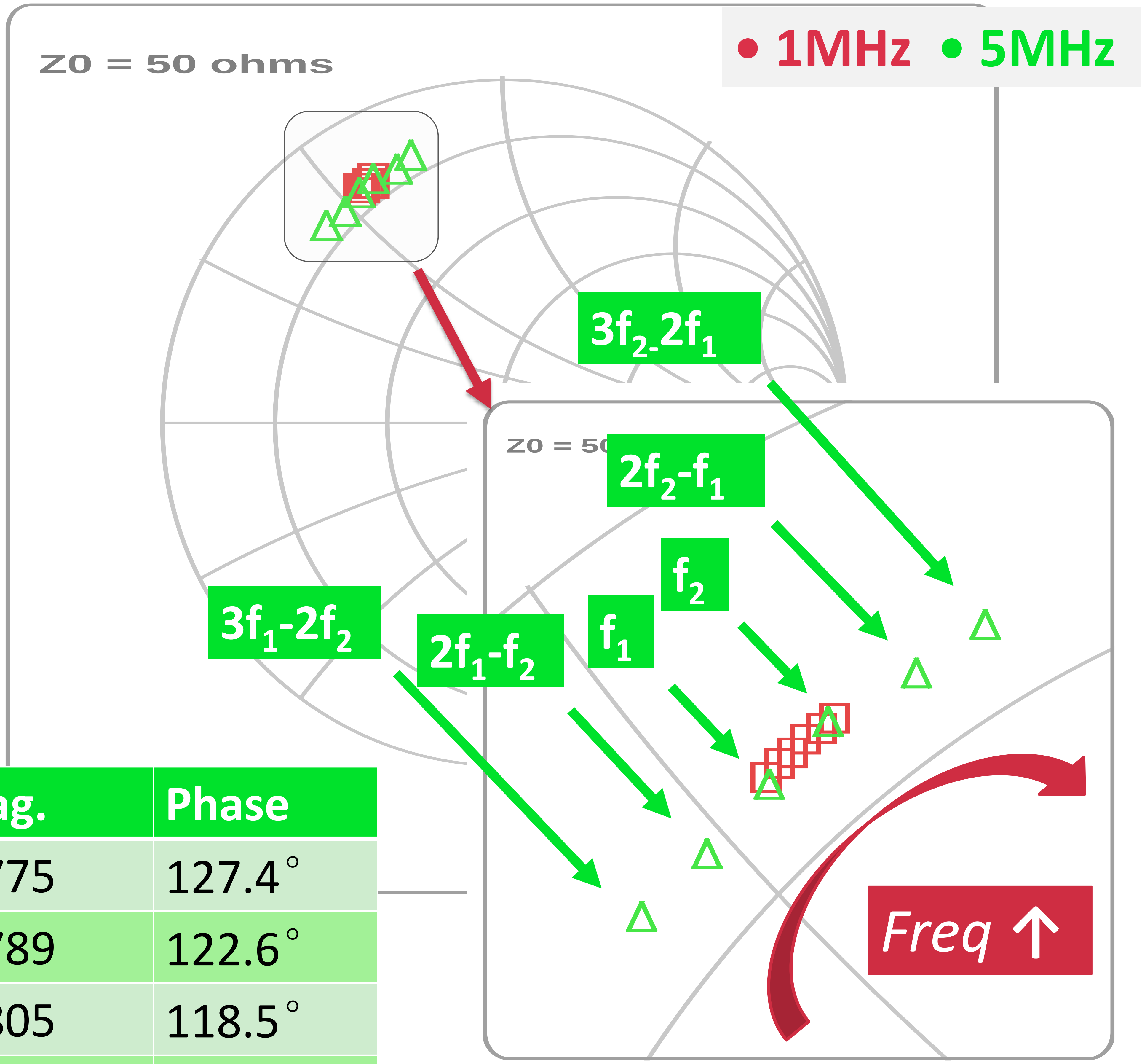
Setup for passive 2 tones benchmark



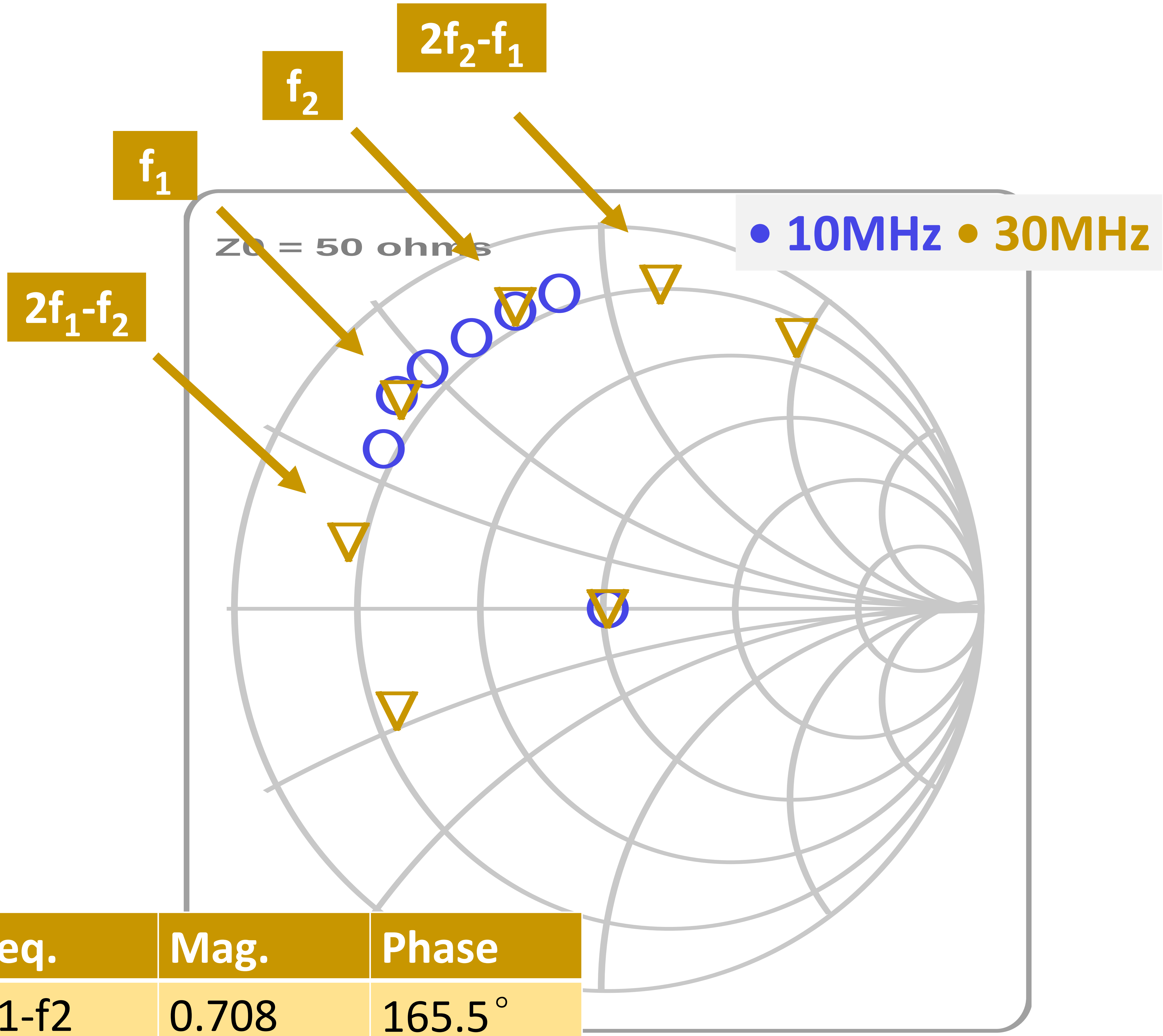
Load pull bench for 2 tones measurement
*Measure the load impedance in **real time** on a thru*

Summary of the challenges, NO. 1, phase shift

Carrier freq.: 3.5GHz
Load gamma: 0.8<120 ° (carrier)
Tone space: 1, 5. 10, 30MHz



Freq.	Mag.	Phase
2f1-f2	0.775	127.4°
f1	0.789	122.6°
f2	0.805	118.5°
2f2-f1	0.807	113.3°



Freq.	Mag.	Phase
2f1-f2	0.708	165.5°
f1	0.770	134.4°
f2	0.824	106.7°
2f2-f1	0.859	80.18°

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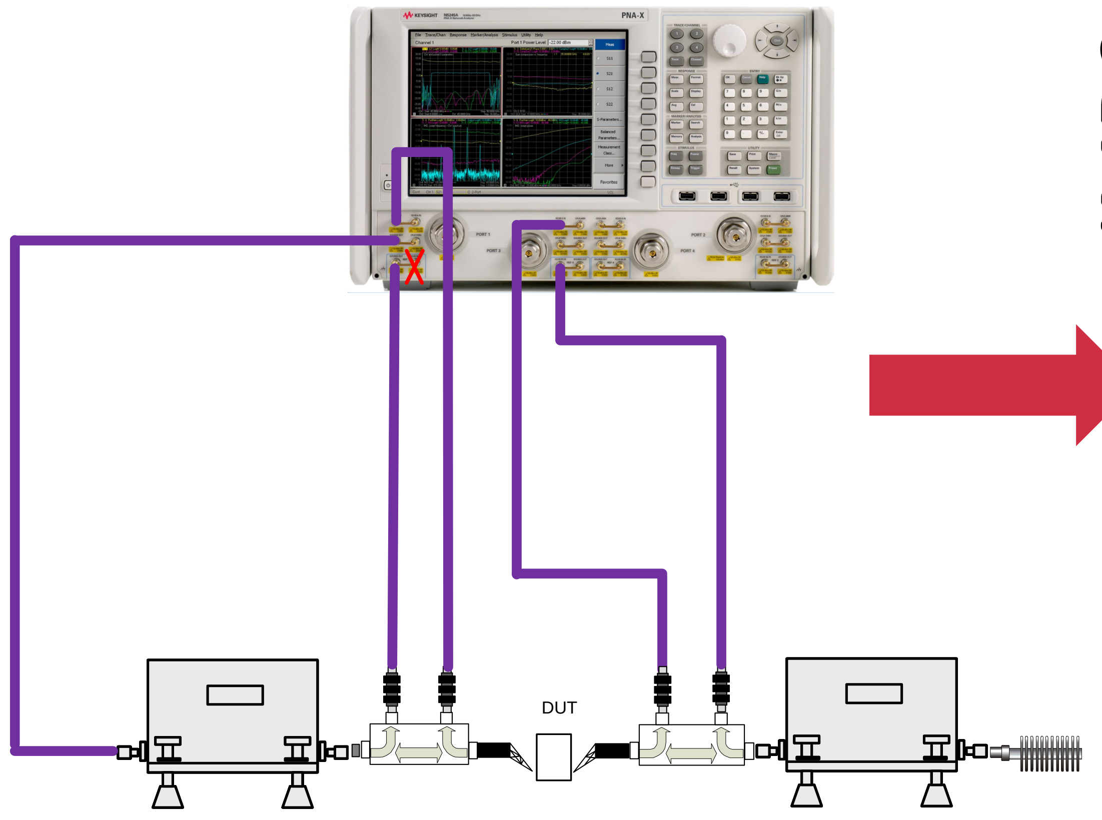
Summary of the challenge , No. 2, system non-linearity

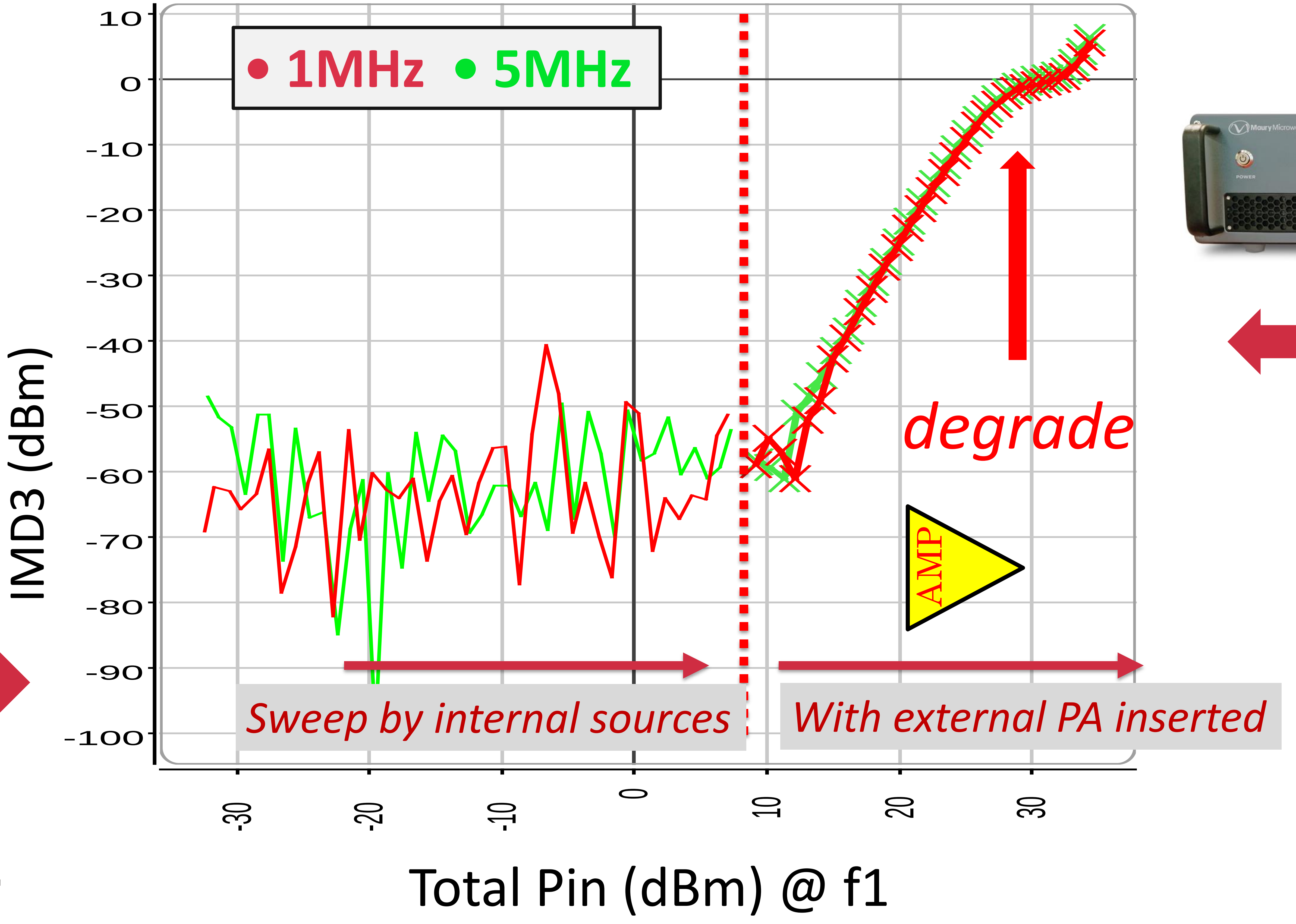
Carrier freq: 3.5GHz

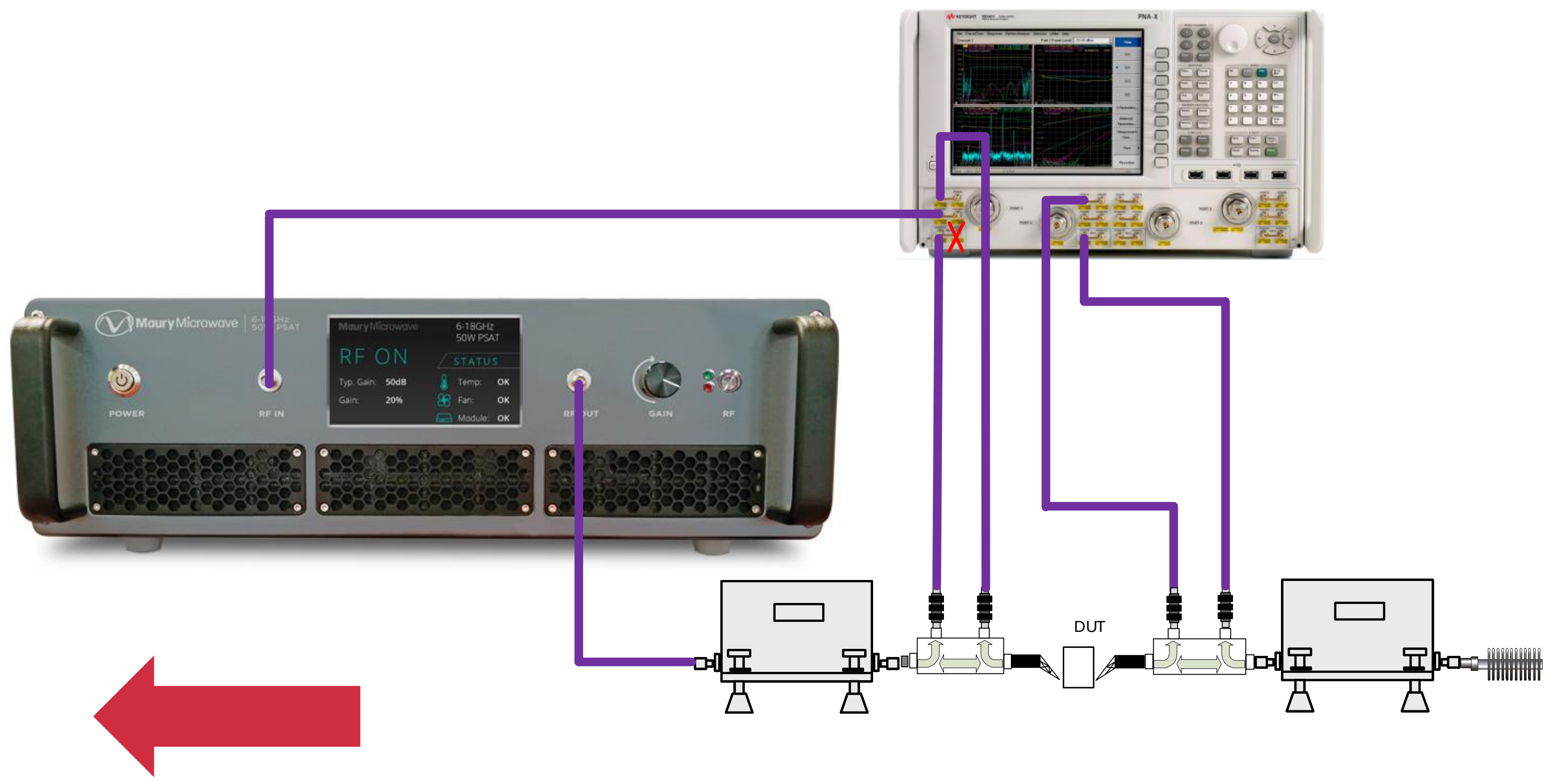
Load gamma: 0.8<120 ° (carrier)

Tone space: 1, 5, (10, 30)MHz

IMD3 (dBm) vs. Total Pin(dBm)



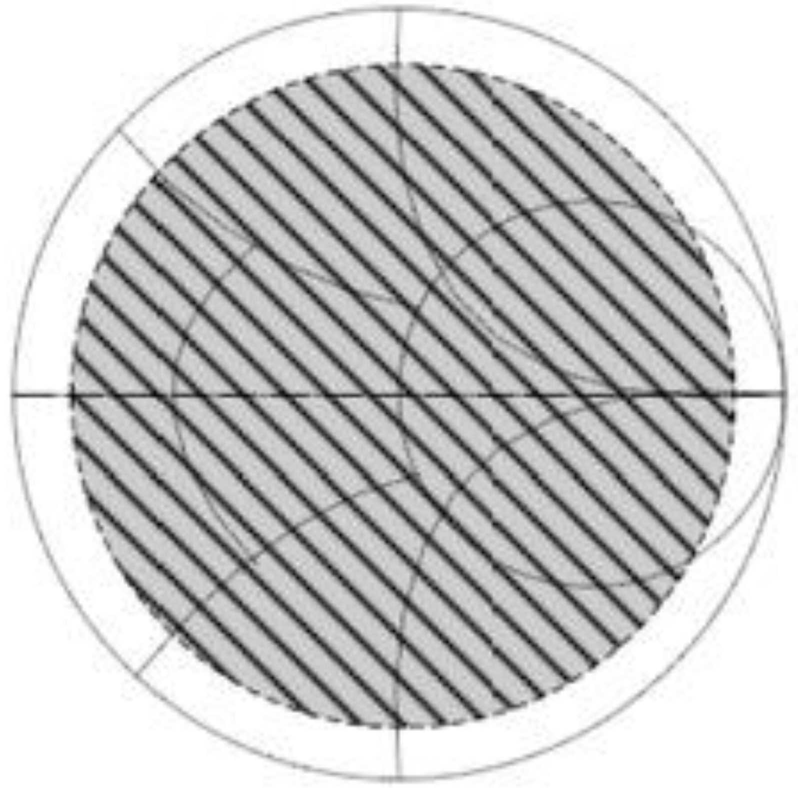




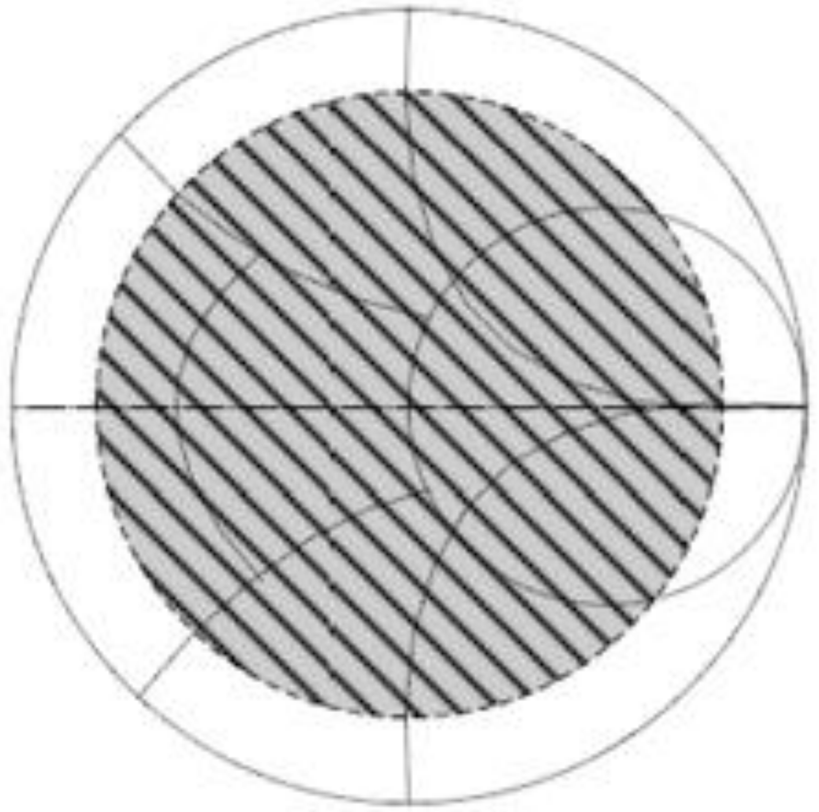
Summary of the challenges, NO. 3, limited matching range

Shrined tuning range, inevitable, insoluble by passive tuner itself

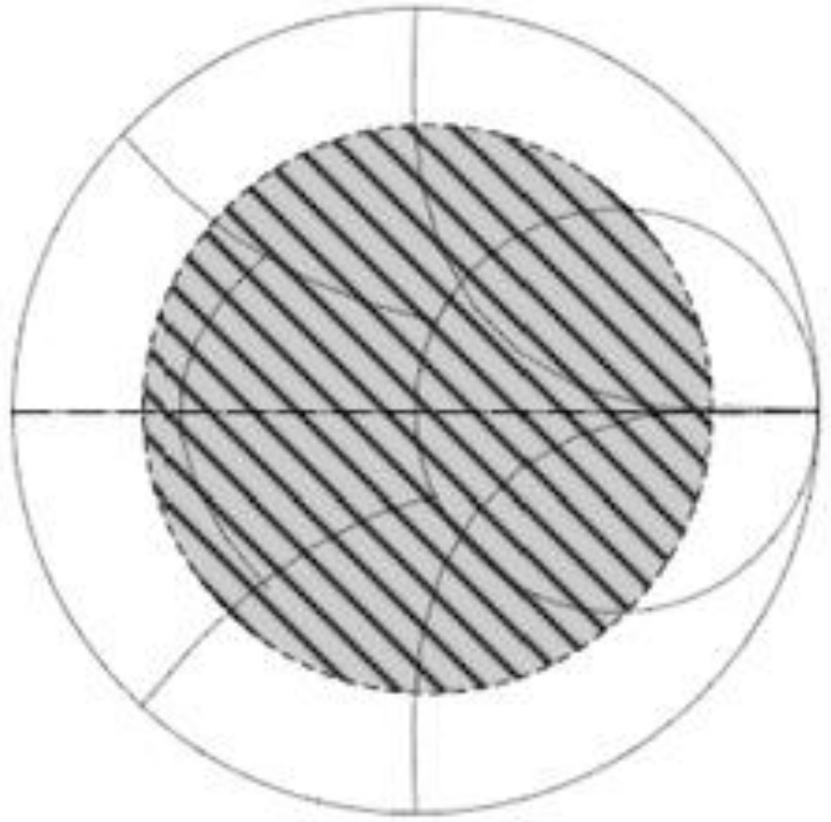
Tuner plane

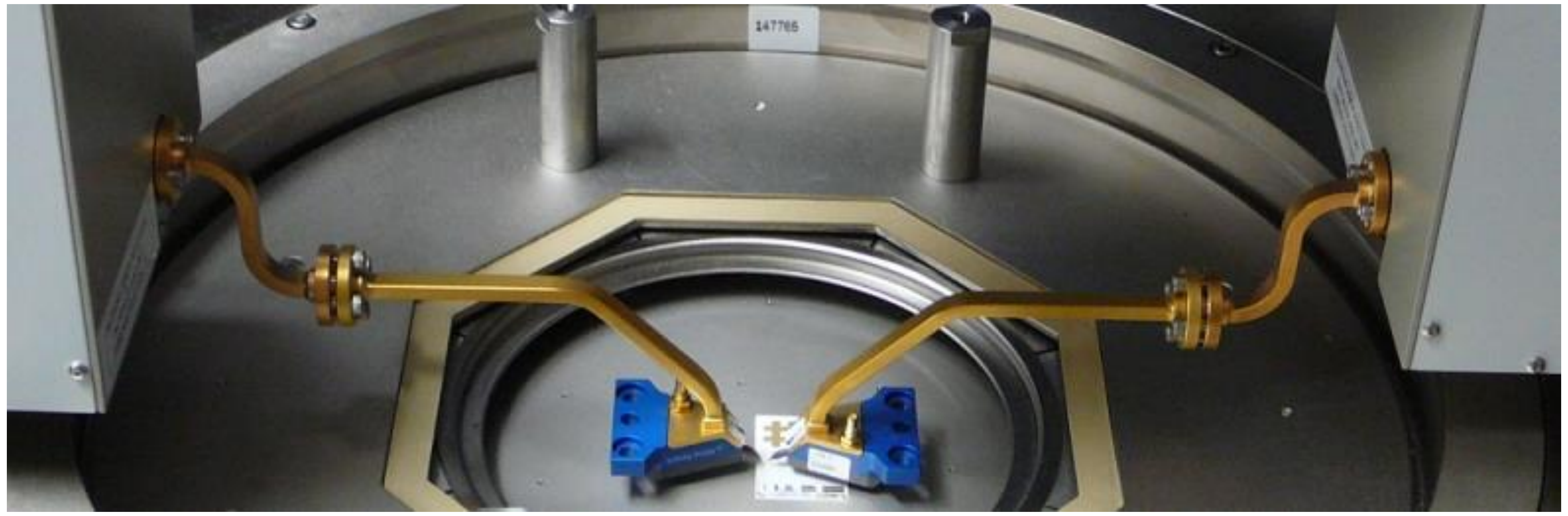


Coaxial/Waveguide plane



Probe tip plane





Greatly subject to loss between Tuner and DUT, especially on wafer!

Common issues of the passive 2 tones loadpull system

- *Tedious tuner calibration*
- *Limited matching range due to passive tuner*
- *2 high independent linear sources with combiner, spectrum analyzer and VNA configurable test set option are not cheap*
- *Tone balancing is necessary which limit the speed*
- *Accurate linearity measurement reply on the linearity of source and amplifier*

A novel 2 tone measurement solution → MT2000!

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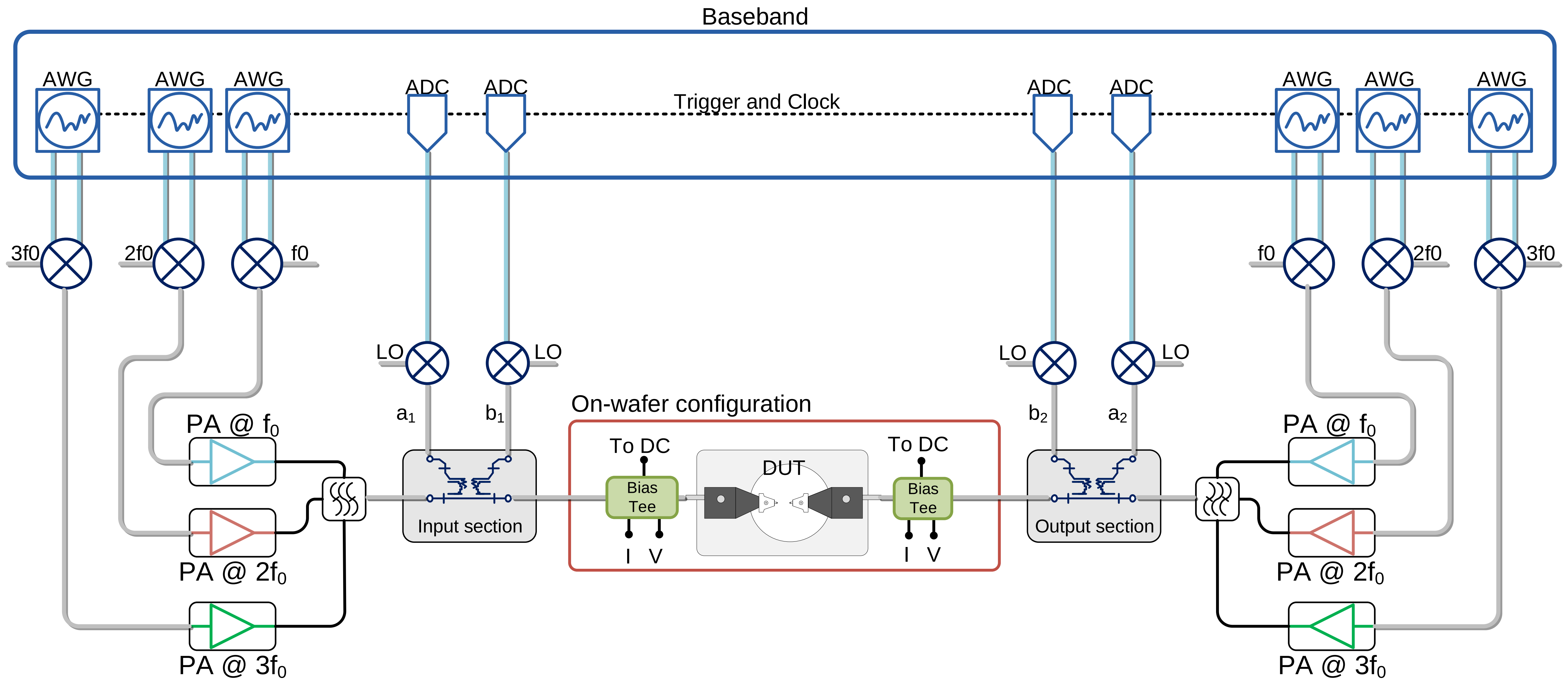
Our solution on the challenging request

A brand new architecture for wideband loadpull

- *Baseband signal generation including 2 tone*
- *Specific receiver covers both small and large signal measurement*
- *DPD similar algorithm for non linearity minimization of source or even driving amplifier*
- *Ultra-broadband tone spacing supported up to 166MHz or wider*
- *Ultrafast system calibration and measurement, order of few minutes*

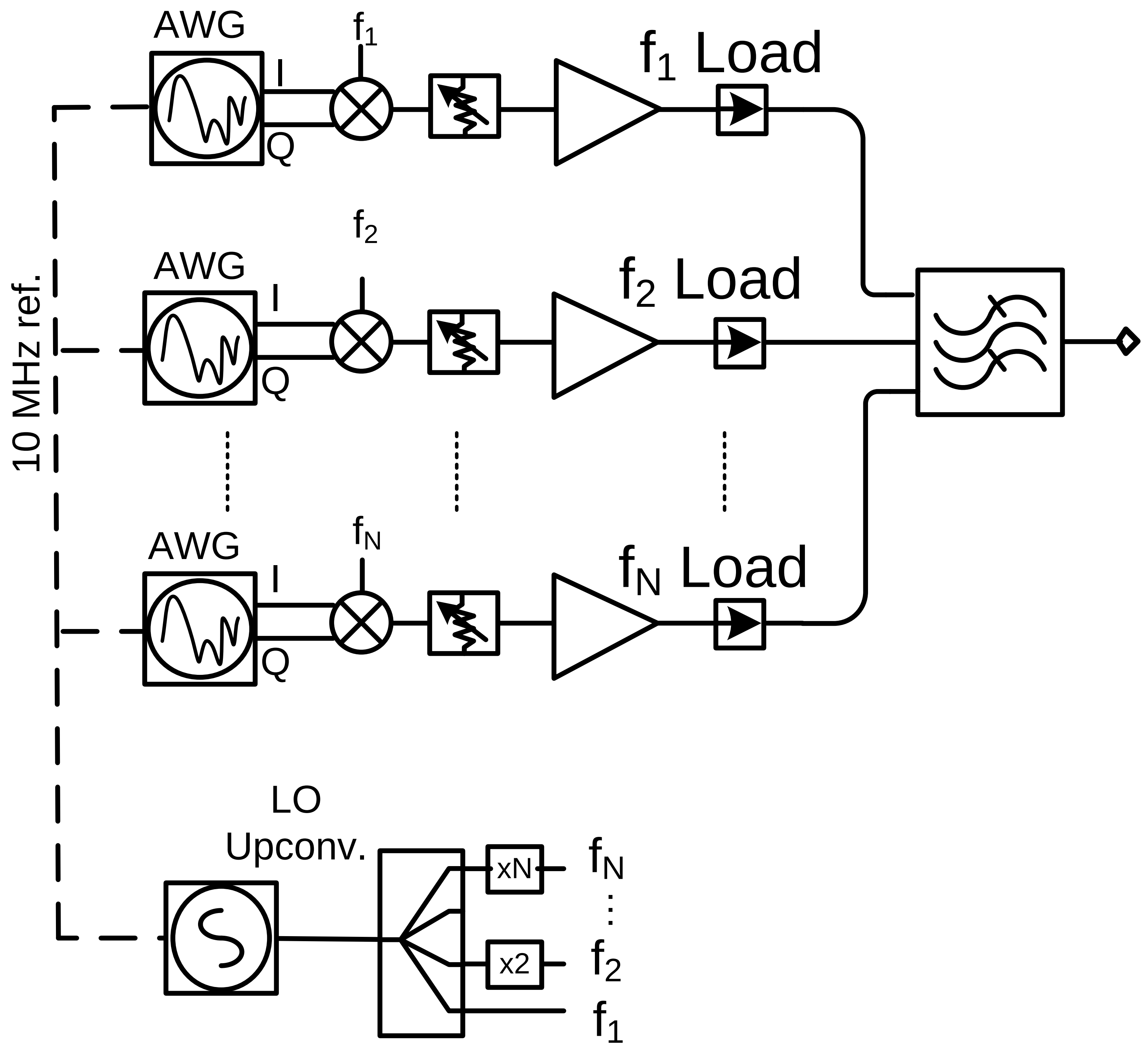
System architecture

MT1000/MT2000 architecture combines traditional analog and microwave techniques with low-frequency signal acquisition (A/D converters) and generation (Wideband AWG).



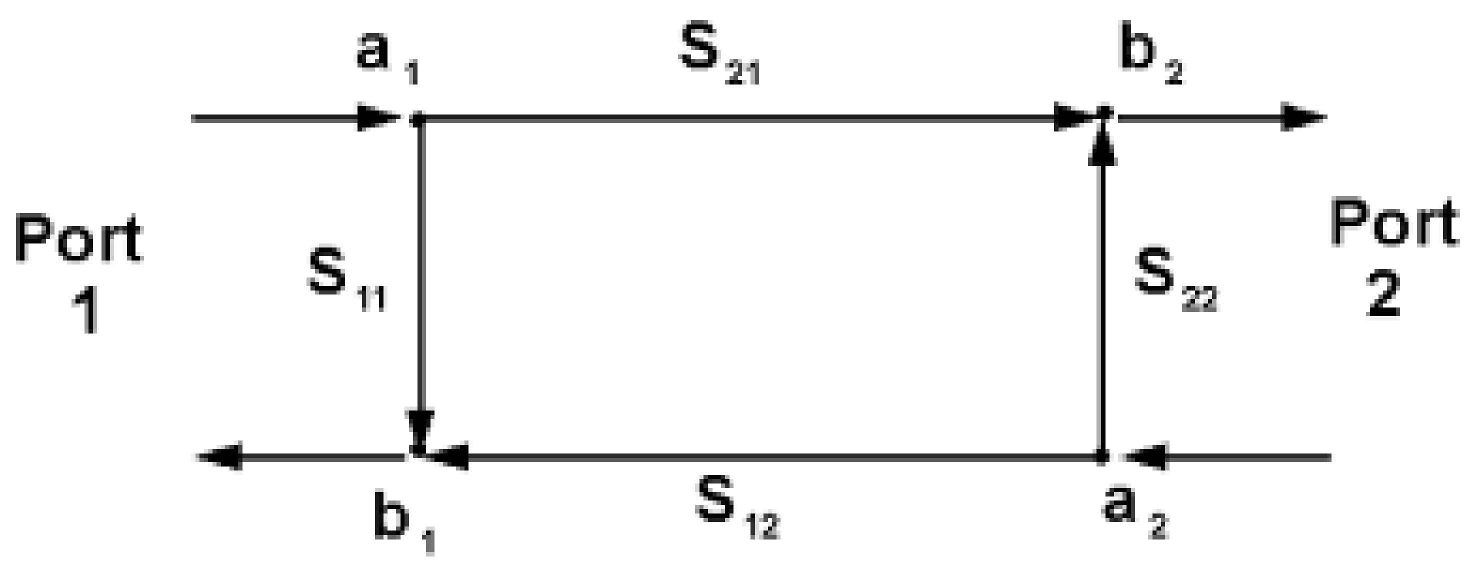
- A vector network analyzer VNA is integrated
- Two-port and power calibration to measure S-parameters and power
- Wideband ADCs allow measurement of wideband signals (power, ACPR, EVM)
- System includes 6 VSGs to generate custom modulations up to 240 MHz bandwidth
- Each VSG can be used as an active tuner

How does it works?



- *Test signals are generated in the time-domain at low frequency with AWGs*
- *Single local oscillator (LO) up-converts the waveforms at fundamental and harmonic frequencies by means of multipliers to guarantee phase coherency*

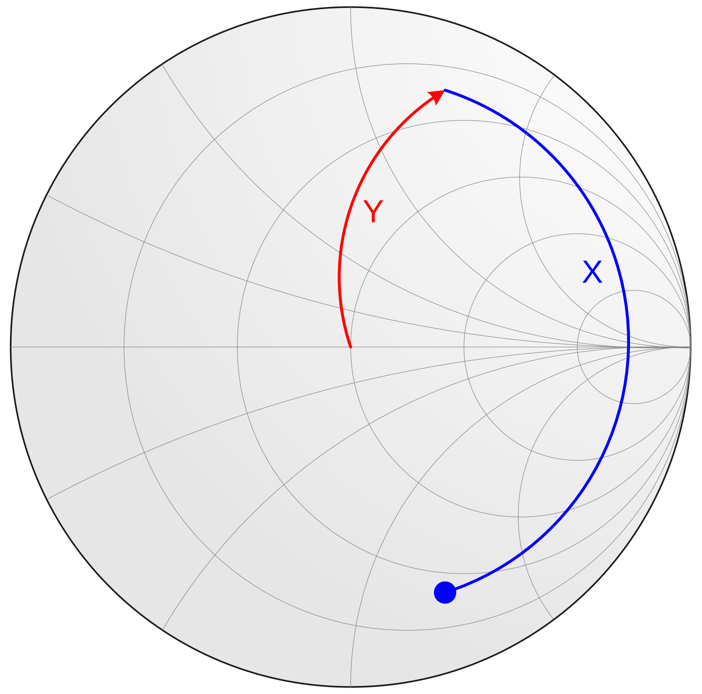
Active load for wideband impedance tuning



Two-port device represented in terms of S-parameters and a-waves and b-waves

$$\Gamma_{x,n}(f_n) = \frac{a_{x,n}(f_n)}{b_{x,n}(f_n)}$$

Formula governing Gamma in relation to a-waves and b-waves

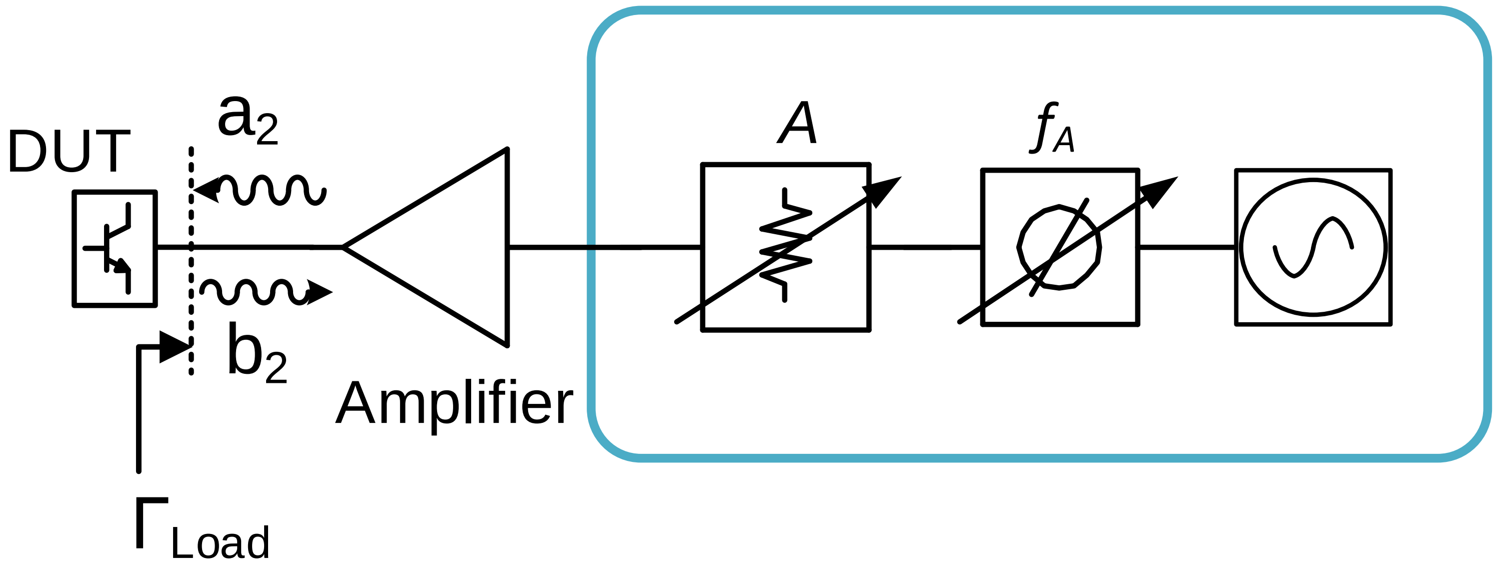


Changing magnitude and phase of b_2 will result in nearly any impedance on Smith Chart

Passive Load Pull

A passive mechanical tuner is used to reflect a portion of the DUT's energy b2 back towards DUT as a_2. The position of the probe will determine the magnitude and phase of the reflection. Γ will be lower than 1 since $a_2 < b_2$ due to losses.

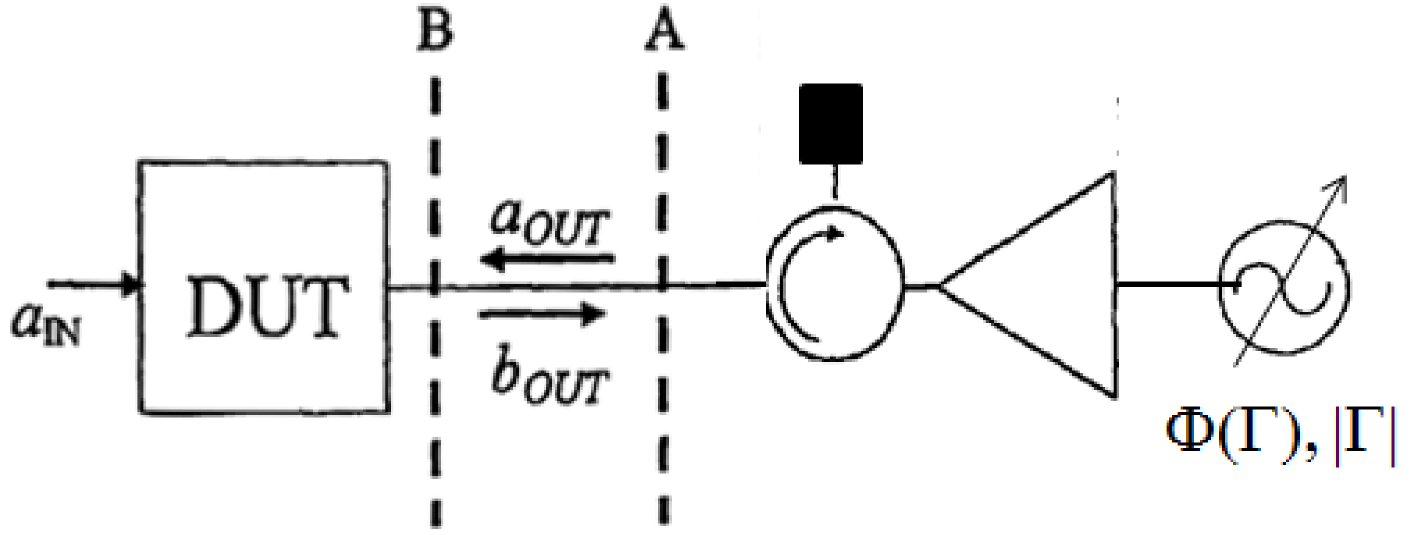
<u>Open</u> <u>Loop</u> Active Load Pull



A signal generator with magnitude and phase control is used to inject a new signal a_2 into the output of the DUT. Γ can be equal or greater than 1 since a_2 is independent of b_2.

Active tuning methodology

Open loop active

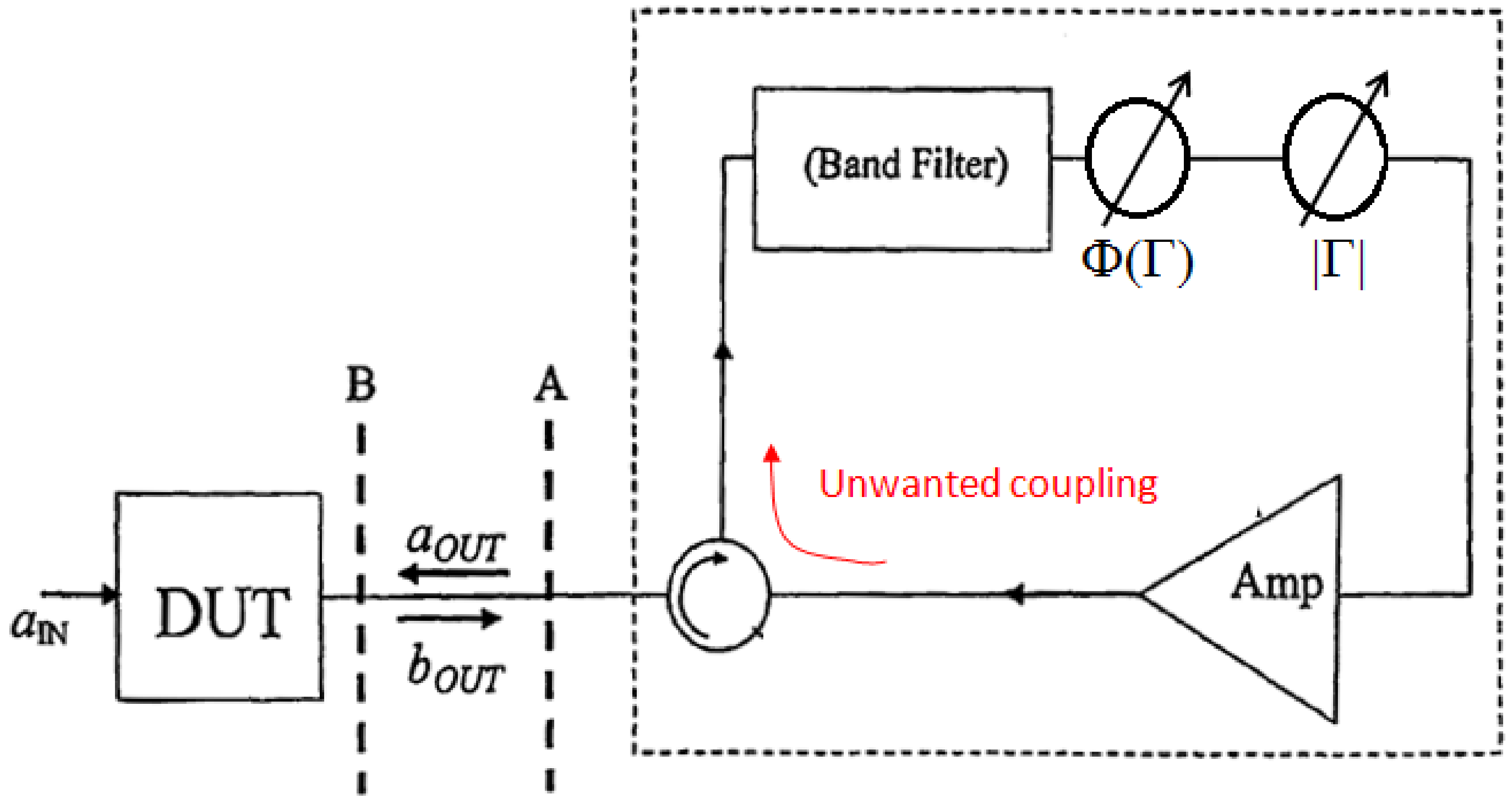


Open loop active requires custom algorithms for iterative convergence to synthesize desired reflection coefficients because the output of DUT (transmitted traveling wave, b2) is dependent on device operating conditions

The load impedance is controlled by an RF signal provided by a load RF source. The load signal is not looped, so <u>oscillation will never be observed</u> (because the loop is only in the software, with an algorithm which controls the gamma)

<u>Maury provides open loop solution!</u>

Close loop active



the bout signal is looped into a circuit that change the magnitude and phase of the coupled RF signal, and this signal is then re-injected toward the DUT (aout).

The oscillation risk is high because some unwanted coupling can take place, and this parasitic coupled signal is then amplified and phase shifted as well. Looking at this parasitic coupling path, if the magnitude reach |1|, and the phase reach (180°), then an oscillation will occur.

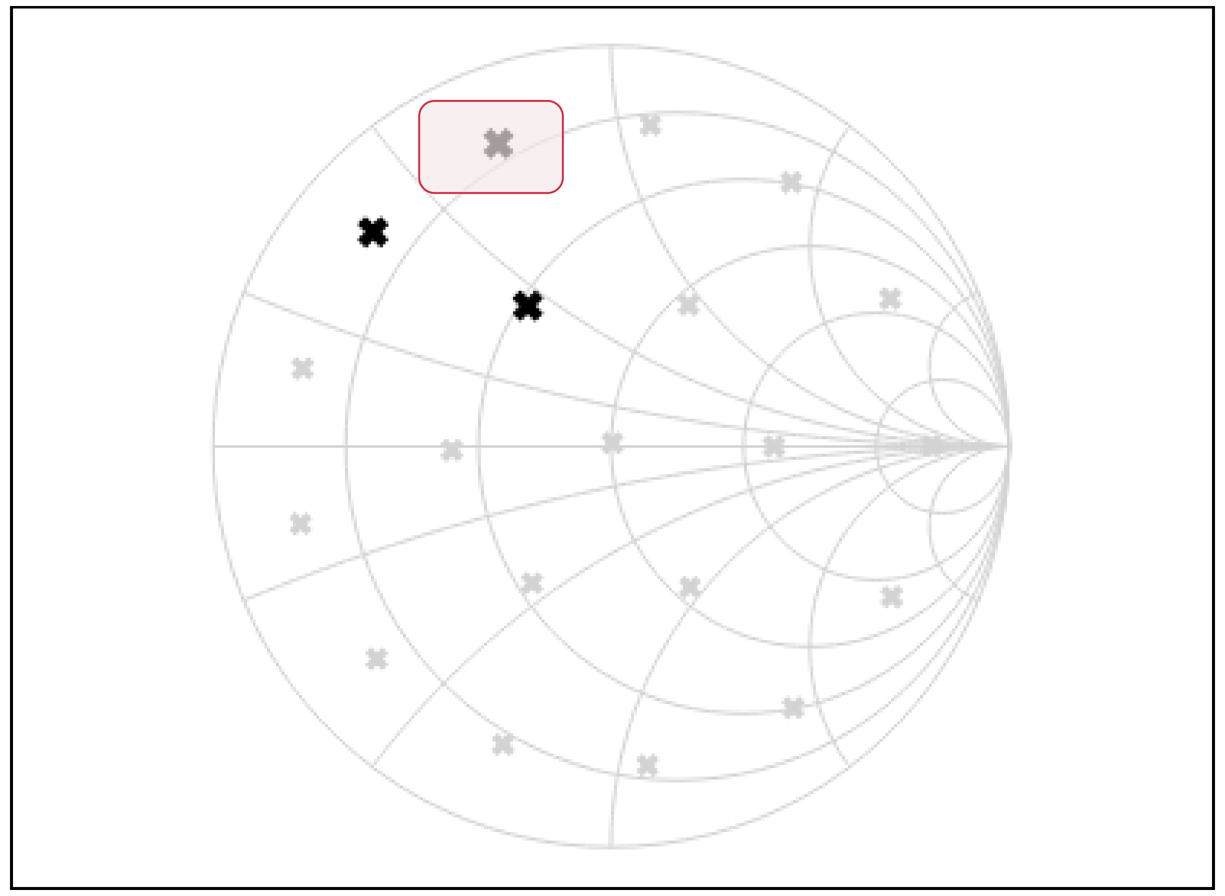
Wideband multi-tones arbitrary impedance tuning

Carrier freq: 2.6GHz

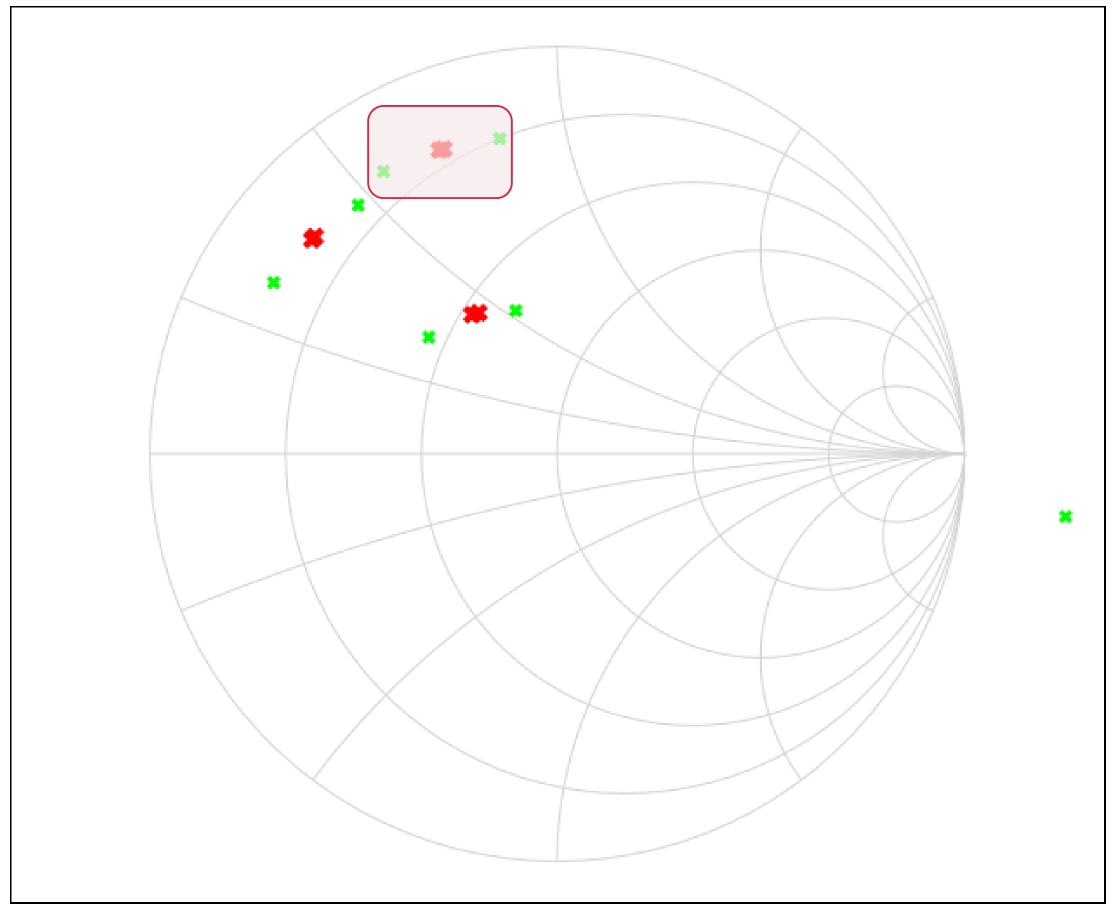
Carrier impedance: 0.8<110 °

Tone space: 20 MHz

× termination
× passive tuning
× active tuning

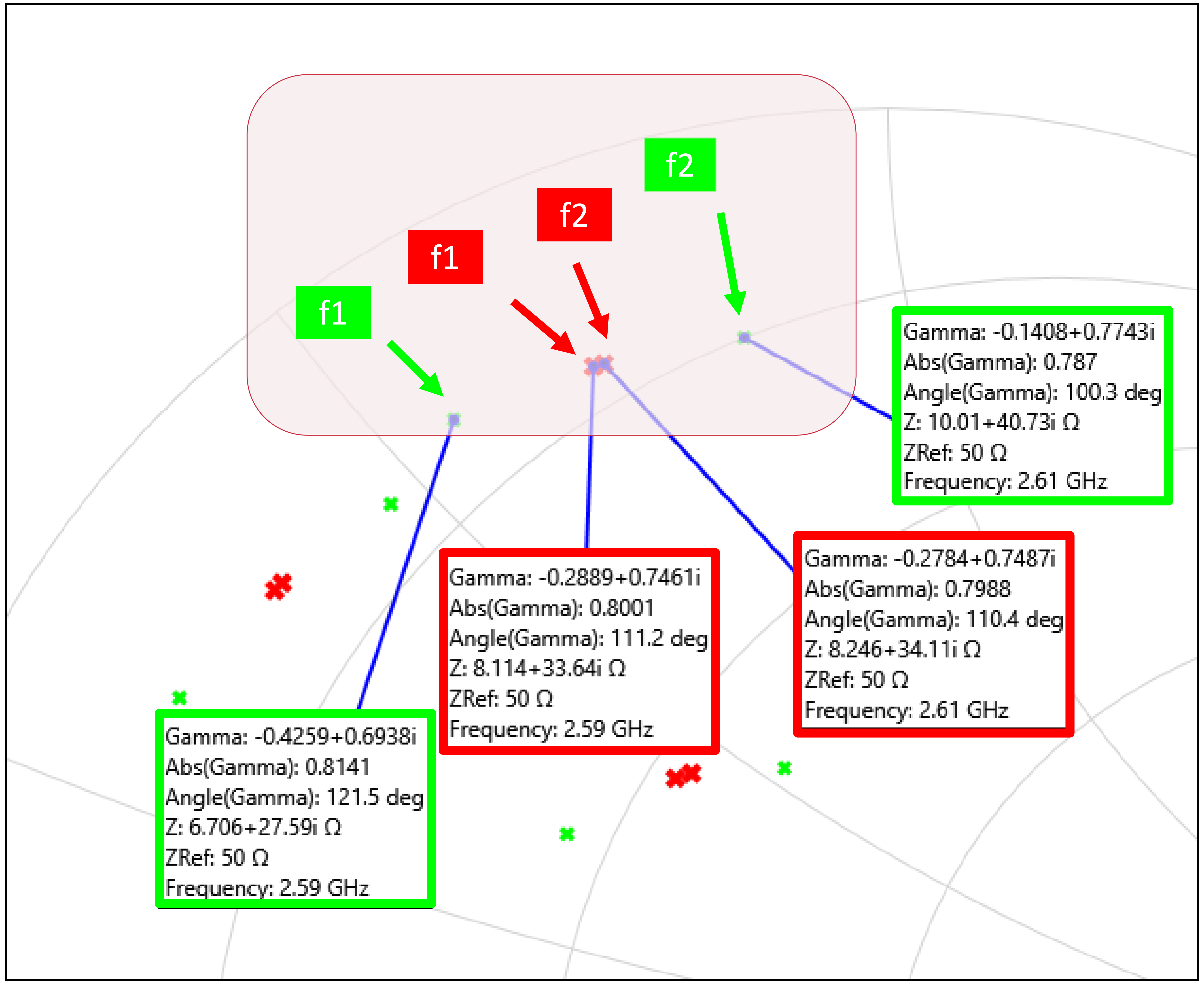


Selected termination



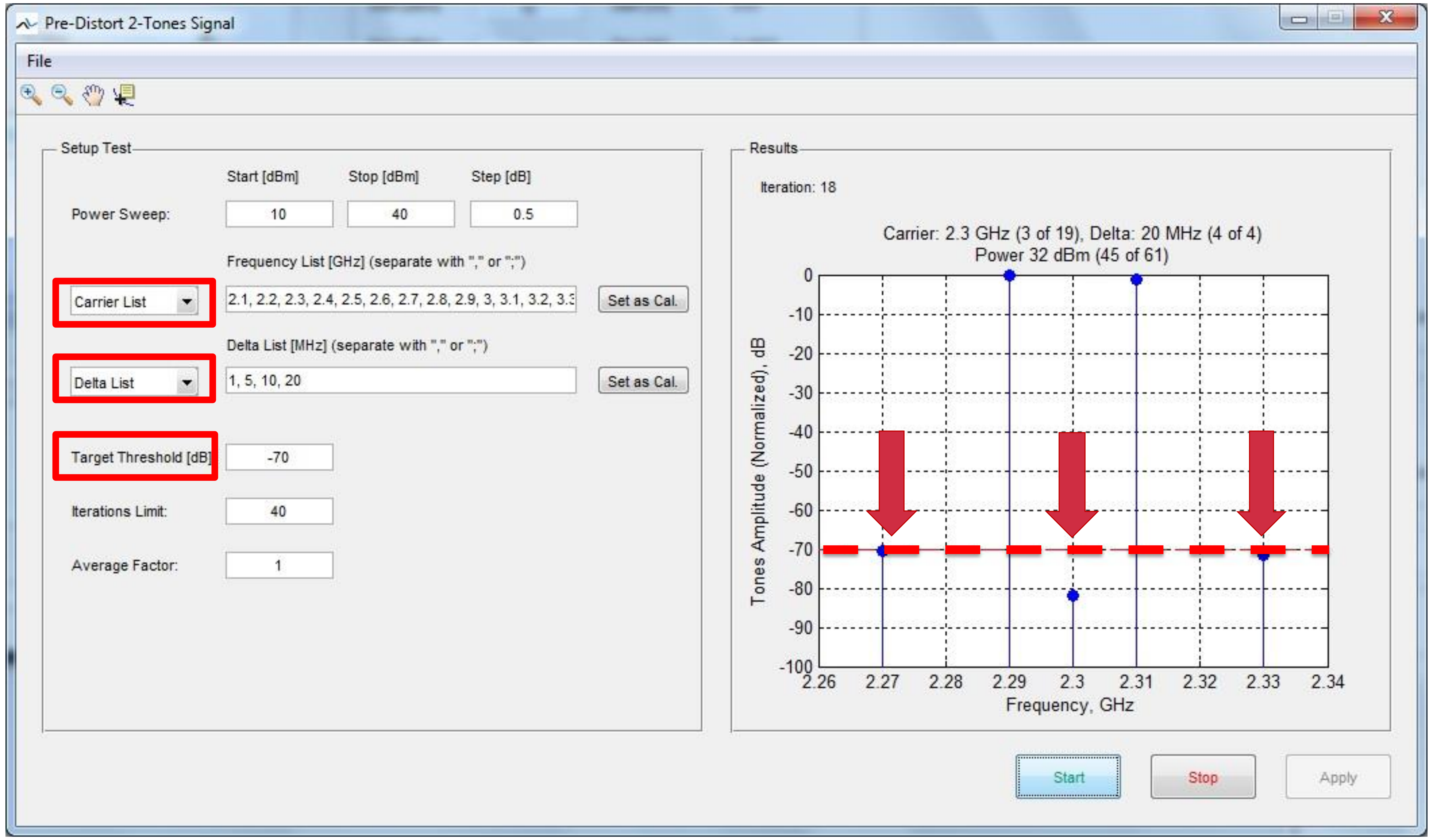
Measured gamma load real time

The impedance of f1 and f2 by active tuning can be converged to desired target, avoid the phase shift by passive tuning naturally



Zoom in plot

Pre-distortion calibration to remove the system non-linearity

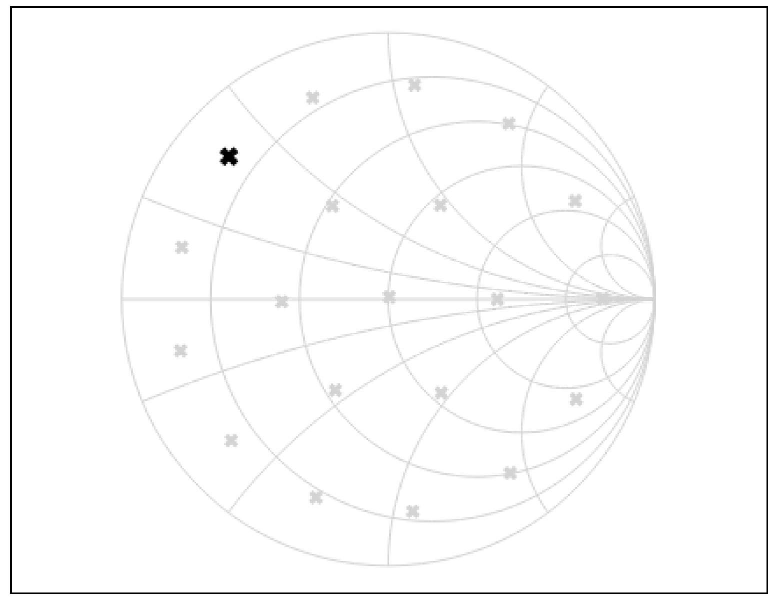


- *Connect the driving amplifier in the loop*
- *Input the target of minimization*
- *Run the pre-distortion algorithm for each carrier, tone space*
- *It will cost few minutes before test, but worthy!*

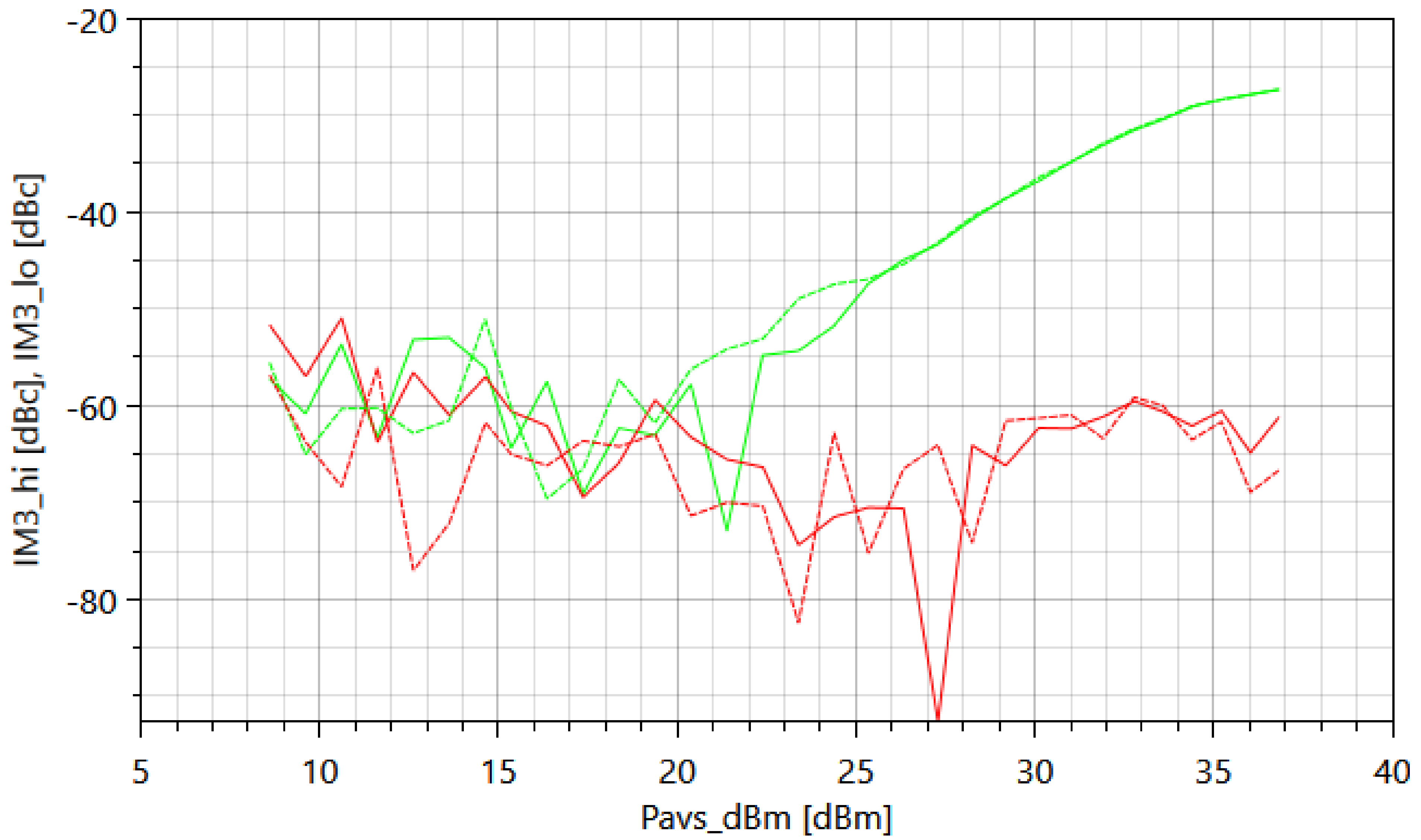
Wideband multi-tones pre-distortion calibration

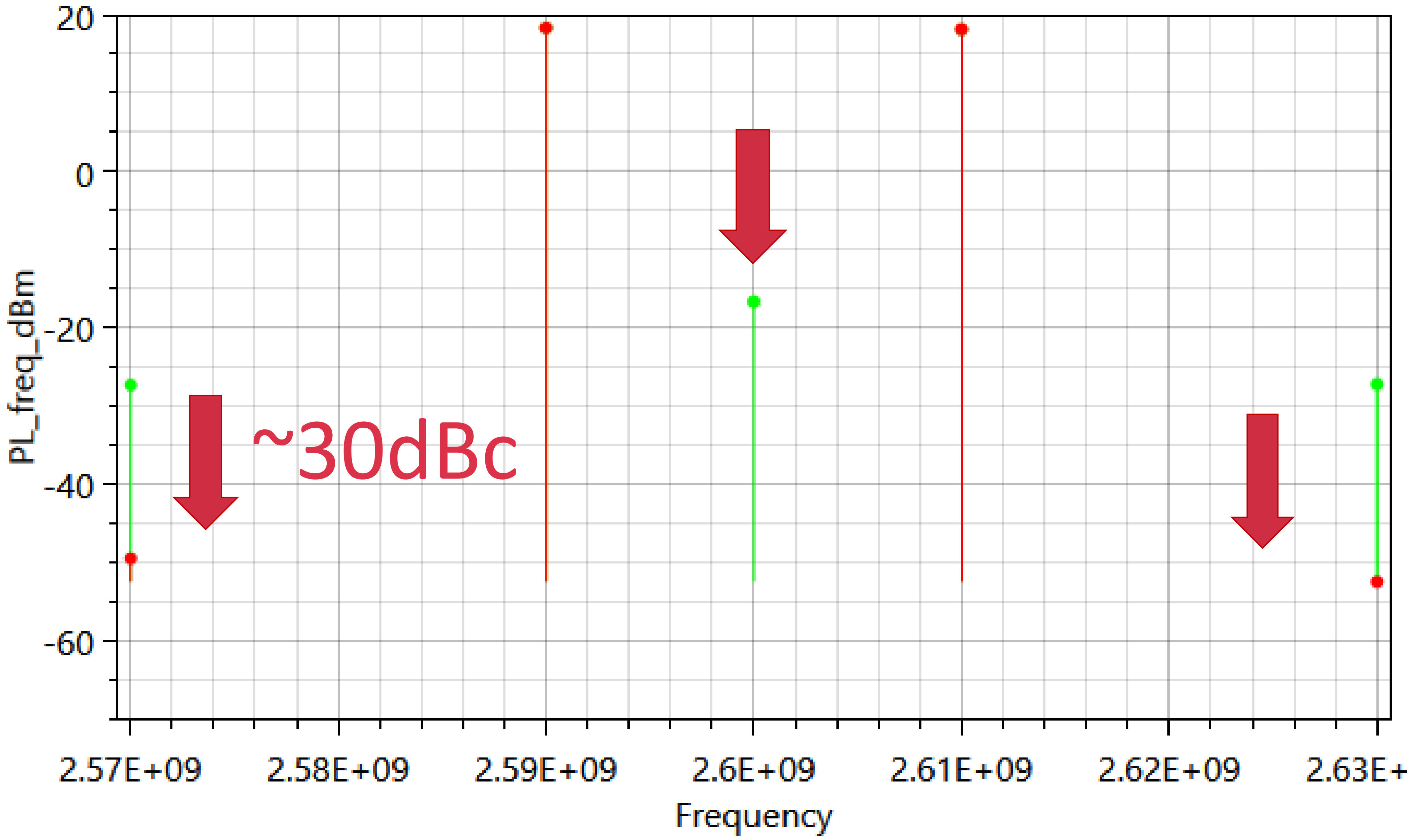
Carrier freq.: 2.6 GHz
Carrier impedance: 0.8<110 °
Tone space: 20 MHz
Power sweep: P_{avs} from 3 to 37 dBm (DUT plane)

× Termination
- With pre-distortion
- W/O pre-distortion



Selected termination





With the pre-distortion calibration, the non-linearity of system has been removed completely with the same hardware configuration, user get greatly improved system capacity **without any cost** except the calibration time of few minutes!

Calibration routine

- ~~*Tuner calibration*~~

~~*-> much lower density needed compared with traditional one.*~~

- *Receiver vector calibration*

-> fast, no sensitive to source and load match.

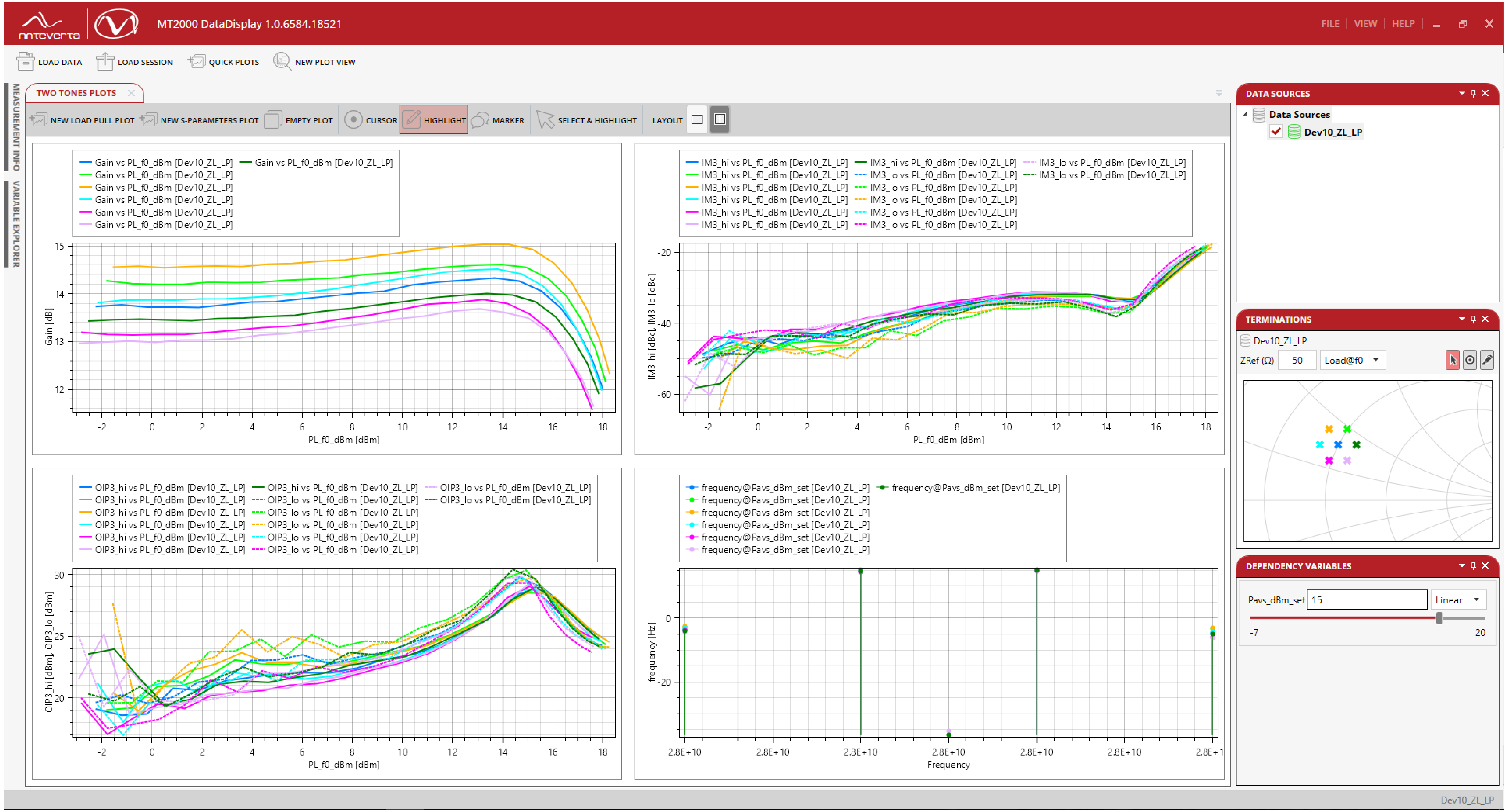
- *Receiver power calibration*

-> absolute power cal. of receiver by power meter

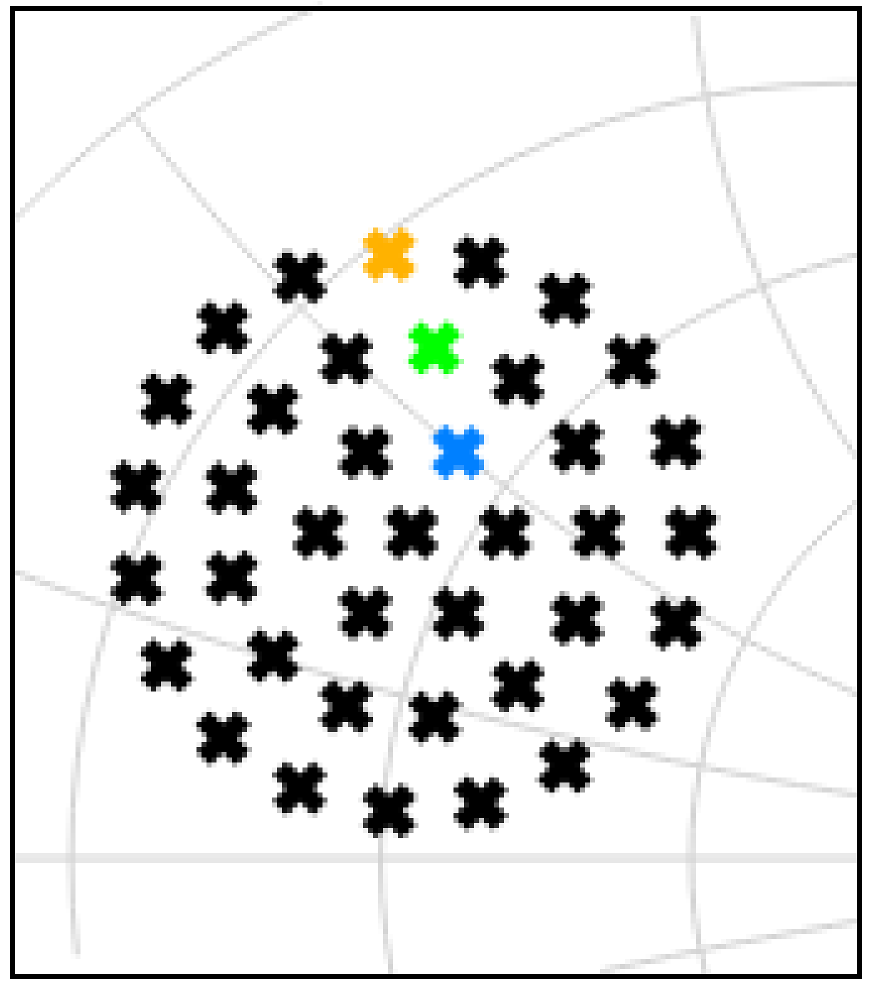
- *Pre-distortion calibration with the driving PA*

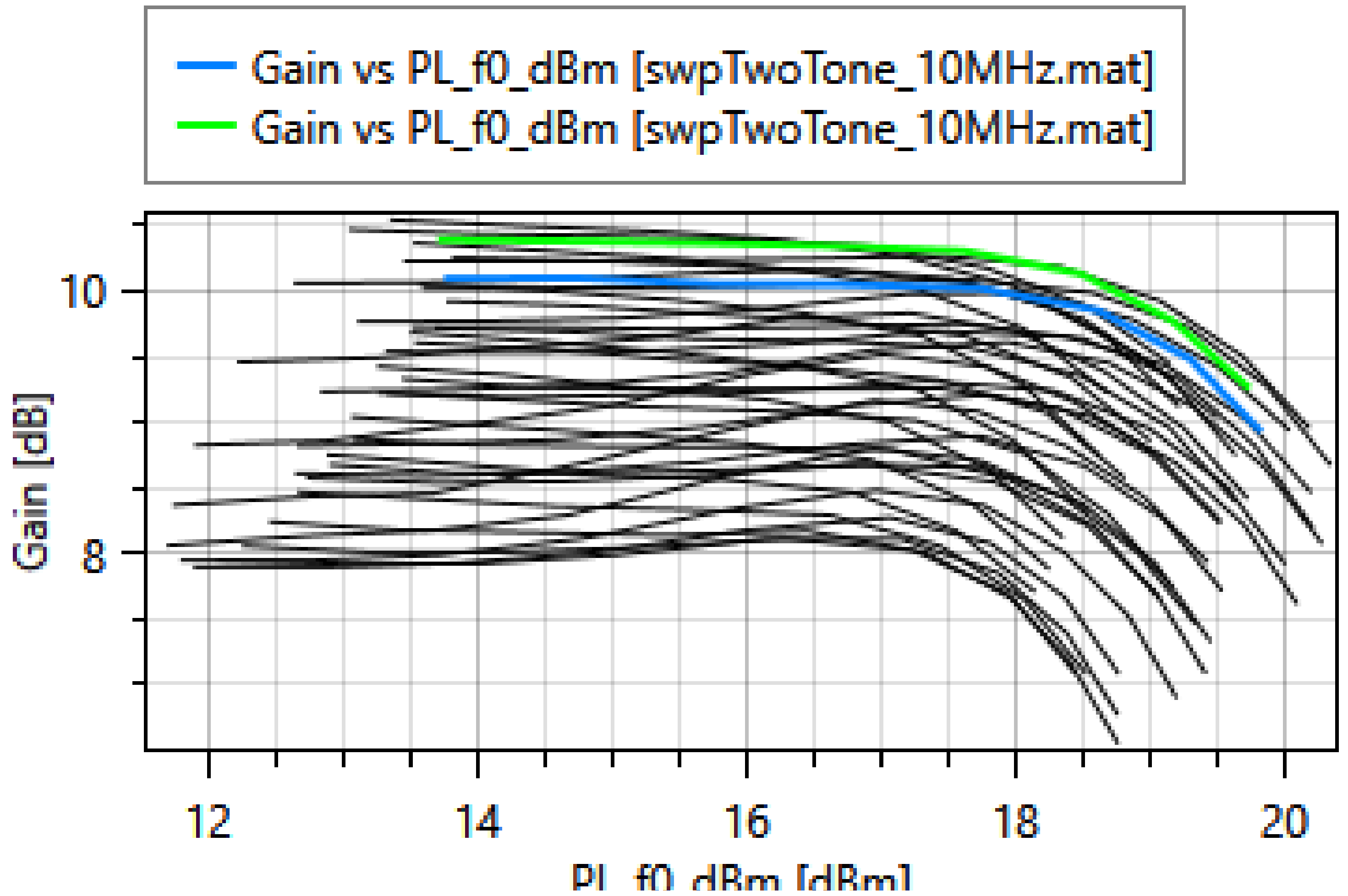
-> Improves the linearity of the system

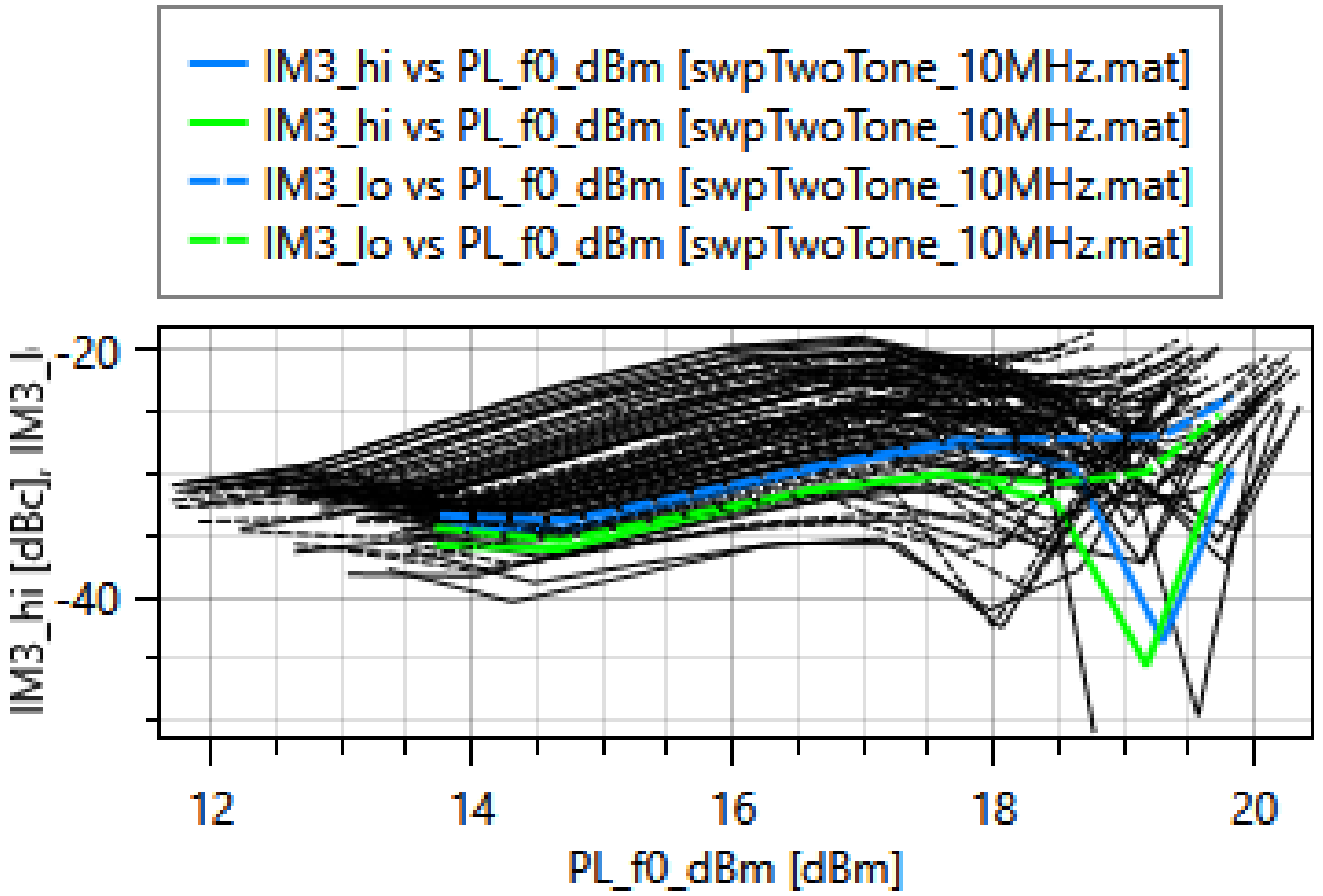
Measurement Example: Two-Tone Load Pull

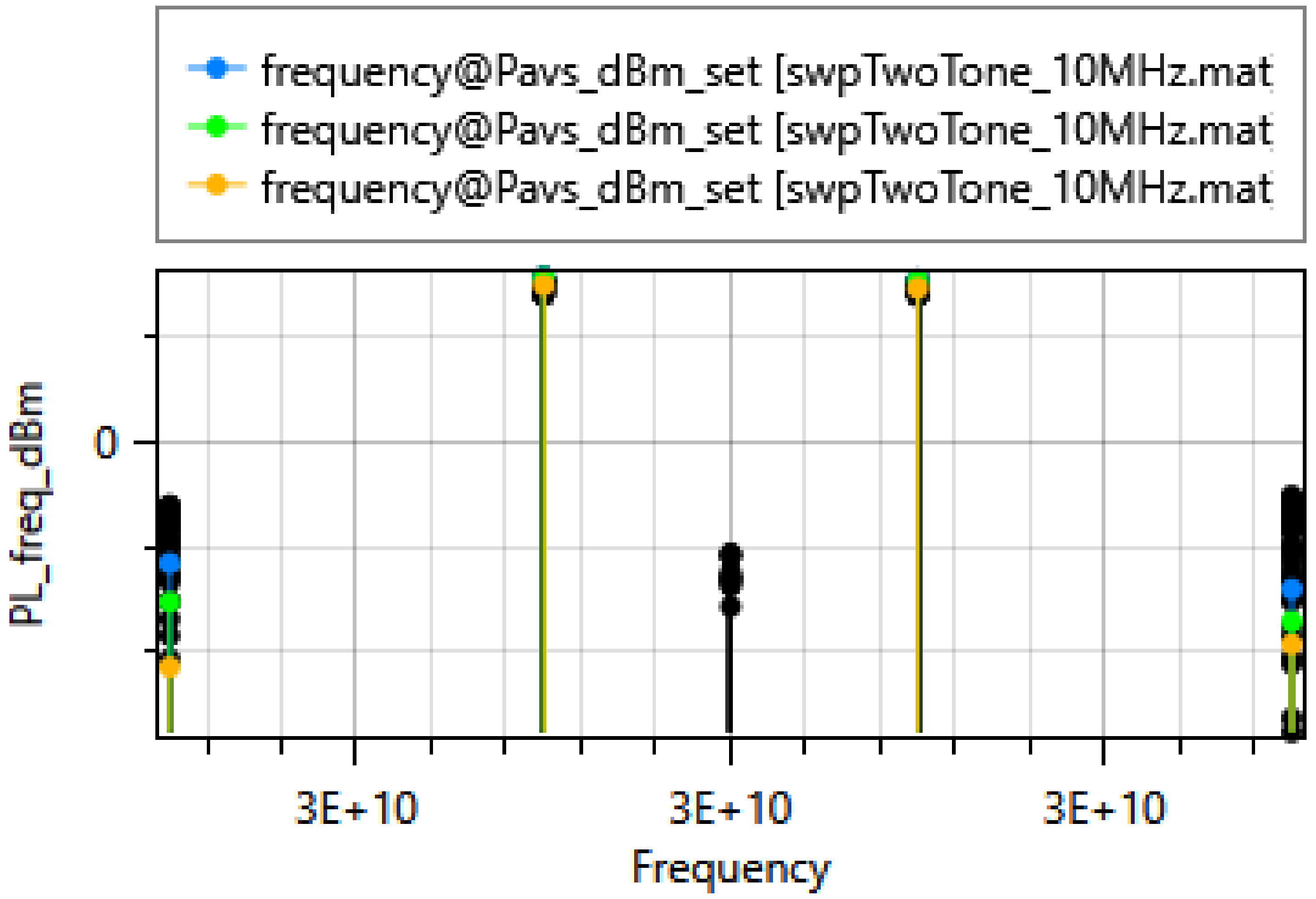


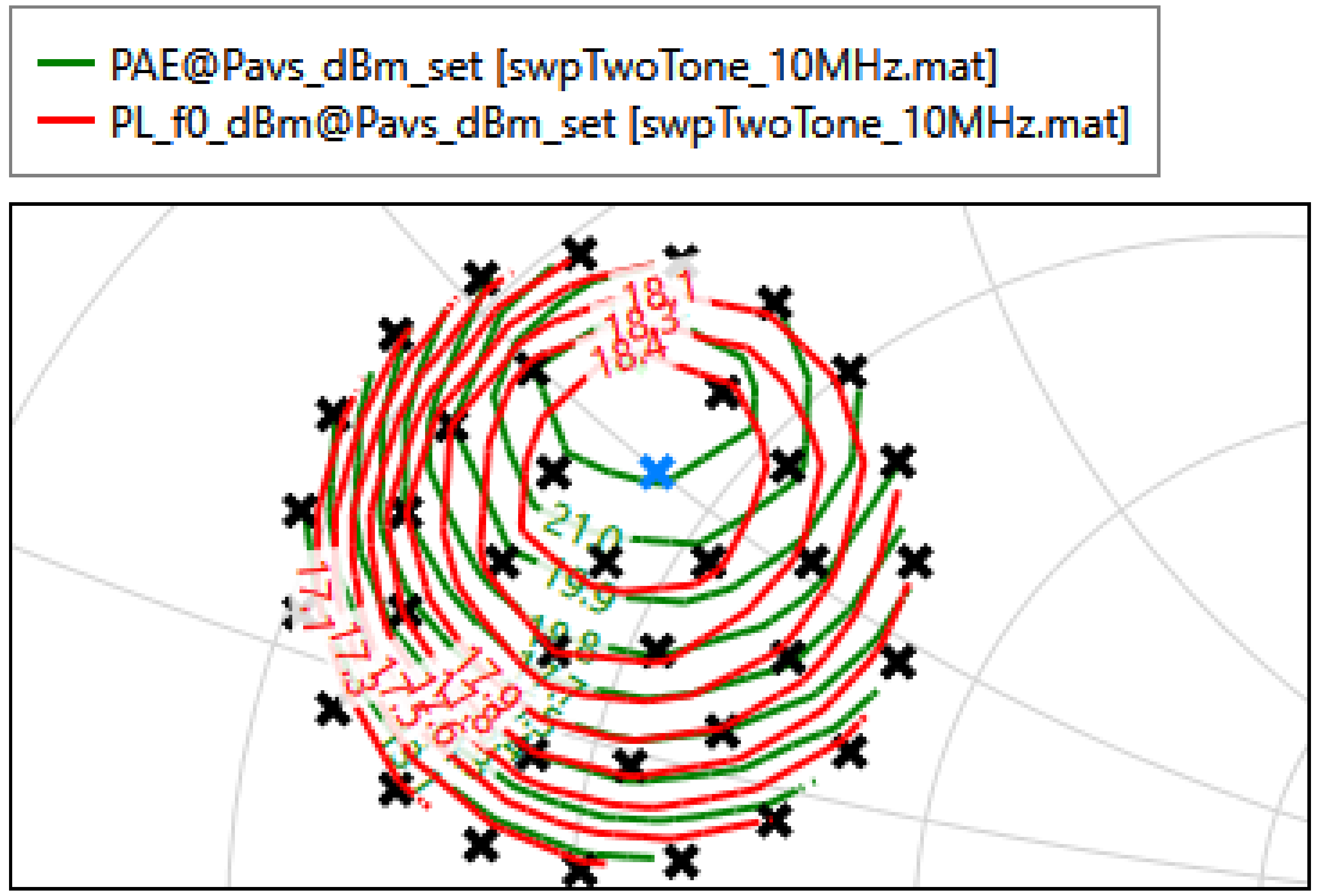
30GHz 2-tone measurement, tone space 10MHz

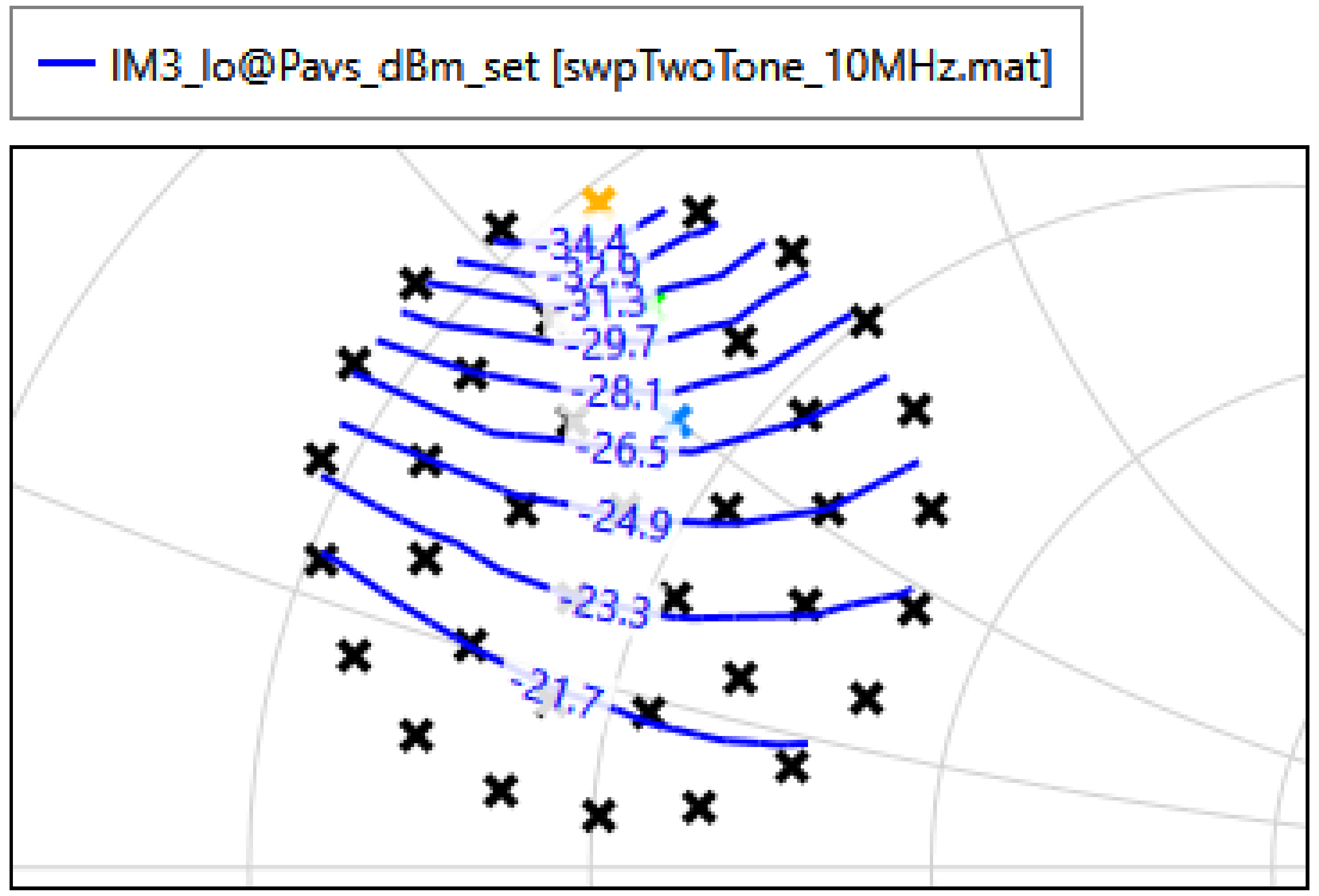












Summary of MT2000's advantages for 2 tones test

A brandy-new active architecture for 2 tones in semiconductor industry

- *Baseband signal generation including 2 tone*
- *Pre-distortion calibration algorithm for non-linearity minimization of external driving amplifier and even system*
- *Ultra-broadband tone spacing supported up to 166MHz*
- *Ultra-fast calibration and measurement speed*

Benchmark of MT2000 on same device

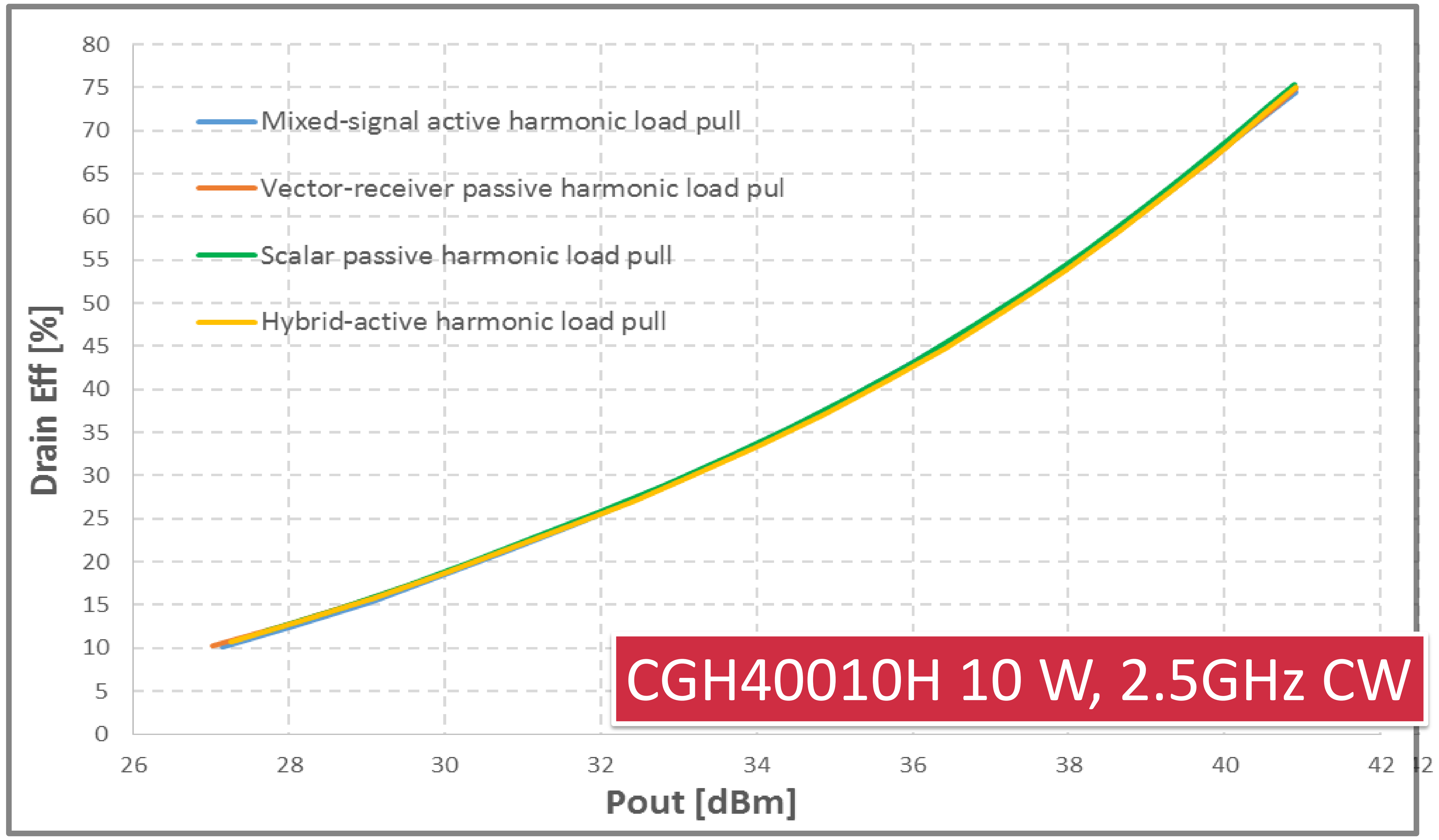


TABLE 1

COMPARISON OF LOAD-PULL MEASUREMENT TIME (MINUTES UNLESS STATED)

Setup	Tuner Cal	System Cal	Step 1 f_0 Load-Pull, Fixed $2f_0$ at 50 ohms (35 Loads, 16 Powers)	Step 2 $2f_0$ Load-Pull, fixed f_0 at Optimized Value (20 Loads, 16 Powers)	Step 3 f_0 Load-Pull, fixed $2f_0$ at Optimized Value (35 Loads, 16 Powers)
Scalar Harmonic (2 tuning elements)	22	3	11.1	6.4	11.1
Vector-Receiver Harmonic (2 tuning elements)	22	5	5.3	3.1	5.3
Hybrid-Active Harmonic (1 tuning element)	11	5	4.2	7.3	7.5
Mixed-Signal Active (0 tuning elements)	No Tuner	5	15 seconds	35 seconds	50 seconds

Beyond active loadpull

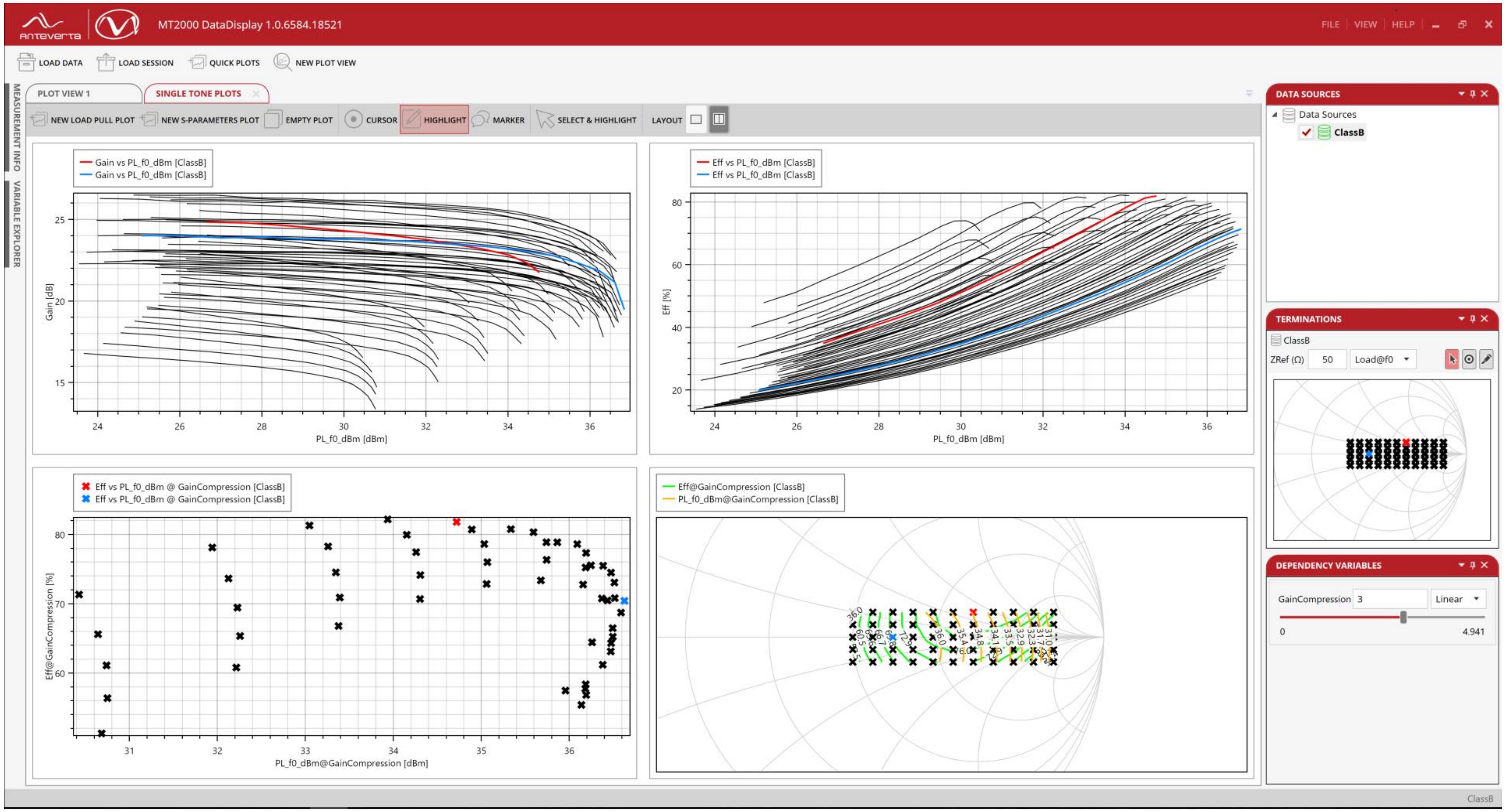
Measurement Example: High-Speed F0 Load Pull

CW signal at 2 GHz
55 F0 impedances

** Every impedance is accurate within -40 dB because of software convergence iterations*

16 power levels
880 measurement states
Total time: **3 minutes**

a-waves and b-waves measured from which we calculate Pout, Pin, Pavs, Eff, PAE, Vin, Vout, Iin, Iout



Measurement Example: 2F0+3F0 Load Pull

CW signal at 2 GHz
16 2F0 impedances
16 3F0 impedances

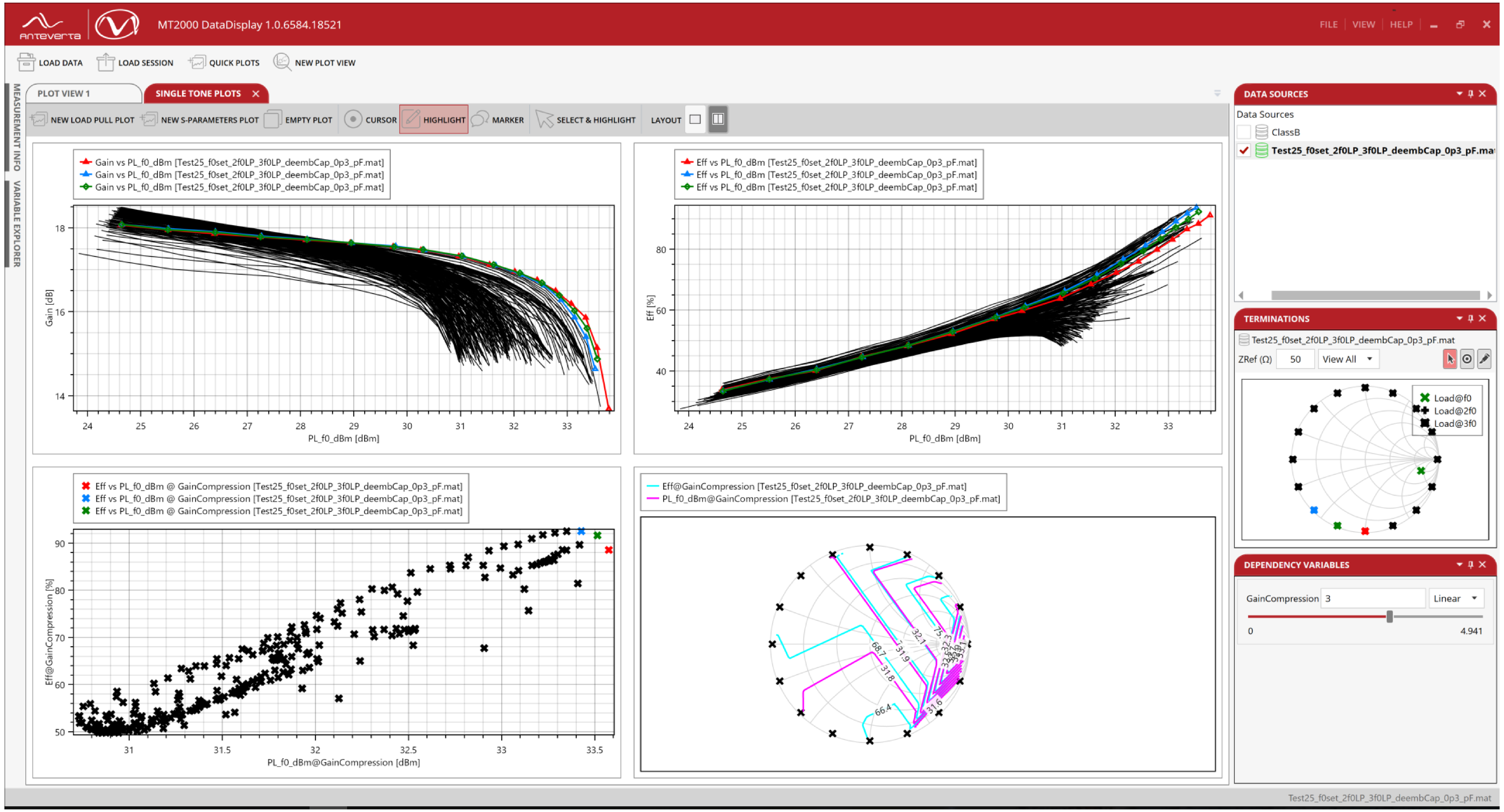
** Every impedance is accurate within -40 dB because of software convergence iterations*

17 power levels

4352 measurement states

Total time: **15 minutes**

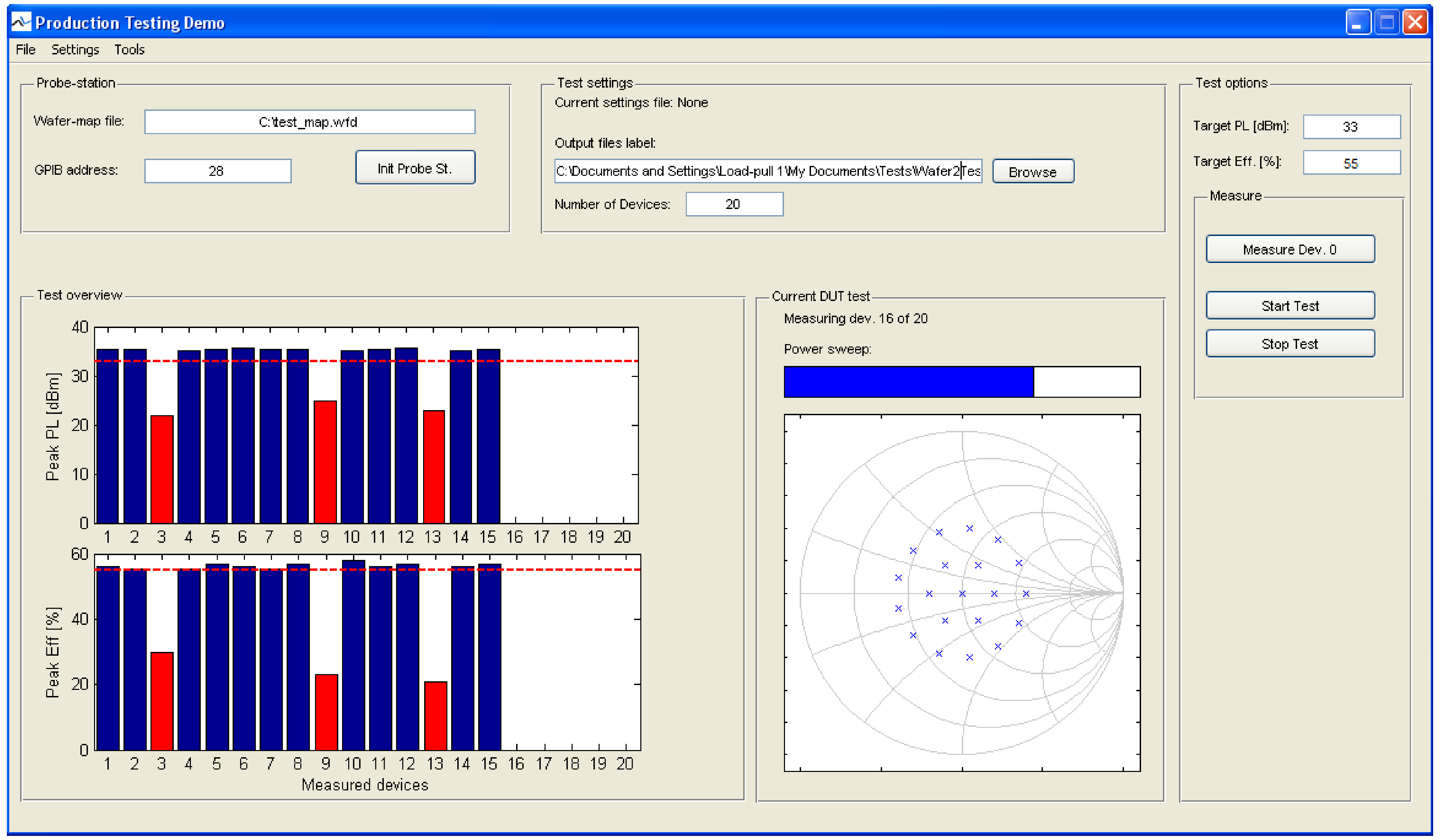
a-waves and b-waves measured from which we calculate Pout, Pin, Pavs, Eff, PAE, Vin, Vout, Iin, Iout

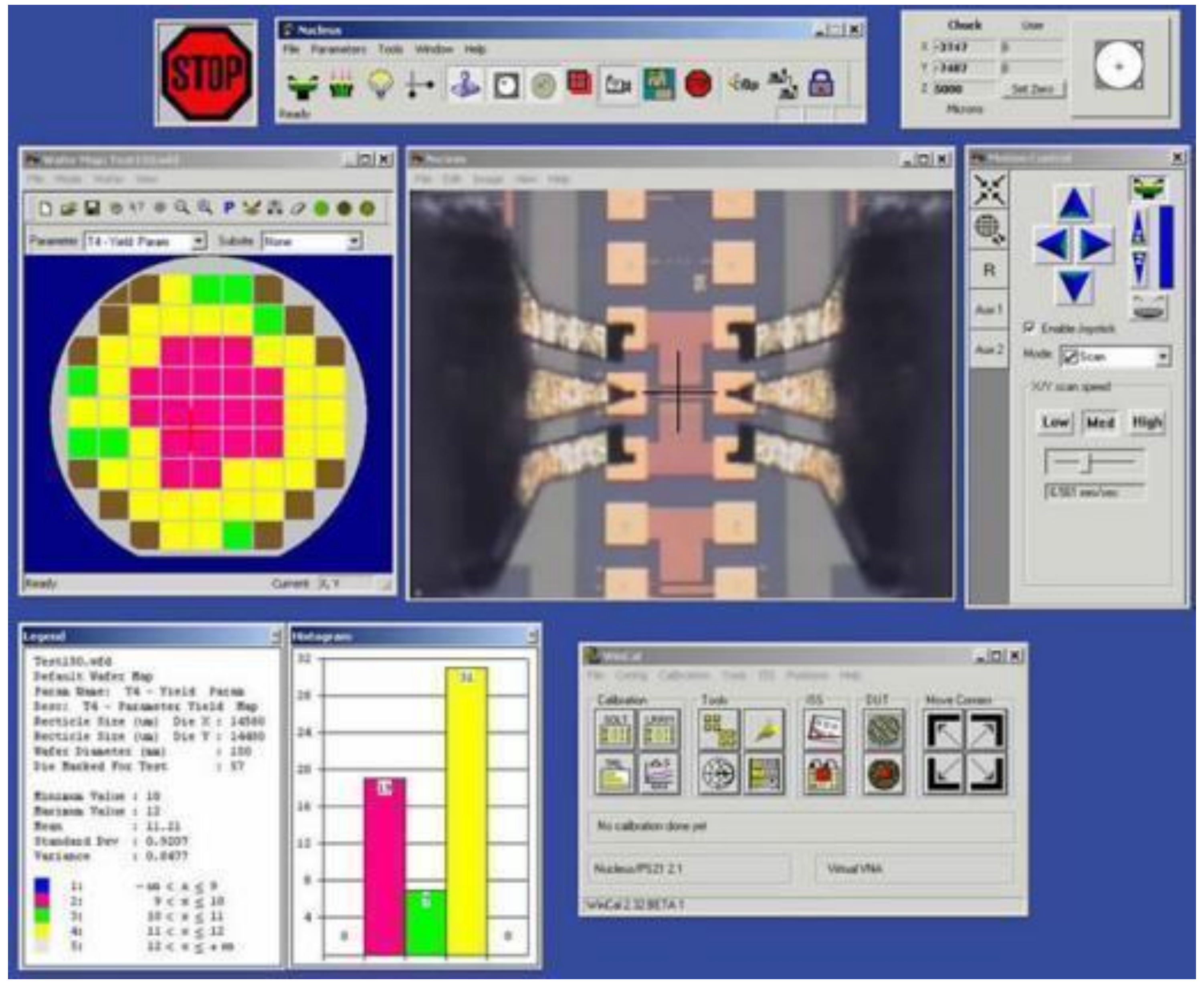


Application Example: On-Wafer Production Test

High-speed load pull measurements optimized for on-wafer production test (check every device at the wafer level before dicing)

0.4 seconds per load pull for 50 points on Smith Chart at one power level, 1.4 seconds per load pull at 20 power levels





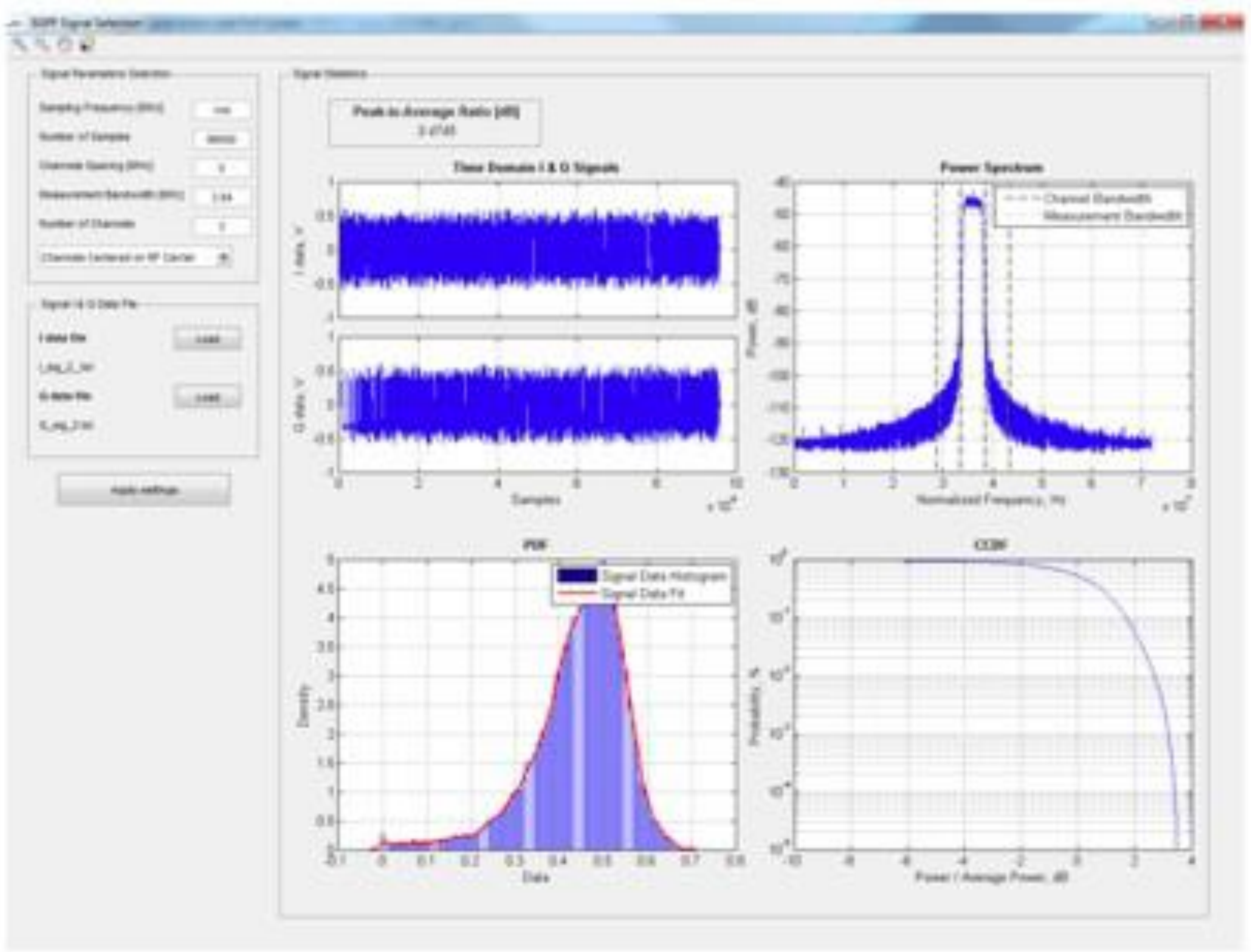
http://www.youtube.com/watch?v=NFFGW34tjYM&feature=youtu.be

Multi-Tone and Modulated Load Pull

For multi-tone and modulated load pull, each tone of the wideband baseband signal constitutes a portion of an RF wideband signal. Therefore the entire wideband baseband signal is required to set a single impedance at a single power.

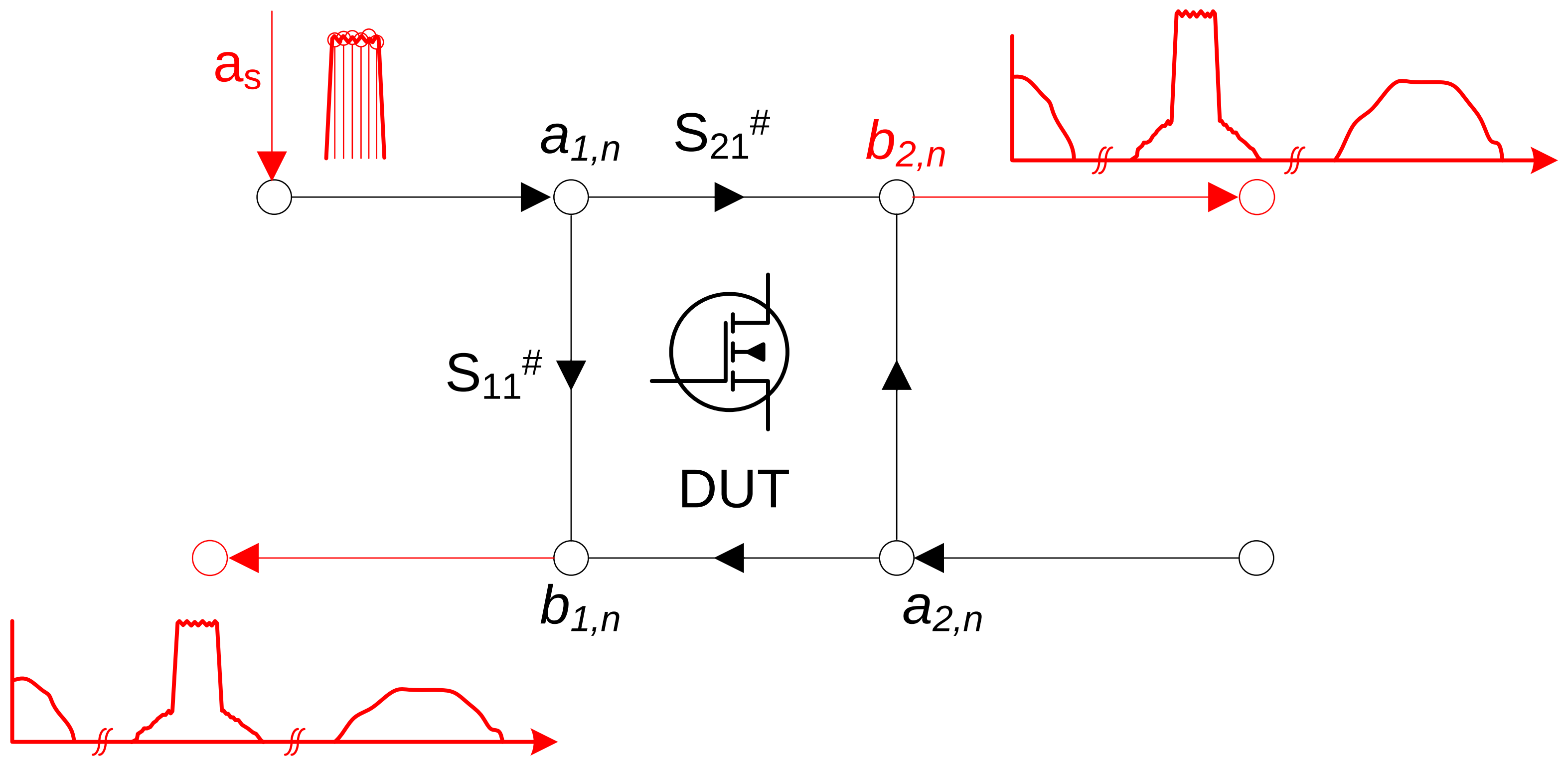
- Step 1: specify the list of impedances and powers at the DUT reference plane
- Step 2: calculate the baseband waveform required to present each impedance and power
- Step 3: set the wideband baseband signal and measure RF signal at DUT reference plane
- Step 4: correct baseband signal as required

Note: impedance can be fundamental and/or harmonic, two-tone or modulated

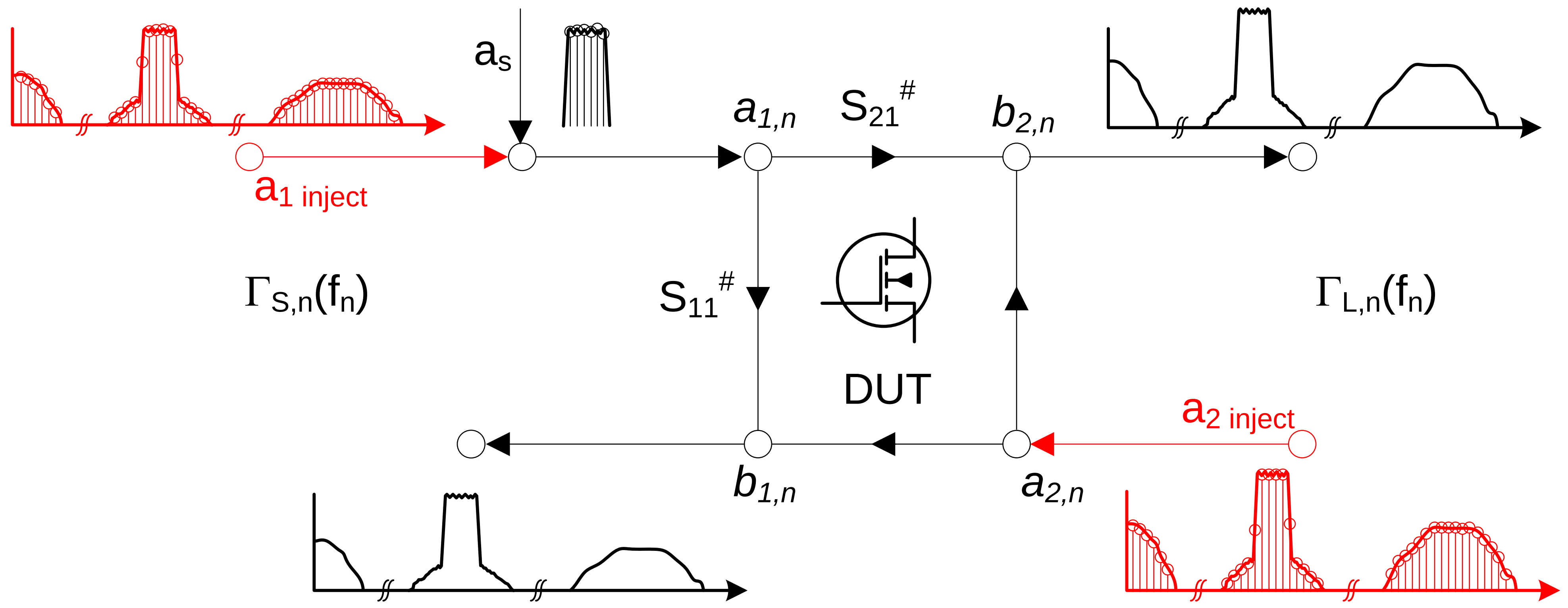


Modulated waveform for realistic wideband signal

MT1000/MT2000 Basic Load Pull Algorithm



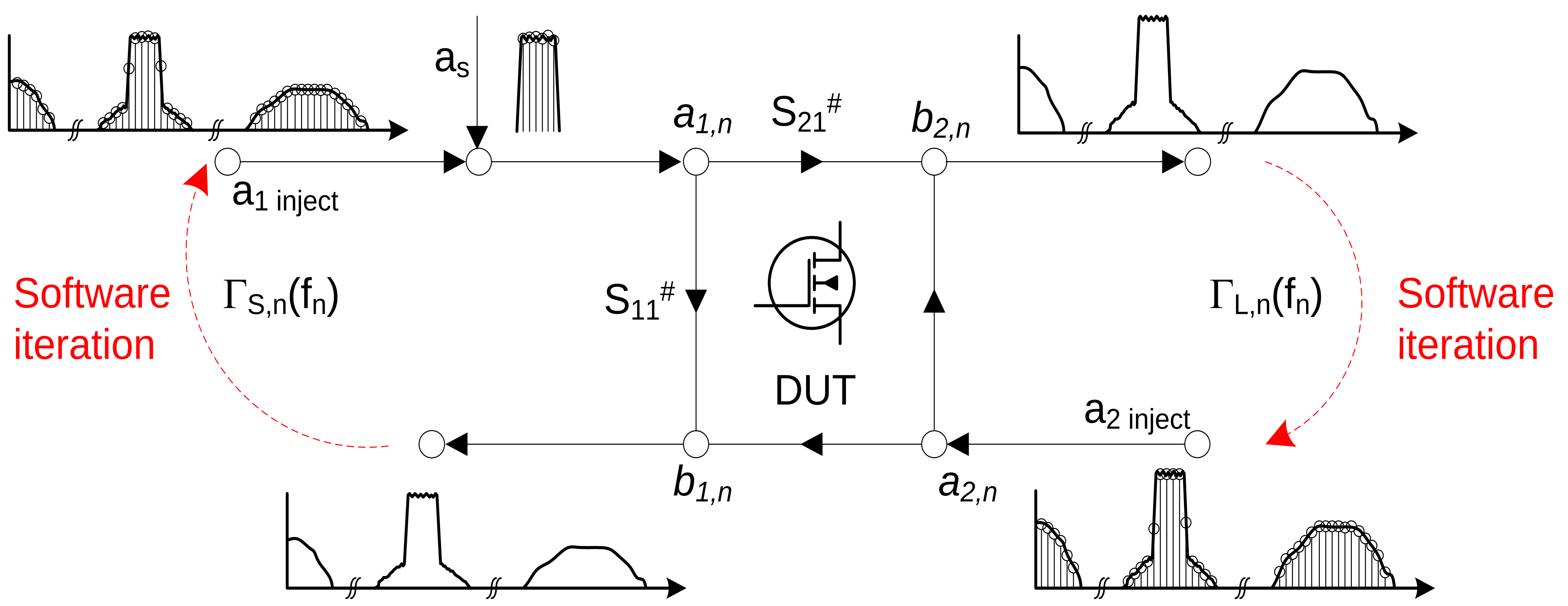
Step 1: *A non-linear device excited with a modulated signal will emanate waves (b-waves) at the harmonic and baseband frequencies*



Step 2: *By measuring the b-waves scattered by the DUT, the a-waves to be injected to obtain a user-specified reflection coefficient can be estimated.*

$$a_{x,n}(f_n) = b_{x,n}(f_n) \cdot \Gamma_{x,n}(f_n)$$

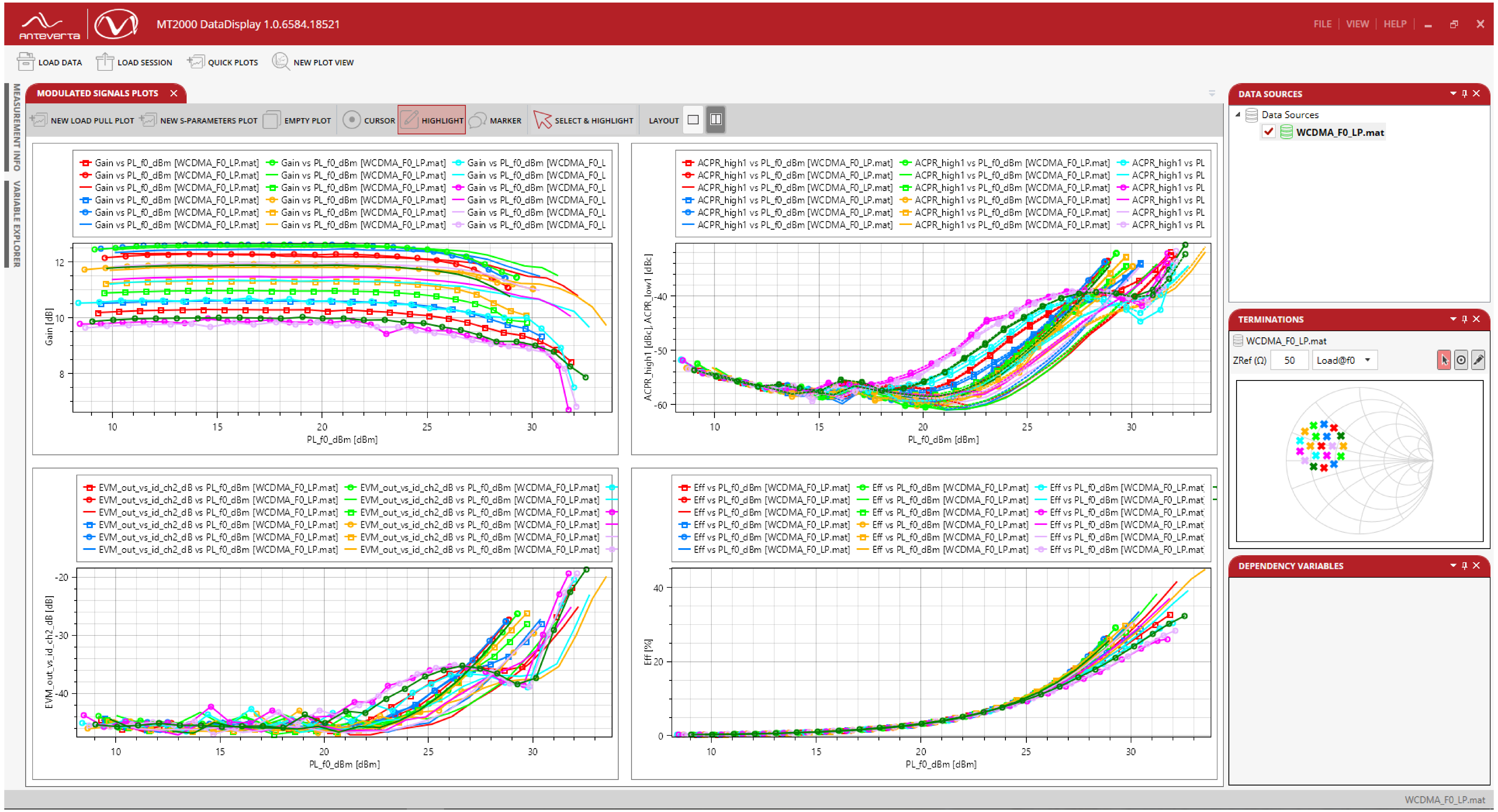
x = source (s) or load (l)
n = frequency band, e.g. baseband (0), fundamental (1) and harmonic (2 and up)
$\Gamma_{x,n}(f_n)$ = user defined reflection coefficient vs. frequency



Step 3: *Software iteration based on the reflection coefficient measurements at the DUT reference planes*

Measurement Example: Modulated Load Pull

- *Impedance vs frequency across bandwidth are balanced so that 99% of the total signal power converges to within -40 dB at the DUT reference plane*
- *Pout, Pin Pavs are measured at every tone at fundamental and harmonics (up to the frequency band of the MT2000)*
- *Eff, PAE, ACPR and EVM are calculated automatically*



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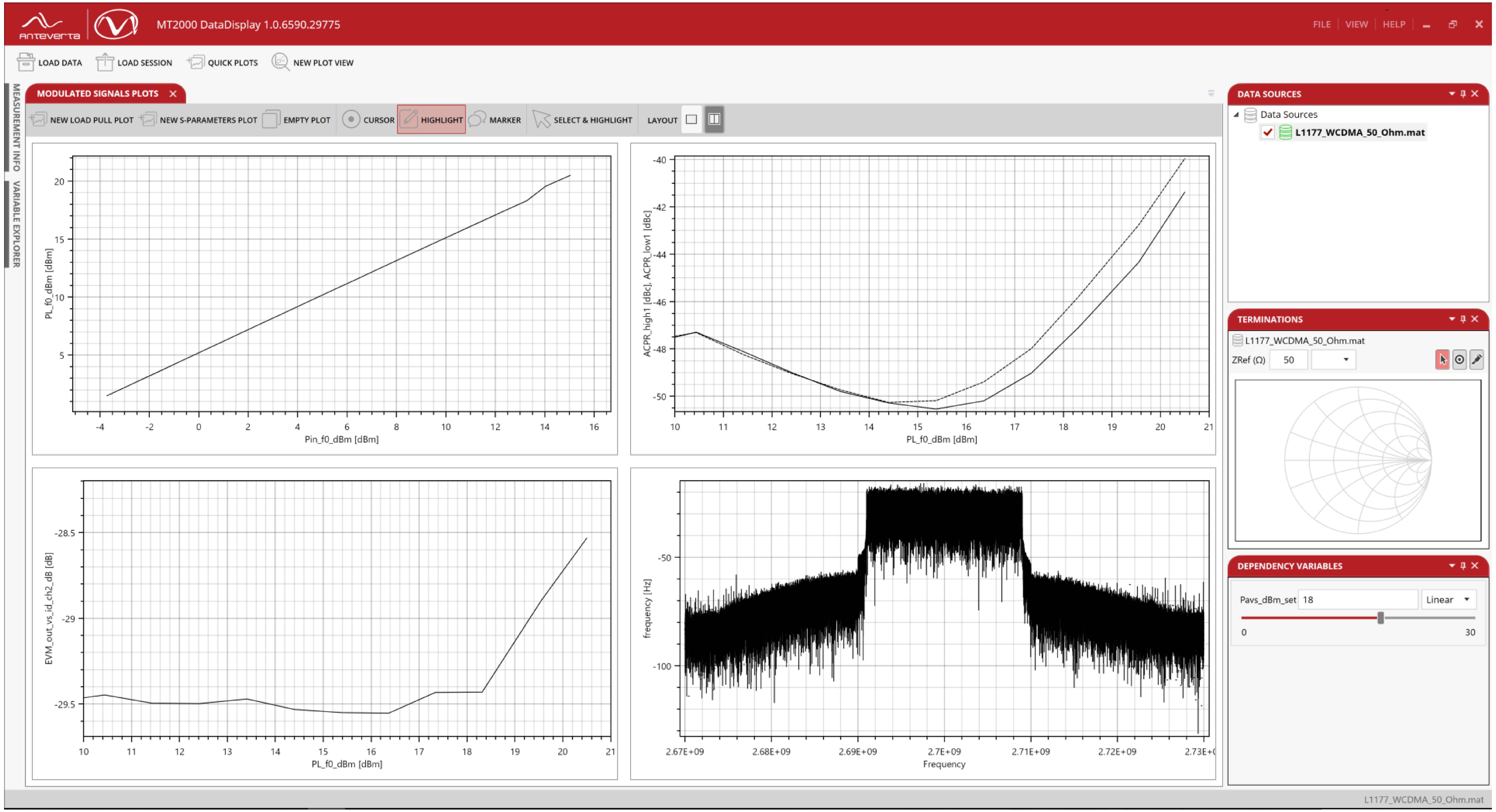
Vector Signal Generator/Analyzer Combination Capable of Measuring ACPR and EVM

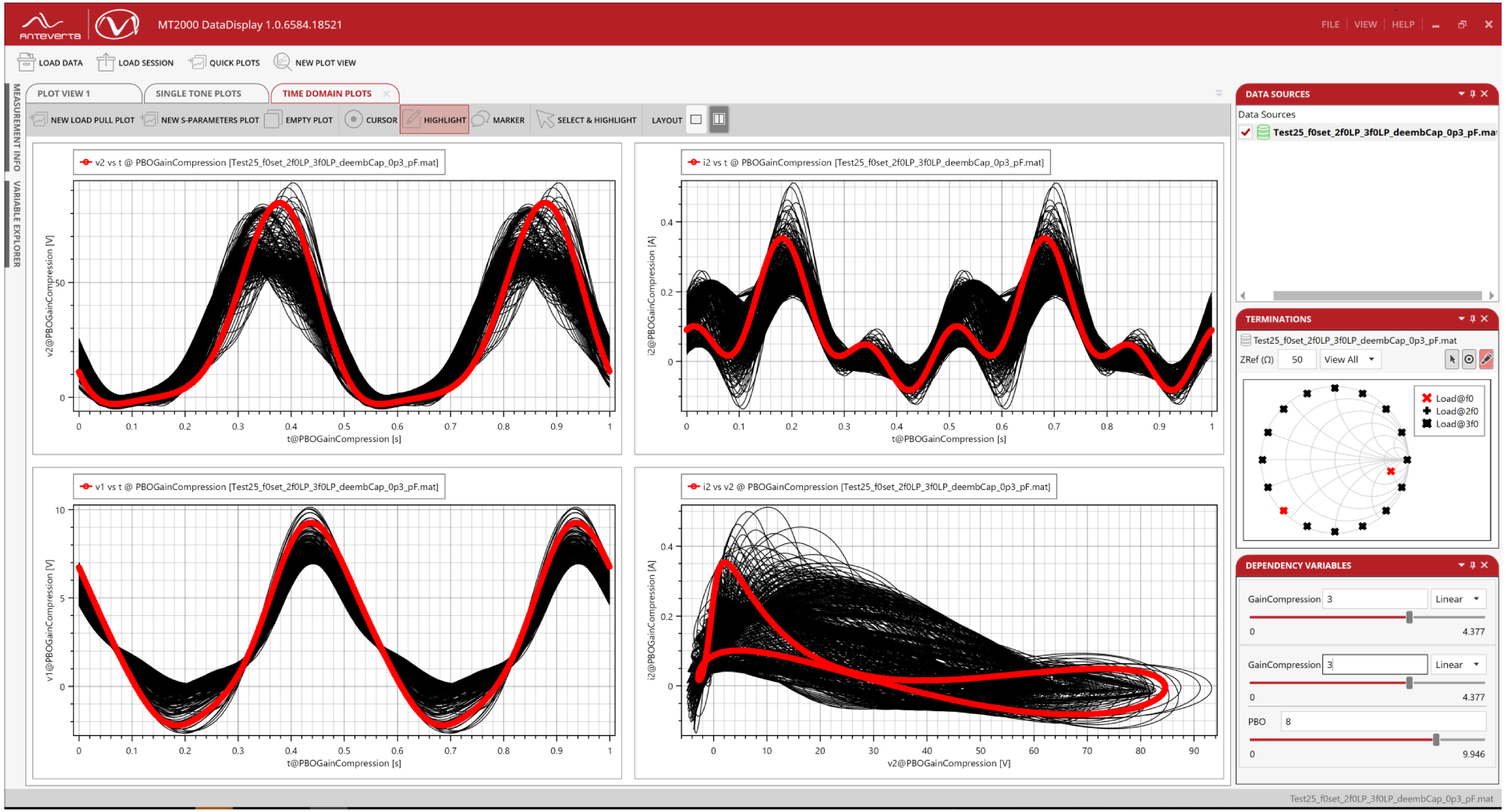


Minimum requirements: 2-loop MT2000 with MT2001A,B software

Min measurable ACPR (LTE): -55dBc
Min measurable EVM: -40dBc
Typical values, influenced by signal, bandwidth, power level…

Measurement Example: NVNA Load Pull, loadline

- *Time-domain waveforms and load lines can be measured by adding a phase calibration step*
- *MT1000/MT2000 has integrated tone generator which acts as a harmonic phase reference*
- *NVNA measurements do not add any additional time to load pull measurements*



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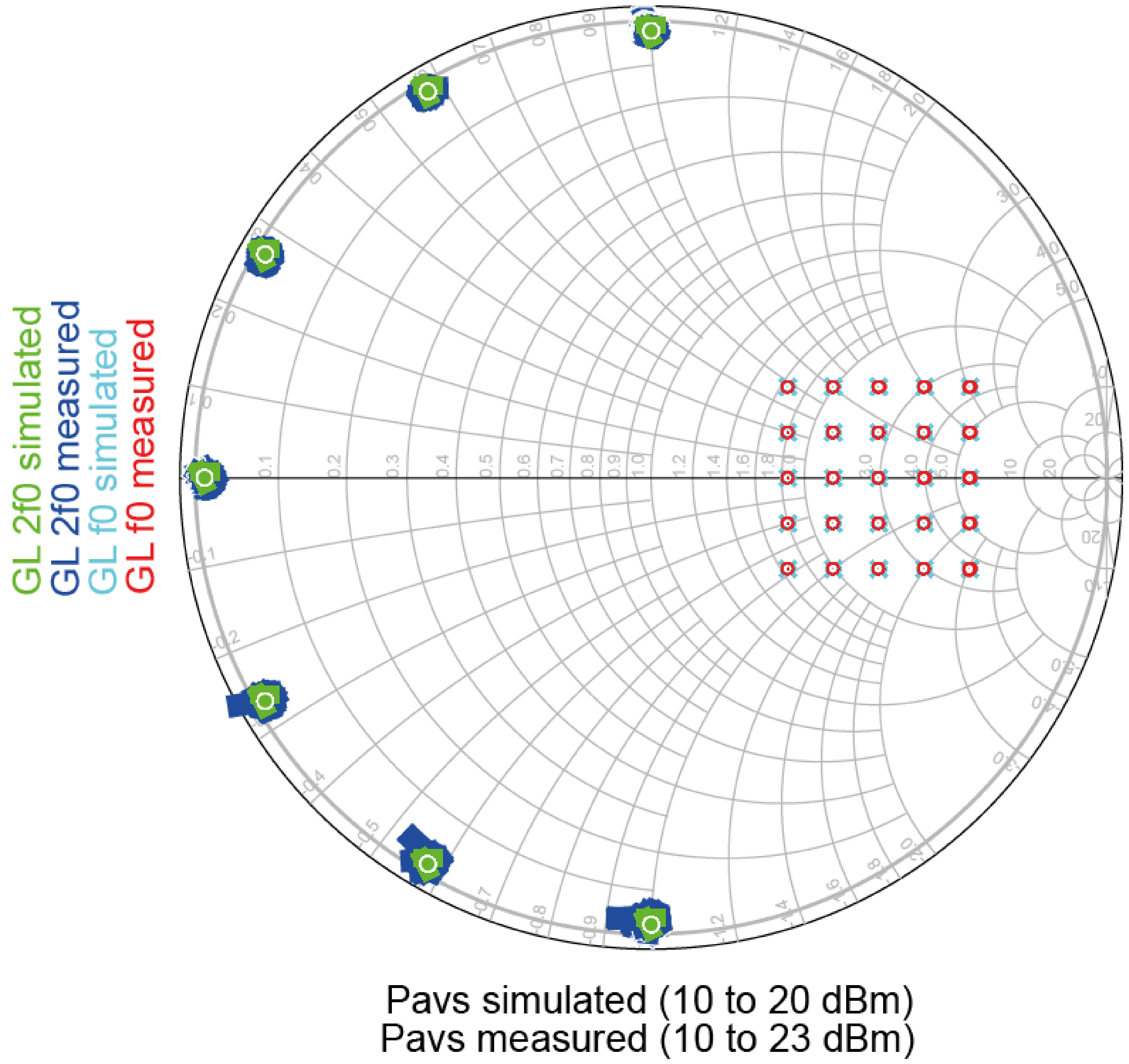
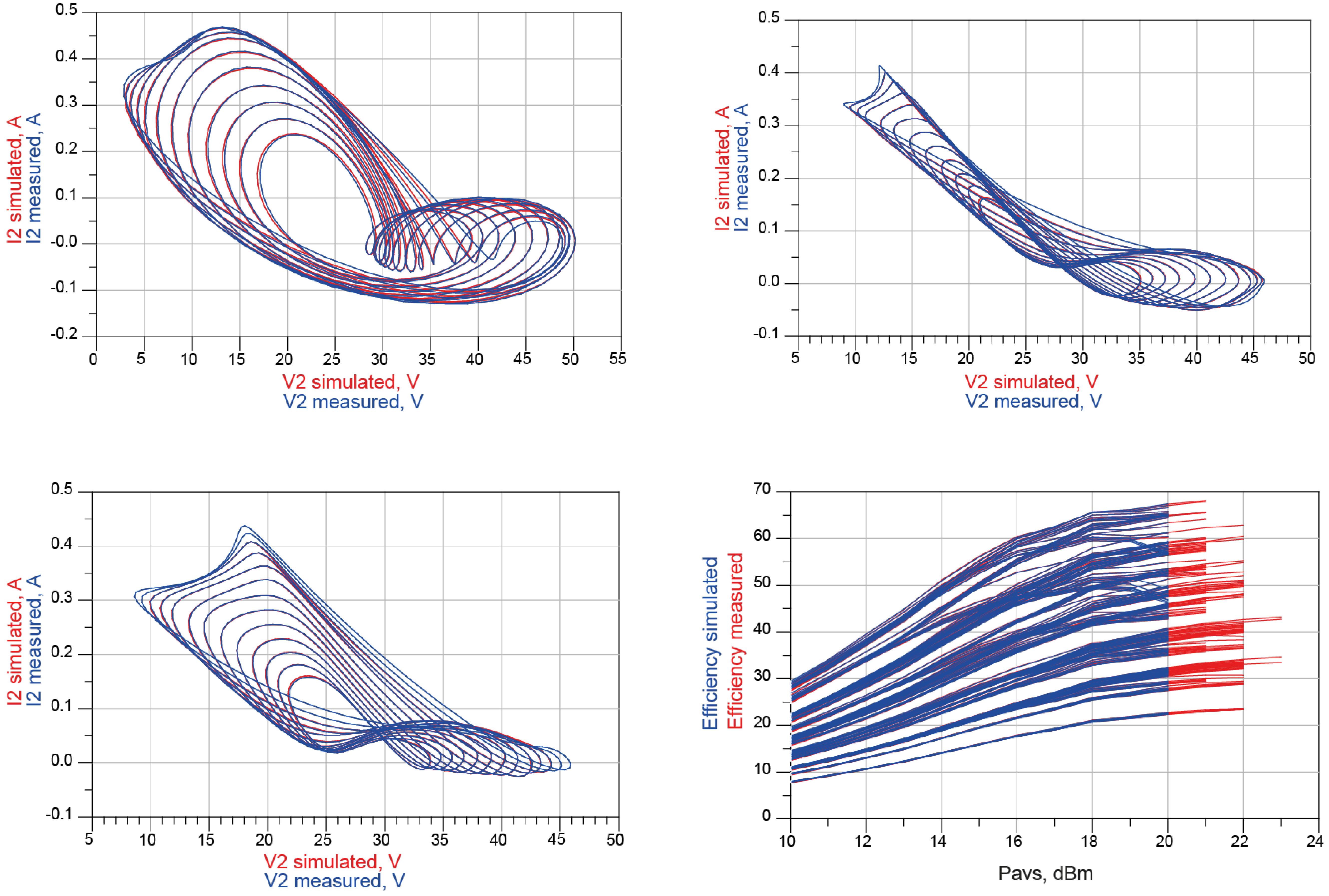
Behavioral Model Extraction Tool Capable of Black-Box and Database Modeling

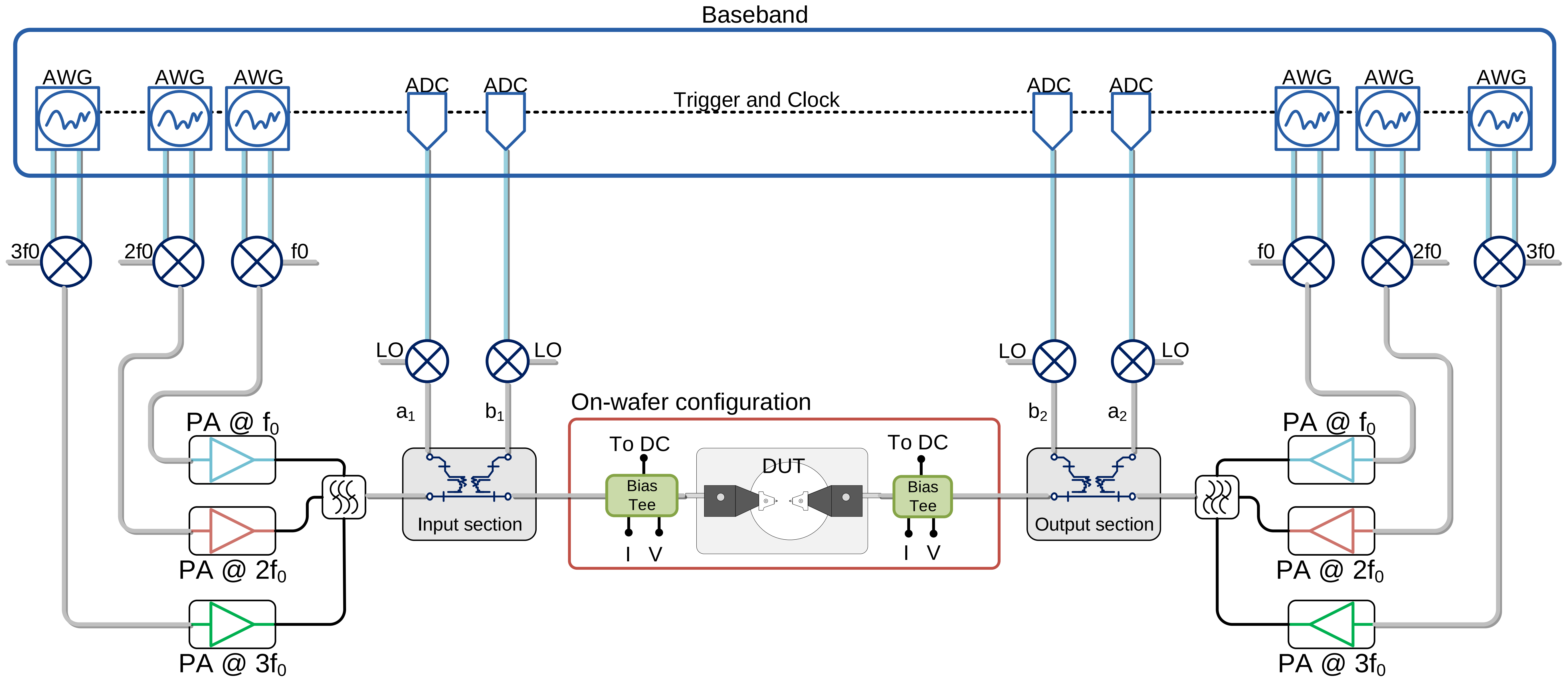




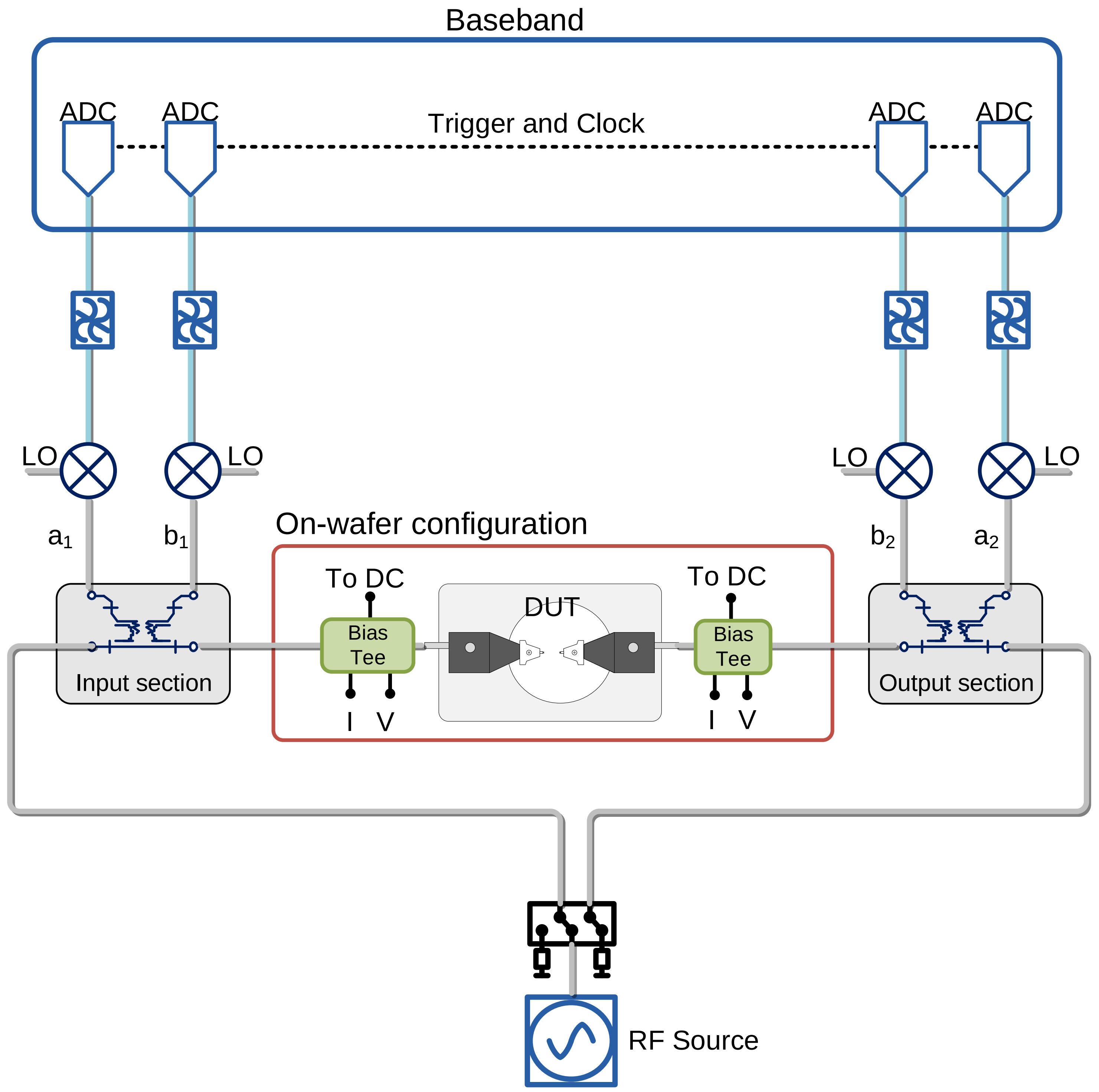
Red = measured   Blue = model simulation

Minimum requirements: 2-loop MT1000 or MT2000 with MT2001A,D software

MT1000/MT2000 Architecture



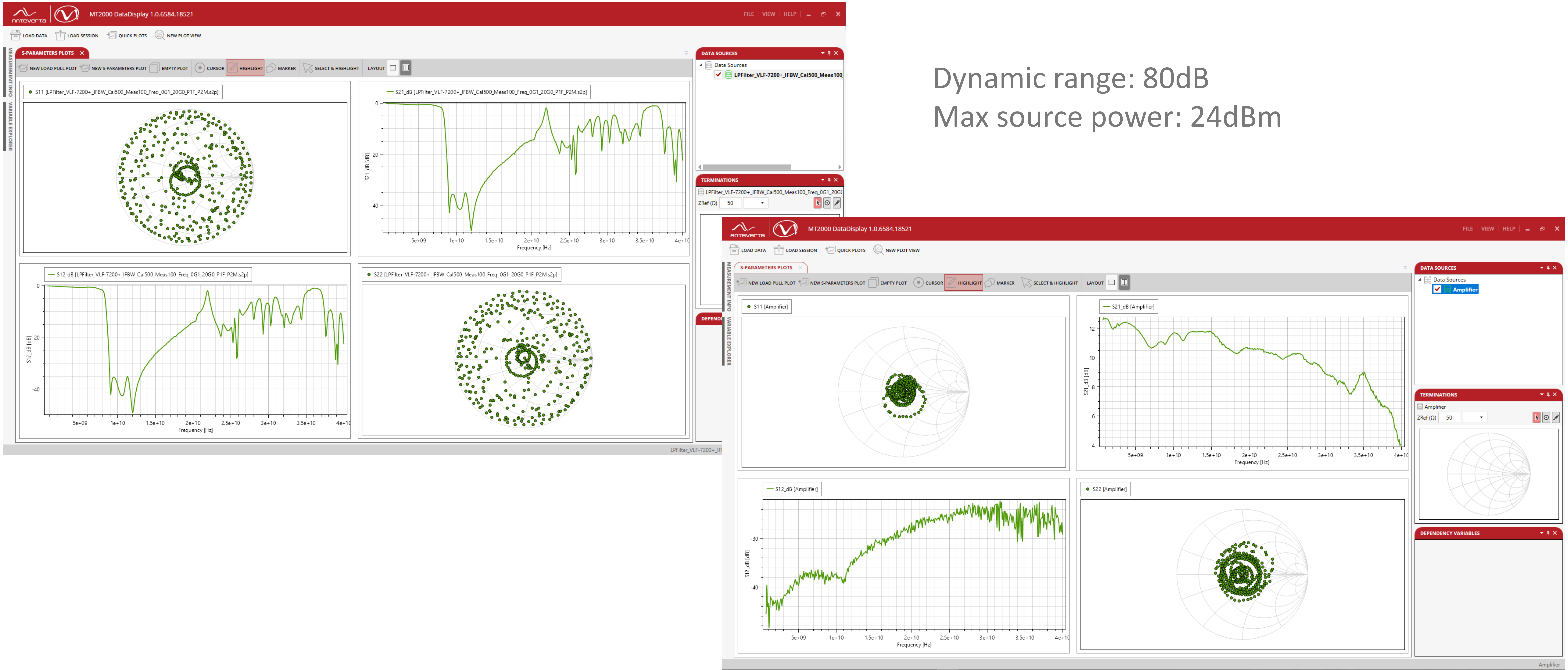
MT1000/MT2000 Architecture



Standard VNA Architecture

- *Similar basic receiver architecture*
- *VNA uses narrowband filtering; MT2000 does not use narrowband filtering in order to allow wideband modulation acquisition*
- *VNA uses single CW source; MT2000 uses multiple vector signal generators (AWGs)*

VNA Capable of Measuring CW and Pulsed-CW S-Parameters



Dynamic range: 80dB
Max source power: 24dBm

Minimum requirements: 2-loop MT1000 or MT2000 with MT2001A software

Introduction (recap)

In 2010, the MT1000/MT2000 technology was launched as the fastest active load pull system in the world, and the only load pull system capable of controlling impedances over wide bandwidths for modulated measurements

The system architecture required to achieve these breakthrough measurements included the following capabilities:

- **VNA capable of measuring CW and pulsed-CW S-parameters**
- **NVNA capable of measuring time-domain waveforms and load lines**
- **Multi-tone signal generator/spectrum analyzer combination capable of measuring intermodulation products**
- **Vector signal generator/analyzer combination capable of measuring ACPR and EVM**
- **Oscilloscope capable of measuring voltages and currents**
- **Behavioral model extraction tool capable of black-box and database modeling**

While marketed as the world's most advanced load pull system, the MT1000/MT2000 can be used equally as well in 50Ω as in non-50Ω

References

Most MT1000/MT2000 customers have signed NDAs, however several have published IEEE papers and others have agreed to be contacted as references

GeMiC 2014 • March 10-12, 2014, Aachen, Germany

1569864695 1

Source/Load Pull Investigation of AlGaN/GaN Power Transistors with Ultra-High Efficiency

V. Carrubba, R. Quay, S. Maroldt, M. Mußer, F. van Raay, and O. Ambacher
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vincenzo.carrubba@iaf.fraunhofer.de

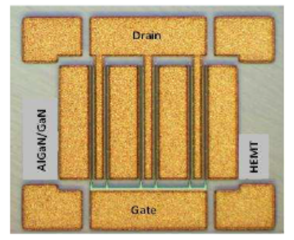

Fig. 1. Microscope photograph of the IAF 1.2 mm AlGaN/GaN HEMT power transistor.

ISBN 978-3-8007-3585-3

Improvements in High Power LDMOS Amplifier Efficiency Realized Through the Application of Mixed-Signal Active Loadpull

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DESIGN OF AN ULTRA-EFFICIENT GAN HIGH POWER AMPLIFIER FOR RADAR FRONT-ENDS USING ACTIVE HARMONIC LOAD-PULL

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Design of an Ultra-High Efficiency GaN High-Power Amplifier for SAR Remote Sensing

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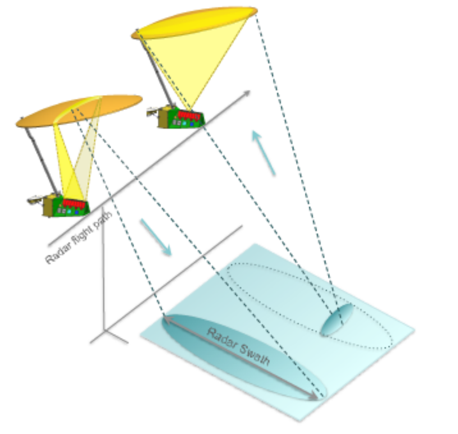


Figure 1. SweepSAR technique highlighting transmit and receive operation. Beamforming on transmit would produce a single large beam covering a wide-swath. Digital beamforming on receive would allow for multiple high resolution beams.

978-1-4673-1813-6/13/$31.00 ©2013 IEEE.

U.S. Patent No. 8,456,175 B2

Several international patents also available

System Offering

MT1000/MT2000 Hardware

Five Frequency Range are available:

- 0.001 – 2 GHz *(50W CW, 500W Pulsed)*
- 0.03 – 2 GHz *(50 CW, 500W Pulsed)*
- 0.3 – 6 GHz *(100W CW, 1000W Pulsed)*
- 0.2 – 18 GHz *(100W CW, 1000W Pulsed)*
- 0.7 – 40 GHz *(20W CW, 200W Pulsed)*

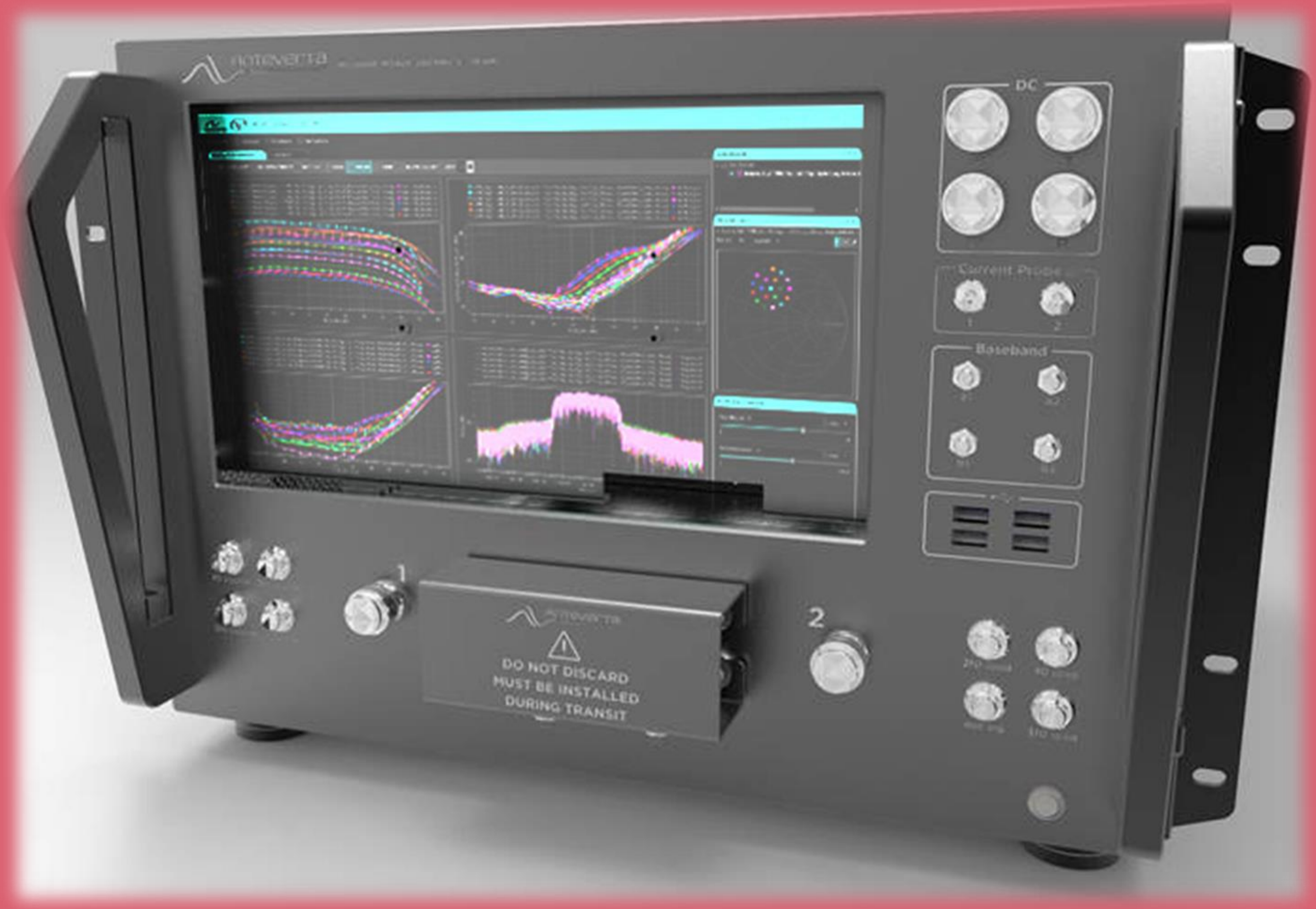
Five options of Active Tuning loops are available:

- 2 loops s*(f0 source/load pull)*
- 3 loops *(f0, 2fo source/load pull)*
- 4 loops *(f0, 2f0 and 3f0 source/load pull with 4 of 6 possible combinations)*
- 5 loops *(f0, 2f0 and 3f0 source/load pull with 5 of 6 possible combinations)*
- 6 loops *(f0, 2f0 and 3f0 source/load pull)*

*Three Modulation Bandwidth options are currently available (**MT2000 only**):*

- 100 MHz
- 200 MHz
- 500 MHz
- *2019 – 1 GHz*

*Note: **MT1000** series doesn't support two tones and modulated measurements*



Maury's MT1000/2000 works closely with commercial VNA, help complete device measurement perfectly with distinguished power together!

Thank You!

For more info. Pls. visit:

https://www.maurymw.com/MW_RF/Mixed_Signal_Active_Load_Pull_System.php

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