Broadband Measurements for Wireless Telecommunications

ARFTG Nonlinear Measurements Workshop

NIST USMS Roadmapping Workshop

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ARFTG Nonlinear Measurements Workshop

Fall ARFTG conferences since ARFTG 58 (2001)

Past topics include:

- Large-signal measurements
- Nonlinear device measurements
- Large-signal behavioral modeling
- Pulsed Measurements

This fall: Broadband Measurements for Wireless Telecommunication Systems

Feeds into NIST assessment of measurement infrastructure (USMS)

NIST Initiative on the U.S. Measurement System (USMS)

Methods, instruments, entities, institutions, and standards – both physical and documentary – involved in *measurements*

USMS stakeholders include…

- Customers / potential customers for, and providers of, measurement improvements/services
- Major associations representing many measurement customers, including international standards bodies
- Decision makers guiding priorities and resources

USMS Objective

NIST will:

- Lead an effort to document measurement and measurement-related barriers to technological innovation.
- Advocate solutions for identified needs, either from NIST or from other stakeholders, including international partners.

The USMS Assessment

- Working with stakeholders, NIST is preparing a high-level identification of critical measurement needs
- Each USMS workshop will result in a “Measurement Needs” datum in the assessment
- This assessment will be provided to Congress and the Administration in 2006

Questions to Answer

1. What phenomena do you need to observe and measure, but cannot do so?
2. What validated reference standards or facilities will be needed, but are currently unavailable?
3. What are your technological barriers to innovation?
4. What are the relevant economic impacts?
5. What actions do you recommend?

Why Broadband Wireless?

Premise: **"Test engineers need to provide the wireless industry with accurate methods to characterize distortion in broadband signals"**

Computer wireless cards

Handheld devices

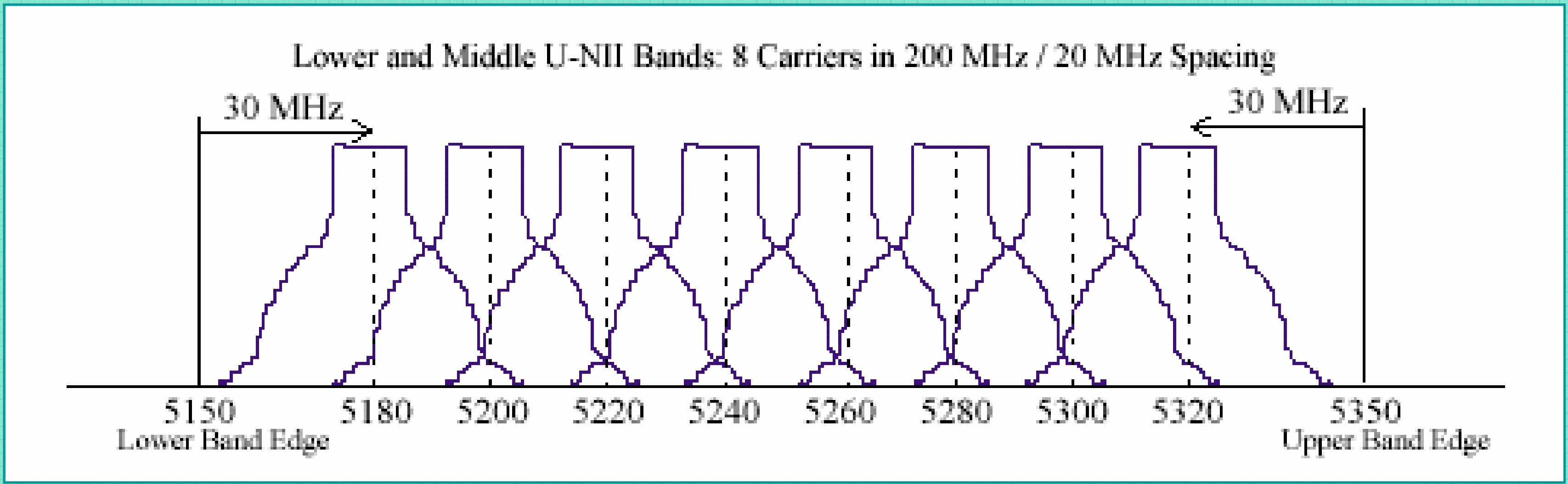
Access points and repeater nodes

Products represented in this talk are for illustrative purposes only. Such identification does not constitute endorsement by NIST. Other products may work as well or better.

Measuring Broadband Modulated Signals

Orthogonal Frequency-division Multiplexing (OFDM):

- WLAN 802.11a between 5.2 and 5.8 GHz
- Dedicated Short-Range Communications at 5.9 GHz
- Public-safety band at 4.9 GHz



- 52 subcarriers per channel
- 20 MHz channel spacing
- 4 or 8 channels per band

A real measurement challenge!

Wireless System Figures of Merit

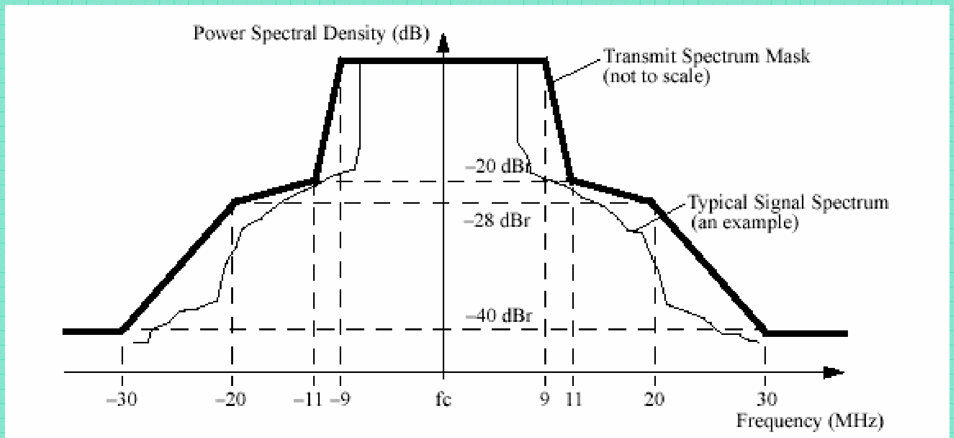
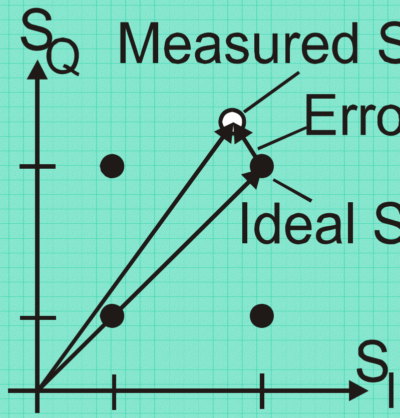


Figure 120—Transmit spectrum mask

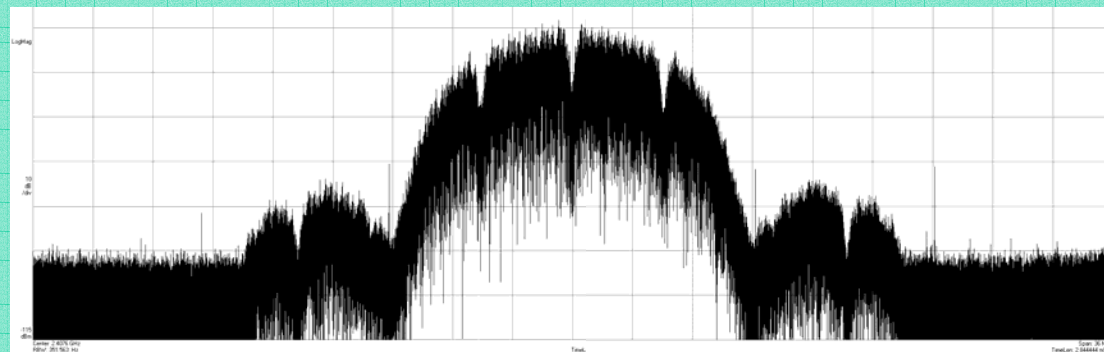
Adjacent channel power ratio (ACPR)

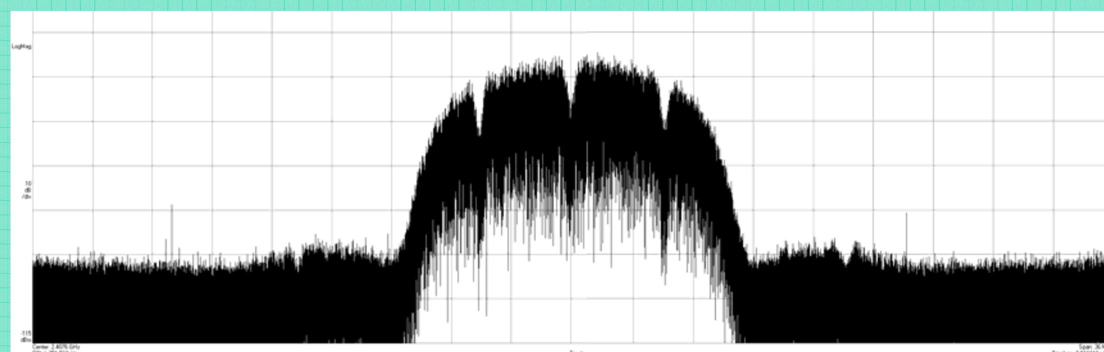


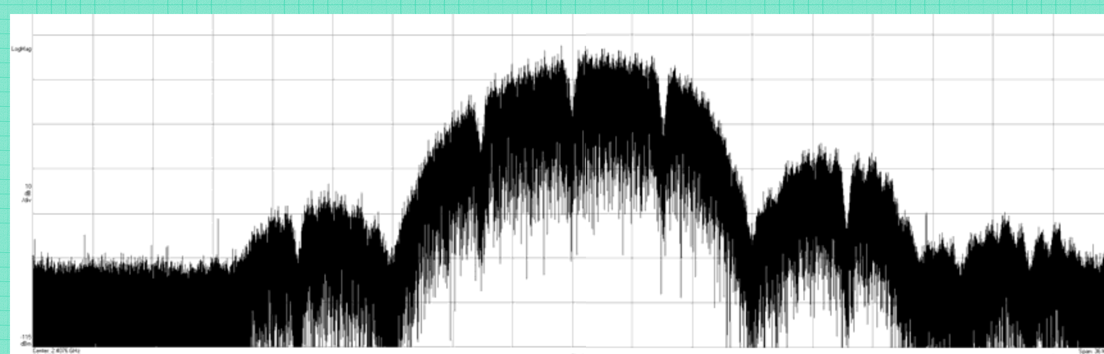
Error Vector Magnitude (EVM)

Wireless LAN Measurements

Three WLAN cards from three different manufacturers





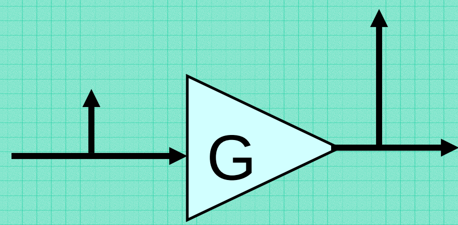


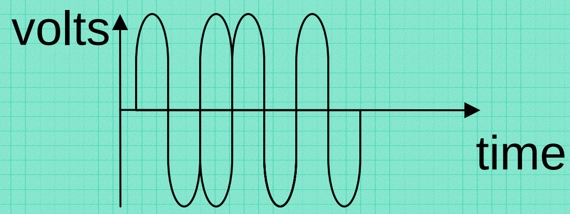
Note:

•sidebands

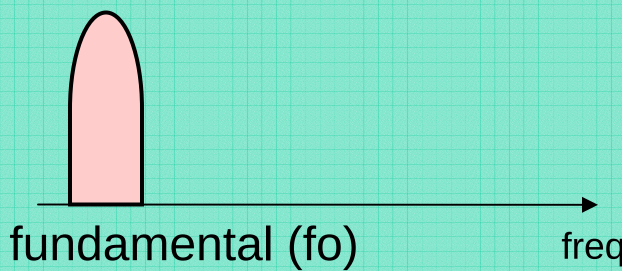
•passband

Amplifier: Linear Behavior

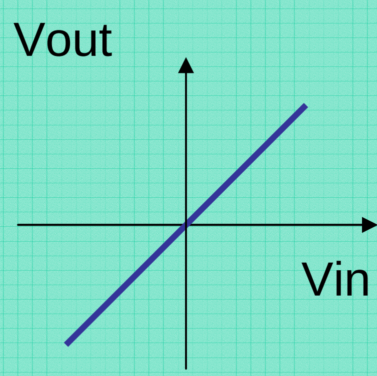




Time Domain



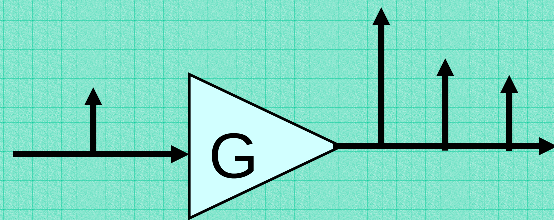
Frequency Domain

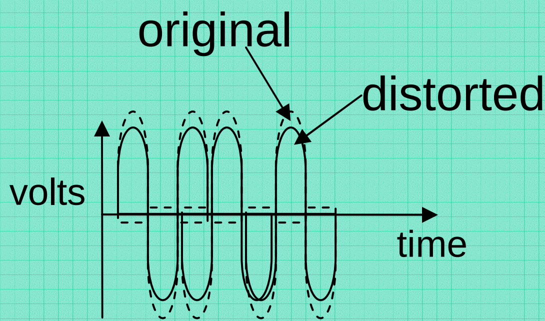


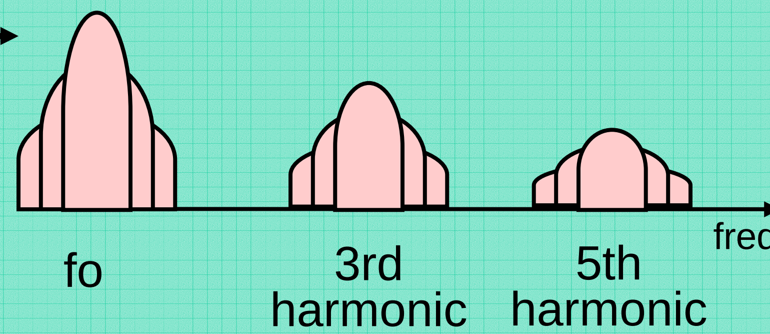
Amplifier Response

Output proportional to input for low input power

Amplifier: Nonlinear Behavior





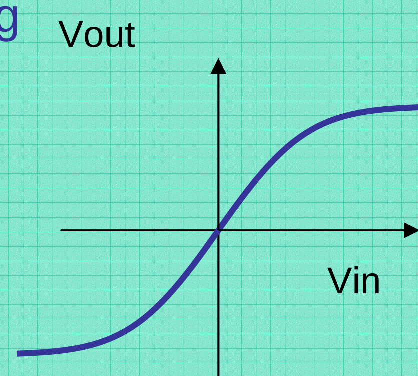


Time Domain:

- Compression and/or Limiting

Frequency Domain:

- Harmonic generation
- Intermodulation Distortion



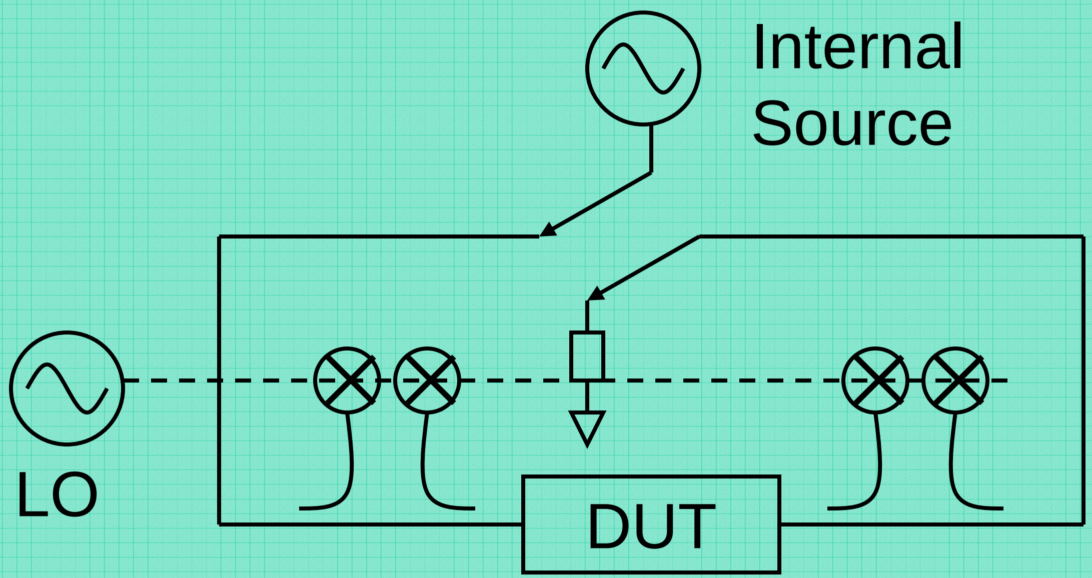
Harmonics and in-band distortion generated

Amplifier Response:

- Compression

Vector Network Analyzer

Good for linear circuits, small-signal measurements



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- Test set calibration
- Two-port measurement
- High dynamic range

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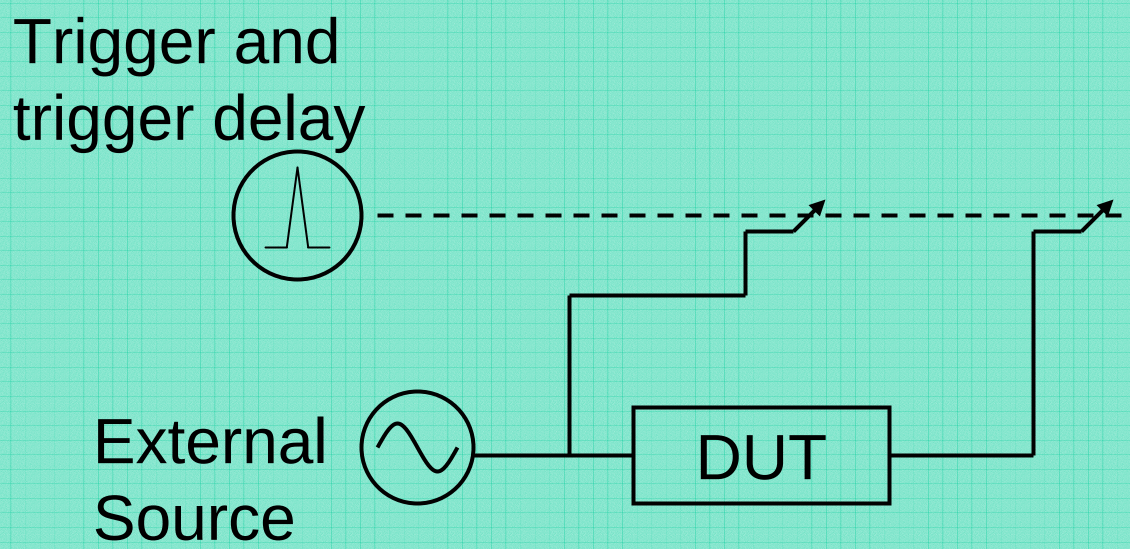
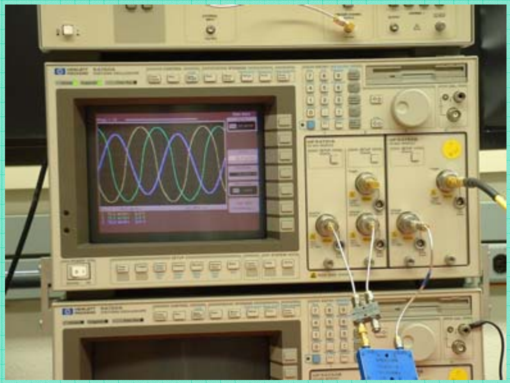
- Single-frequency acquisition, no phase info for NL systems

Equivalent-Time Sampling

Digital Sampling Oscilloscope





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- Broadband acquisition: relative phase maintained
- Aperiodic signals OK

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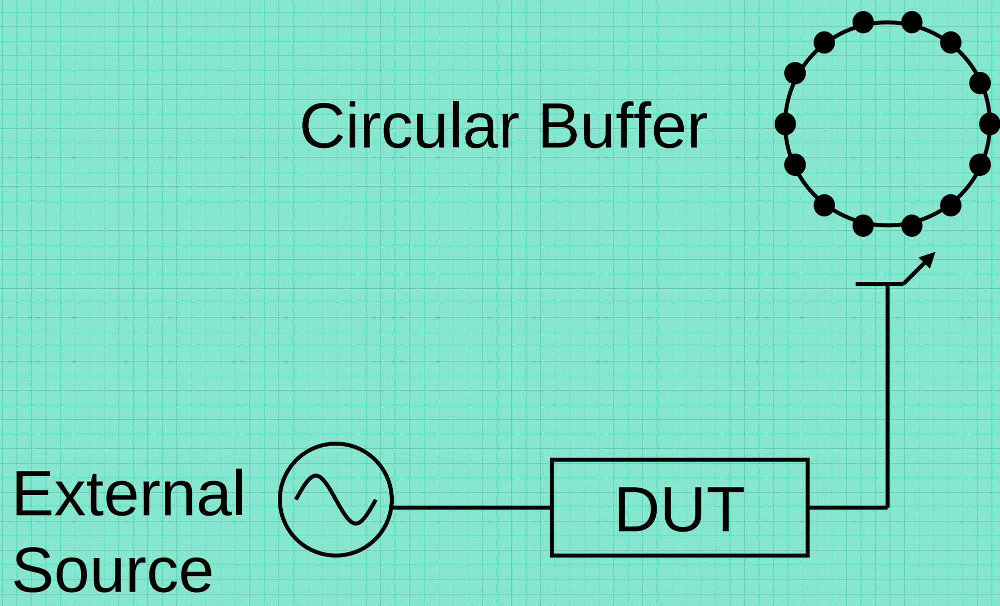
- Broadband acquisition: low dynamic range
- Calibration difficult
- Single (or two) channel

Real-Time Sampling

Real-Time Sampling Oscilloscope



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•Broadband acquisition: relative phase maintained

•Aperiodic signals OK

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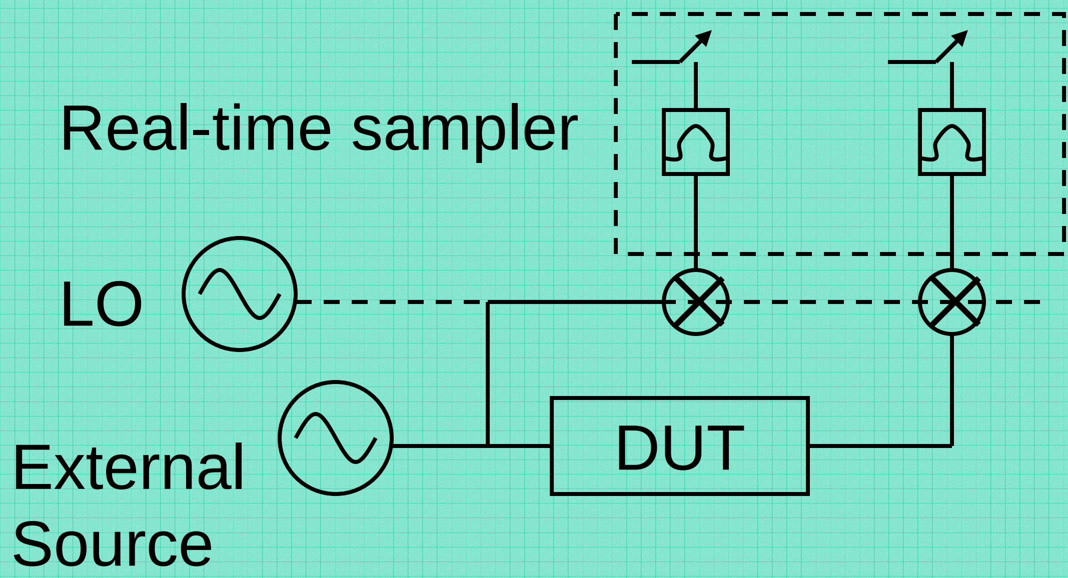
•Broadband acquisition: low dynamic range

•Calibration difficult

•Single channel

Vector Signal Analyzers (Real-Time)

Modulated-signal measurements



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- RT sampling maintains relative phase

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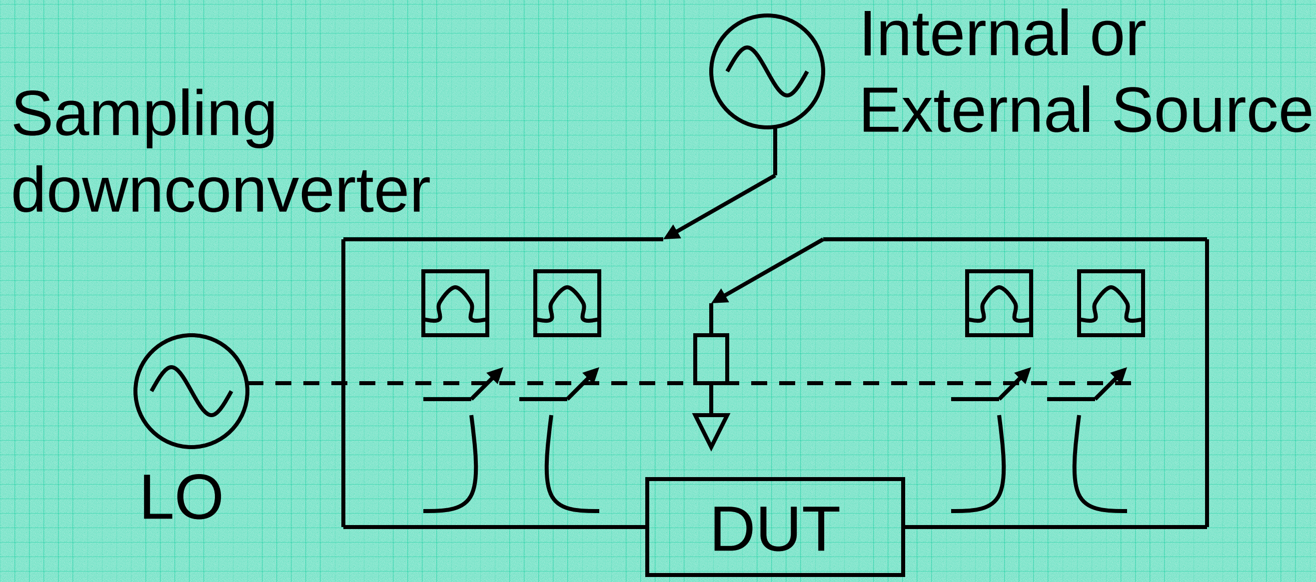
- No harmonics
- Calibration difficult

Large Signal Network Analyzer

Harmonics and distortion products



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- Test set calibration
- Two-port measurement
- RT sampling

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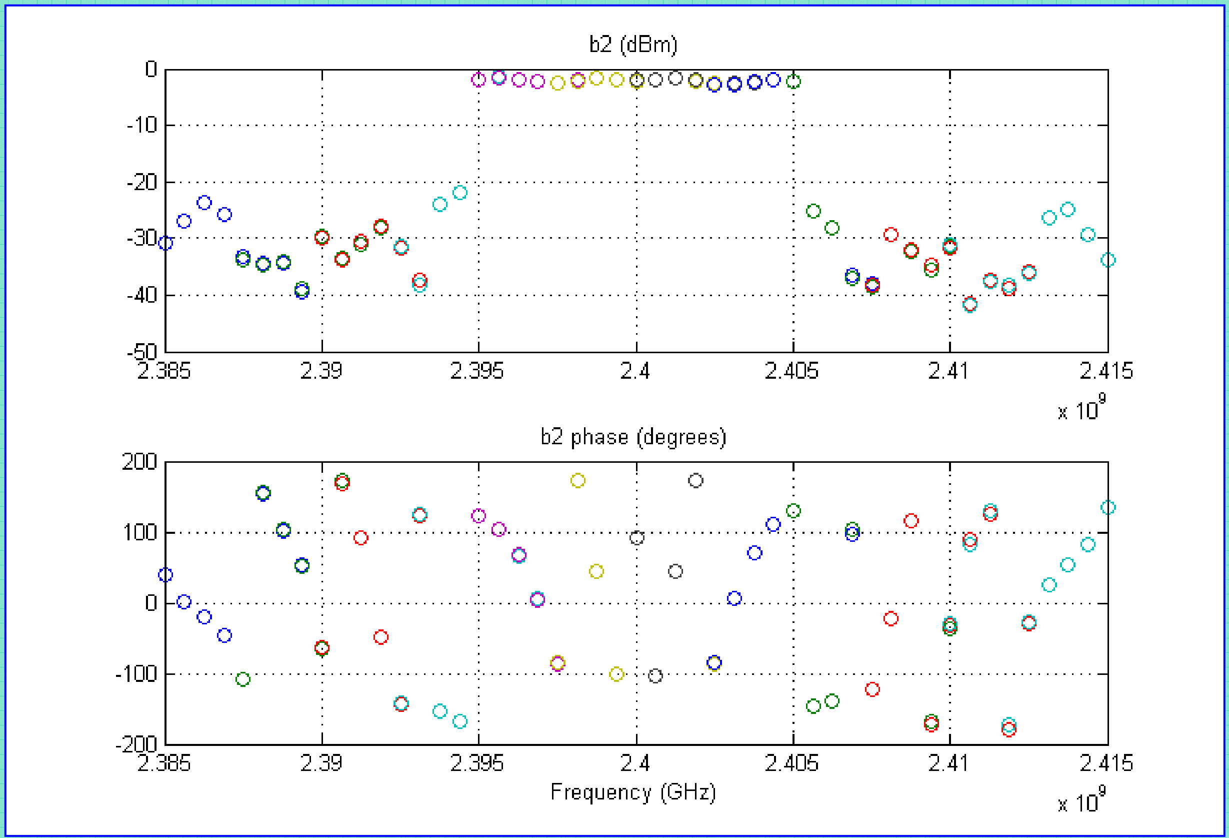
- Narrow IF bandwidth
- Expensive

Post-Processing Methods

Applicable to a variety of hardware



30 MHz wide LSNA measurement

Measurement Issues

Hardware limitations:

- Frequency converters
- IF Filters
- Samplers
- Memory

Data Interpretation

- Calibrations
- Post-processing
- Digital Signal Processing

Questions to Keep in Mind

- What are recent successes at your lab in increasing the measurement bandwidth of your instrumentation?
- What improvements do you see enabling increased measurement bandwidth?
- What are the factors inhibiting technological innovation?
- Are there obvious research/development roles for government and academic labs?
- How does the measurement infrastructure in the U.S. compare to other countries/regions?
- What are the economic impacts of increasing or not increasing measurement bandwidth?

Presentations

•**Wideband RF Measurement Challenges**, Tektronix, *Bill Byrom*

•**Vector Signal Generators: Metrology Needs**, Anritsu, *Brian Lee*

•**Phaser Quattro Broadband Measurements**, Agilent, *Jonathan Scott (presented by Dylan Williams)*

•**Bandwidth Extension Using "Stitching Approach"**, K.U. Leuven and NIST, Dominique Schreurs, Kate Remley

•**Wideband Time-Domain Measurement/Modeling: Motivation, Issues**, Aerospace Corp, *Christopher Silva*

•**Needs & Prospective for Broader Band Non-Linear Measurements with the LSNA**, The Ohio State University, *Patrick Roblin*

•**The Sampling Frequency Converter and Bandwidth Extension**, Jan Verspecht, bvba, *Jan Verspecht*

Panel Discussion

Proliferation of wireless systems

- ⇒Spectral efficiency
- ⇒Accurate measurements of distortion
- ⇒Nonlinear measurements

Increased data rates

- ⇒Broad modulation bandwidths
- ⇒Accurate measurement over broadband

Panel Discussion

Premise: **“Test engineers need to provide the wireless industry with accurate methods to characterize distortion in broadband signals”**

Questions:

- What are the factors inhibiting technological improvement?
- Are there obvious research/development roles for government and academic labs?
- How does the measurement infrastructure in the U.S. compare to other countries/regions?
- What are the economic impacts of increasing or not increasing measurement bandwidth?

Nonlinear Measurements Workshop
Tektronix Contribution

Bill Byrom (presenter)
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Darren McCarthy
Tektronix Staff
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November 30, 2005

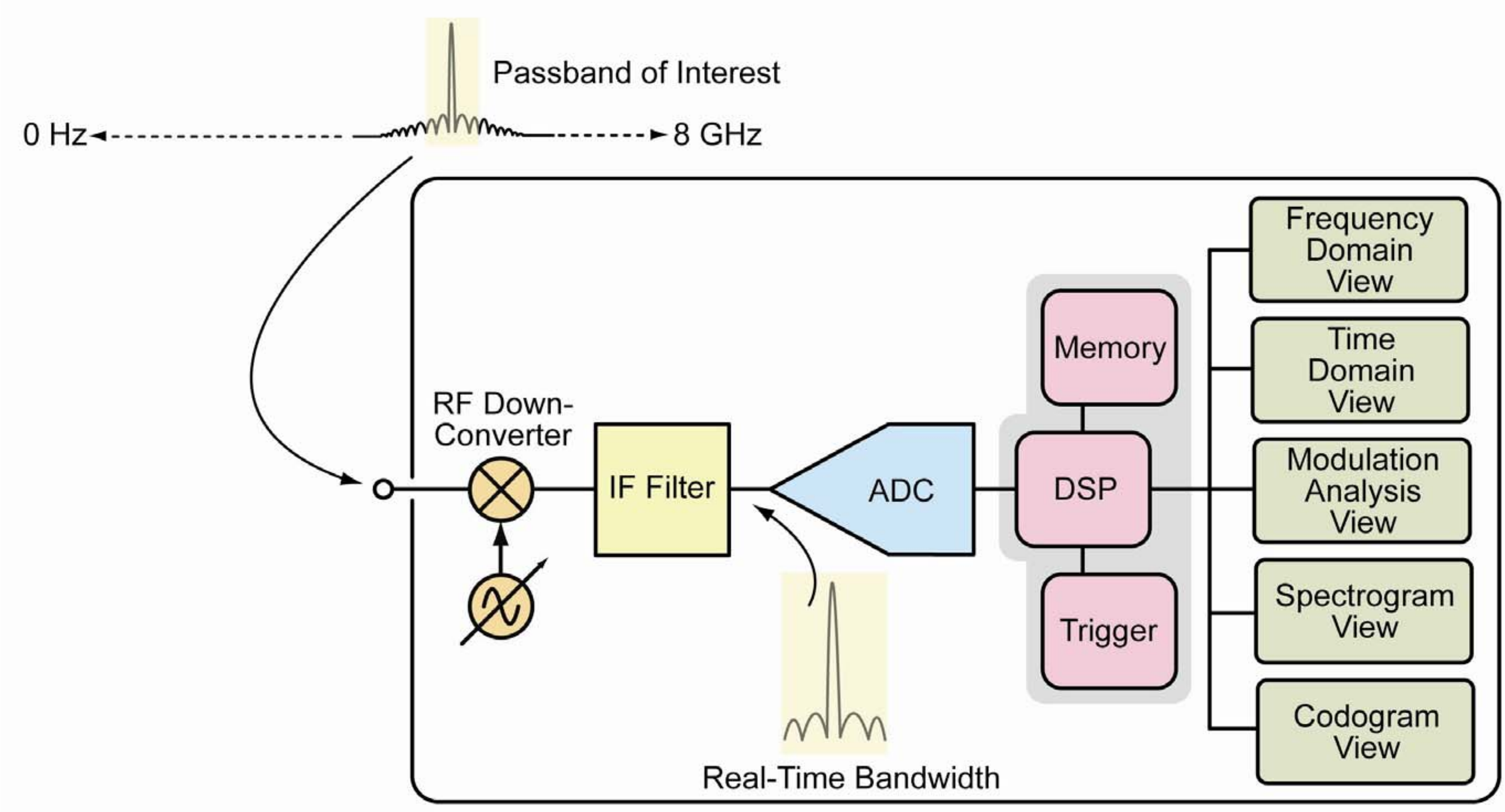
Wideband RF Measurement Challenges

- Behavior of devices require a complex stimulus. New tools are need for the analysis (both communication and non-communication signals)
  - Importance of capturing unexpected behavior ultimately drives success of wireless systems
    - Unintended temporal interference to adjacent user
    - Unintentional signature of device that desires not to be detected
- Measurement frequency response, phase flatness, pulse linearity, and TIME sampling of events all contribute to the test confidence and level of uncertainty
- Most all technology is commercially available worldwide, how you make use of it drives competitiveness – find your problems before someone else does

Evolution of Signal Analysis Architectures

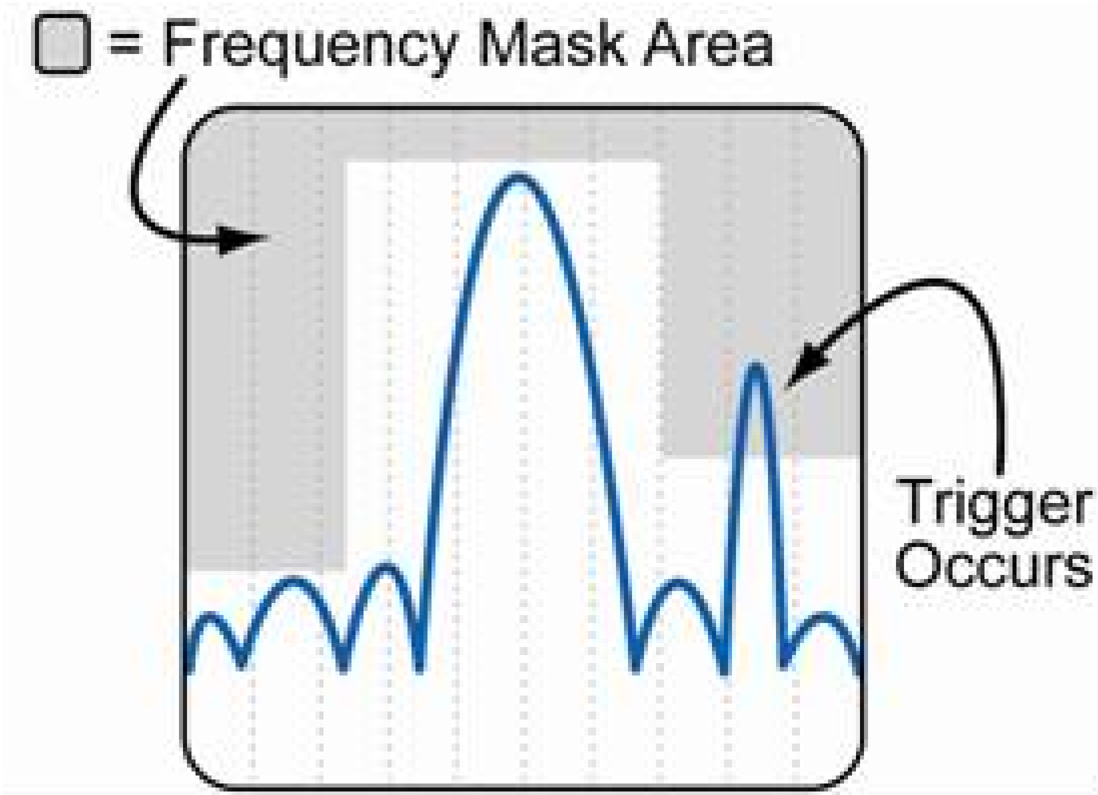
	Swept Tuned	Vector	Realtime
	1960s	1990s	TODAY
Market Drivers	• Communication systems • Emerging solid state technology • Radar systems	• Radar – detect by not be detected • Wireless Proliferation • Spectral efficiency – Digital Modulation	• Congested RF spectrum – focus on spatial utilization • Pervasiveness of low cost RF • Modulation-agile communication systems (bursted)
Measurement Challenges	• Frequency response • Analog demodulation • Repetitive impulse characterization	• Digital Demodulation • Complex signal analysis	• Time-varying, bursted, and transient RF signals • Technology interoperation • Importance of characterizing "Unexpected" events
Solutions	• RF power vs. frequency • Low noise floor • High dynamic range	• Standards-based measurements (define expect results) • Requires wide instantaneous video bandwidth capture over "expected" signal of interest	• Flexible time-correlated multi-domain analysis • Seamless capture of RF signals changing over time • Frequency domain trigger – capture the unexpected

Real-time Architecture



Frequency Mask Trigger

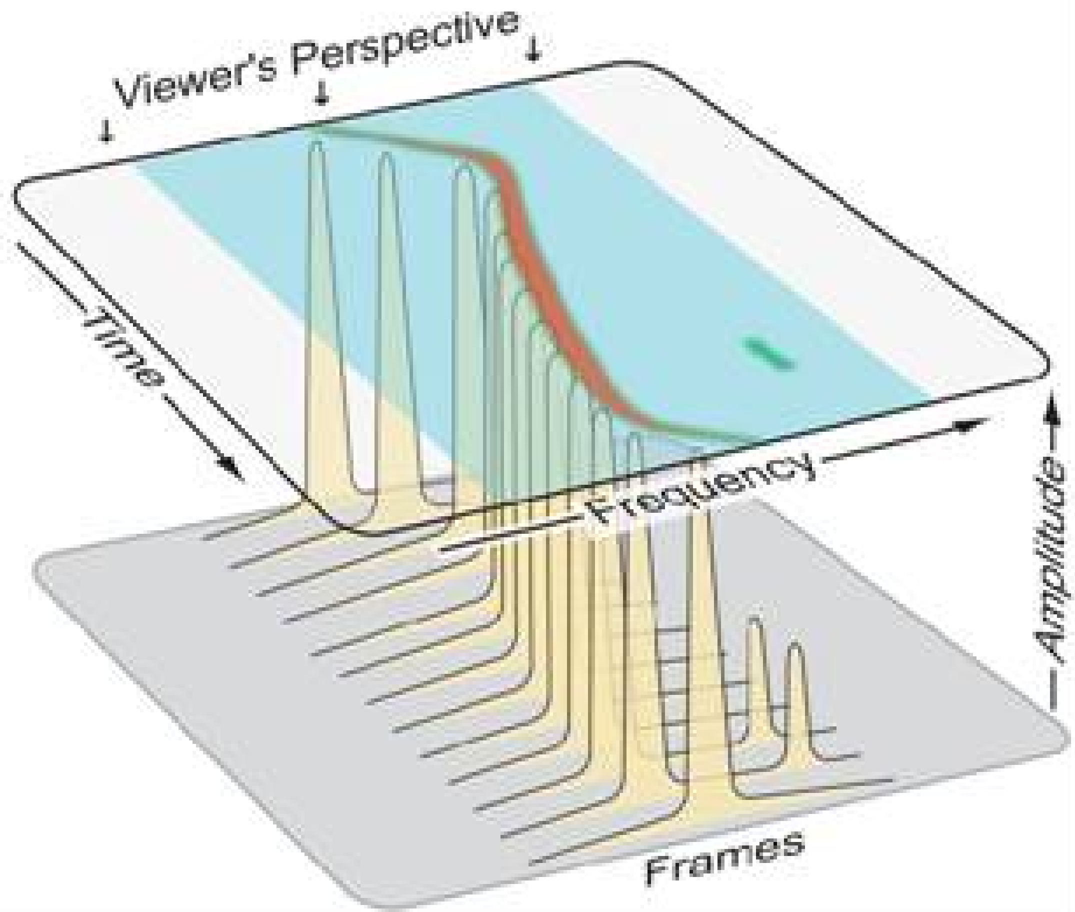
- Define a frequency mask which can be used to trigger on specific events in the frequency domain
- Reliably detect and capture elusive RF signals that a level trigger cannot see in a crowded spectral environment



Seamless Capture and Spectrogram

- The spectrogram shows how an RF signal changes over time in the frequency domain

- Frequency is the horizontal axis, time is the vertical axis, and power is represented by the color of the trace



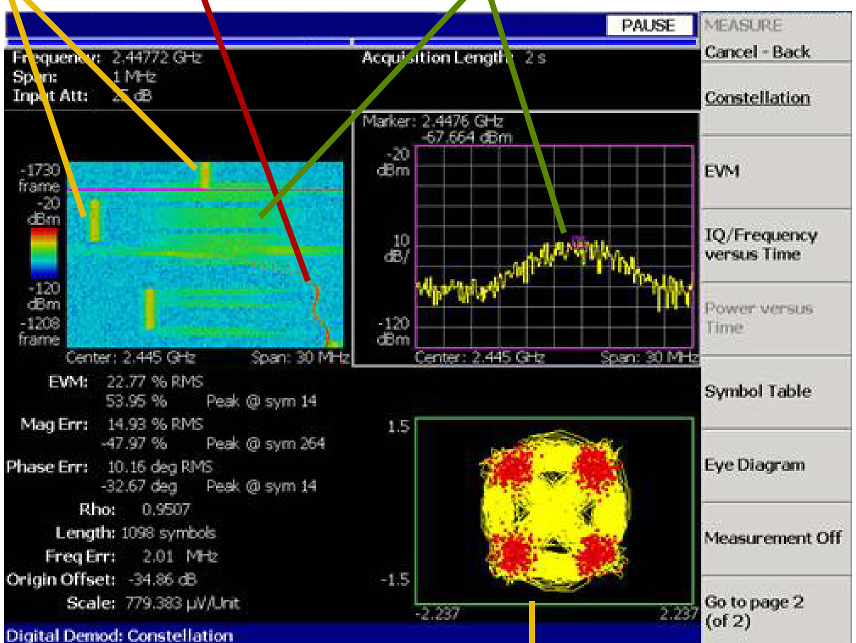
Multi-Domain Time-Correlated View

Before Interference

Bluetooth

Microwave Oven

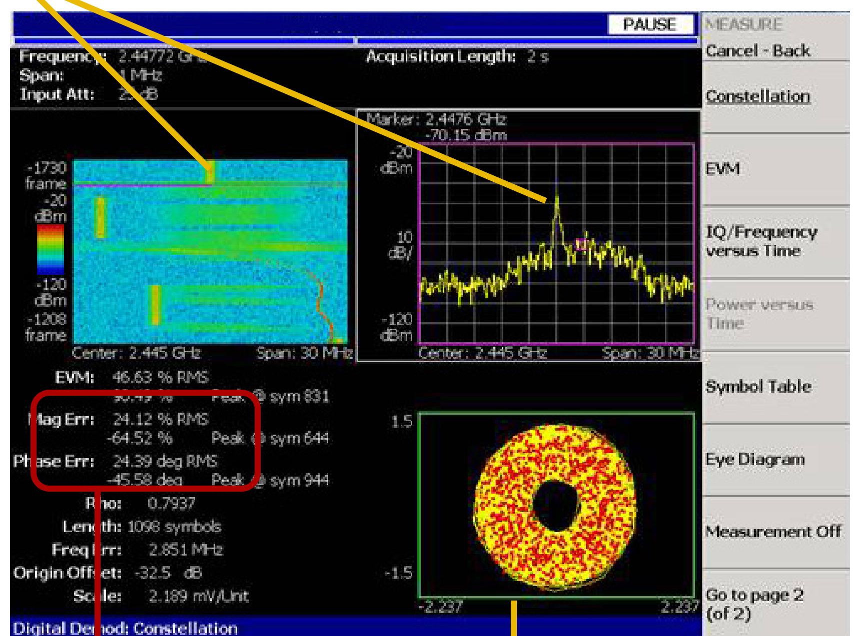
WLAN Signal



WLAN Constellation Synchronized

During Interference

Interfering Bluetooth Signal



WLAN Error Vector Measurement Degraded

WLAN Constellation Out of Synch

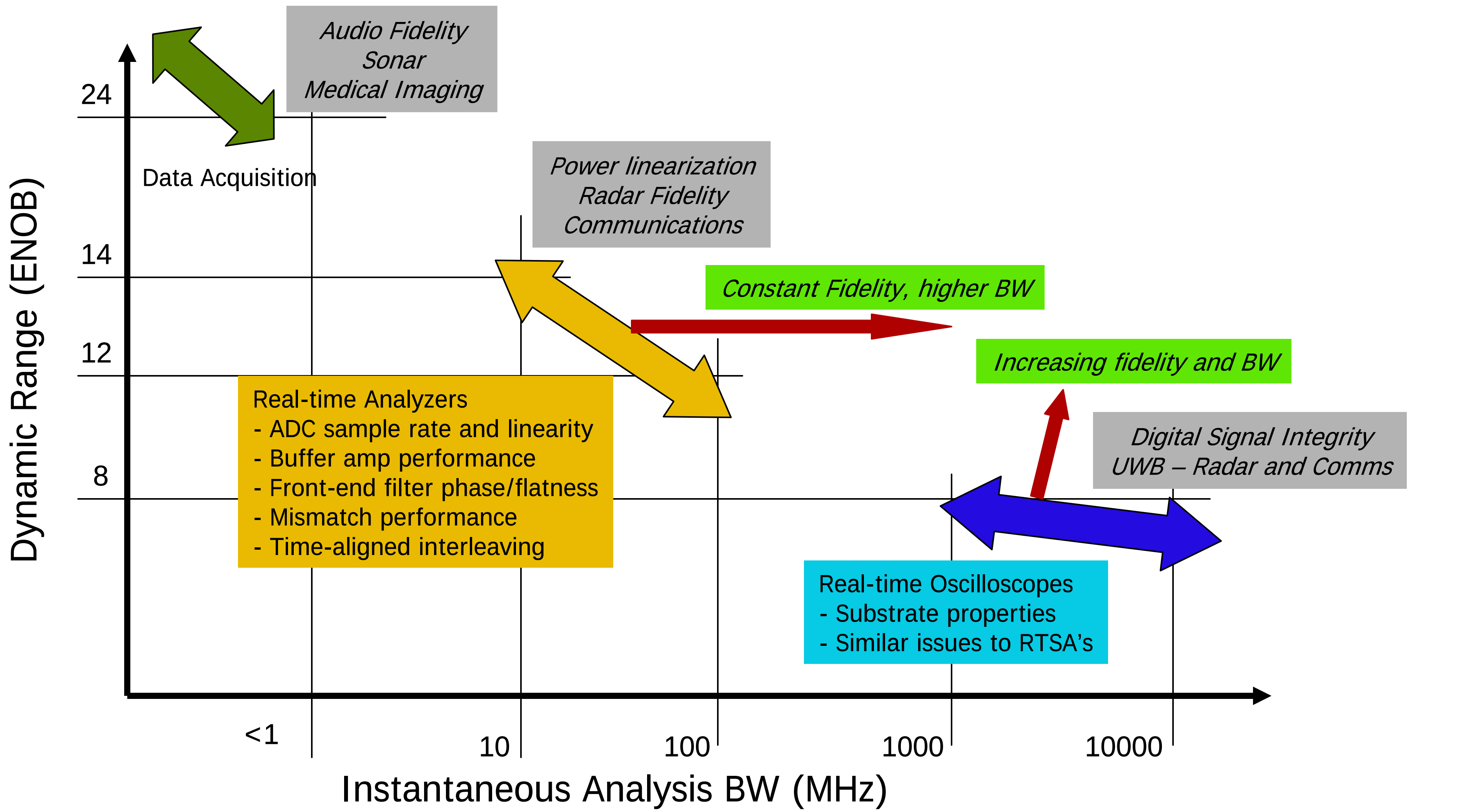
Unique Measurement Challenges

- Intentional Time-Variant signals –
  - Hopping signals
    - Simultaneous measurements of settling time, quality, and phase noise performance allows proper characterization
  - Bursted TDM signals
    - Turn-on transients settling, Turn-around Time (Near Field RFID to Satellite Comms delays)
- Time Dependent Measurements
  - Deterministic – (Fixed and time repetitive sequences)
    - CCDF – long periods of sampling increase measurement confidence
    - Error Vector Magnitude – number of symbols
  - Stochastic –
    - Memory effects – both the detection and the quantification present a major challenge for "Adaptive Digital" linearization in power communication and radar systems

Non-linear Measurement Challenge

- Memory effects –
  - Device characterization dependencies:
    - History of device
    - Unique to a specific modulated signal (BW and statistics)
    - Varies over impedance of device
  - Required Measurement Solution
    - Ability to characterize phase relationship of high-order intermodulation products (bandwidth)
      - minimum 3^{rd} order, but ability to improve performance improves with measurements thru 5^{th}, 7^{th}, and 9^{th} order intermodulation
    - Ability to instantaneous see low level signals (dynamic range)
      - desired 16dB better that specification for test margin and confidence
    - Events occur for only short periods of time (fast time resolution)
      - Events last only several microseconds

Bandwidth and Dynamic Range *(drivers)*



Anritsu VSG 3700A Metrology Needs

Yeou-Song (Brian) Lee
Anritsu Company
Nov. 29, 2005

Discover What's Possible™ Anritsu

Market Trends

- Mobile communication systems are evolving to higher speed and increased wideband modulation.
  - Cellular phones and WLANs are evolving into new communication systems using more information.
- Broadcast and information service systems are developing toward digitization.
  - They are changing from analog modulation to digital modulation for advanced information services and frequency-effective utilization.
- A wide variety of new wireless communication systems, such as last mile and personal communication (WPAN), have appeared.
  - In order to increase cordless mobility, various new communication systems are being introduced.

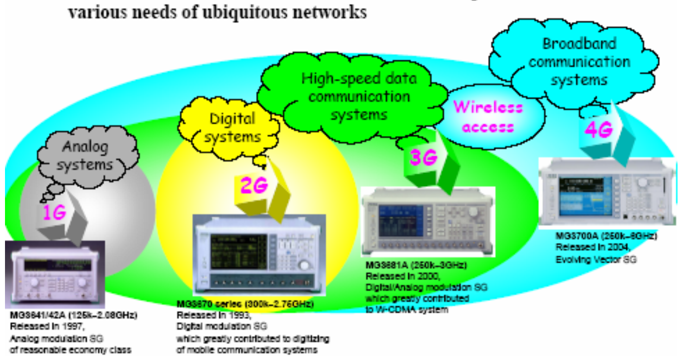
Major Vector Signal Generator Applications

- Signal Source and interference signal source for receiver testing
  - Receiver sensitivity testing uses a wanted signal source. Testing the receiver interference response also needs interference signal sources.
- Reference signal source for evaluating components and devices
  - For components such as power amplifiers, filters, mixers, and modulator/demodulators, path performance and distortion (spectral re-growth) are measured using signal generators and signal analyzers.
- Reference Signal source for verifying base-band chips
  - Base-band chips require verification of decoding algorithm and physical layer processing flows during the development phase.

Vector Signal Generator MG3700A

All-rounder for ubiquitous networks

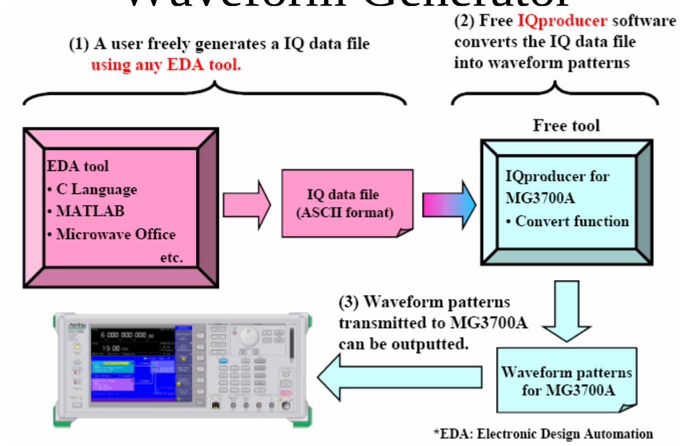
- MG3700A is the all-around brand for a new concept to realize the various needs of ubiquitous networks



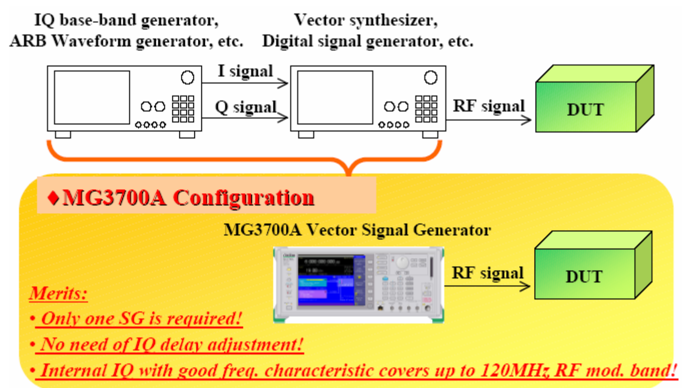
Features

- Frequency Range 250 kHz to 6 GHz
  - 250 kHz to 3 GHz (standard)
  - 250 kHz to 6 GHz (option)
- - Wide vector modulation bandwidth
  - 120 MHz (Internal base band generator)
  - 150 MHz (External IQ input)
- - High level accuracy
  - +/-0.5 dB (Absolute level accuracy)
  - +/-0.2 dB typical (Linearity)
- Standard Waveform Patterns: W-CDMA/HSDPA, GSM/EDGE, cdma2000, 1X/1xEV-DO, Wireless LAN (IEEE 802.11a/b/g), PDC, PHS, AWGN
- Waveform generation software: IQ-producer (HSDPA, TDMA , 1xEV-DO)

MG 3700A Features: ARB Waveform Generator



- As the MG 3700A is an arbitrary waveform based signal generator, it can output any waveform patterns generated by users.
- “Arbitrary waveform generation function” and “arbitrary waveform memory of 1 GB” are built into the MG 3700A.
  - Generate an ASCII format IQ data file with any EDA tool.
  - Convert an IQ data file into waveform patterns for the MG 3700A
  - Transfer the created waveform patterns to the MG 3700A. An output waveform pattern is selected as signal.



- Conventionally, an AWG and a digital signal generator were combined to generate arbitrary waveforms. A single MG 3700 A can perform RF output of any modulated signals.
- Merits:
  - Only a single SG is required.
  - No IQ delay adjustment is needed.
  - Internal IQ with good frequency characteristic coverage up to 120 MHz RF Modulation band

Issues with Digital Modulation

- Modulation quality is a relative measurement.
- If someone could come up with a source with perfect modulation quality, that would be great, but I don't think that's possible—basically every analog impairment reduces modulation quality.
- This includes frequency response (both amplitude & phase), noise, phase noise, AM/AM, AM/PM, inter-modulation, and even VSWR (because it affects frequency response).
- Having a source which is much better than any measurement device would also be great, say 0.1% EVM for 100 Msymbols per second.

High Level Accuracy

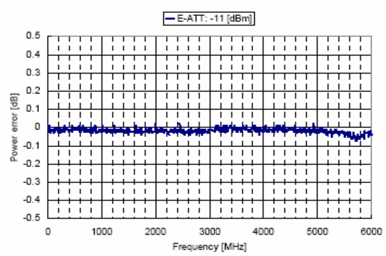
- Output accuracy is a critical specification in order to control the uncertainty of measured values.
  - Sources of Errors: Calibrating instruments, ALC repeatability, Attenuator Repeatability, Flatness and Impedance mismatch.
  - The automatic fast-acting internal calibration routine: Level error between IQ modulation and CW (±0.2 dB)
  - The ability to set output level by 0.01 dB resolution in all ranges is useful to improve receiver accuracy and to adjust low levels.

Improvement of High Level Accuracy

- Automatic Internal Calibration Routine
  - The reference source for internal calibration automatically calibrates at high speed from DAC to ALC loop.
    - At the change of frequency, output level, and I/Q RMS level (Signal pattern selection)
    - The switching time of frequency and output level includes automatic calibration.
  - The improved detector performance of ALC Loop
- Correction at high resolution per unit
  - The frequency response, linearity error of ALC circuit, and attenuation error of the step attenuator
  - Wide dynamic range and high linearity: built-in Correction table

Typical Level accuracy

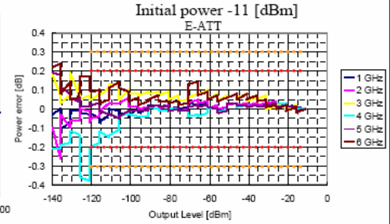
- **Frequency response**
  - » CW



Limits (23 ± 5 °C)

- » ±0.5 dB * 25 M ~ 3 GHz
  - – -120 ~ +6 dBm
  - – -120 ~ +10 dBm * with Option Mechanical attenuator

- **Linearity**
  - » CW
    - – Relative level accuracy Initial power -11 [dBm]

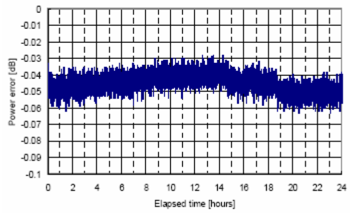


Limits (23 ± 5 °C)

- » ±0.2 dB typ. * 25 M ~ 3 GHz
- » ±0.3 dB typ. * 3 ~ 6 GHz
  - – -120 ~ -11 dBm
  - – -120 ~ -7 dBm * with Option Mechanical attenuator

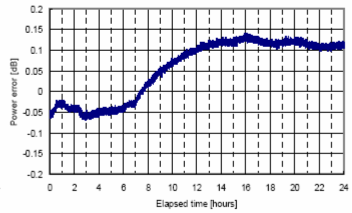
Typical Level stability

- **Aging**
  - » CW (ALC: Active)
    - – 1 GHz, -11 dBm



  - » Difference ≤ 0.035 dB
    -0.063 ~ -0.028 dB

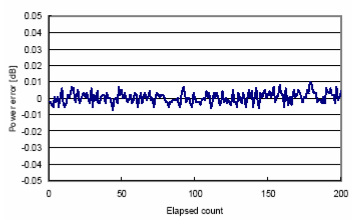
- **Aging**
  - » Level Continuous mode, I/Q modulation (ALC: Hold)
    - – 1 GHz, -11 dBm, W-CDMA UL RMC 12.2kbps



  - » Difference ≤ 0.21 dB
    -0.069 ~ 0.141 dB

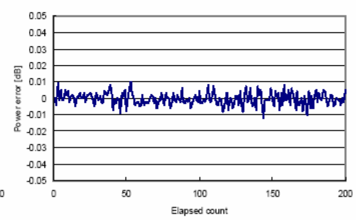
Typical Level stability

- **RF off → on (off [on] off [on] ...)**
  - » CW
    - – 2 GHz, -11 dBm



  - » Difference ≤ 0.017 dB
    -0.007 ~ 0.01 dB

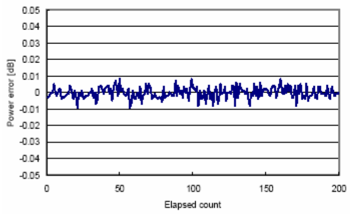
- **RF off → on (off [on] off [on] ...)**
  - » I/Q modulation
    - – 2 GHz, -11 dBm, W-CDMA



  - » Difference ≤ 0.022 dB
    -0.012 ~ 0.01 dB

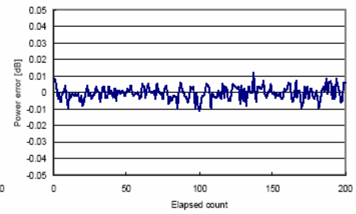
Typical Level stability

- **I/Q Modulation → CW (Mod on [off] on [off] ...)**
  - 2 GHz, -11 dBm, W-CDMA



  » Difference ≤ 0.017 dB
  -0.009 ~ 0.008 dB

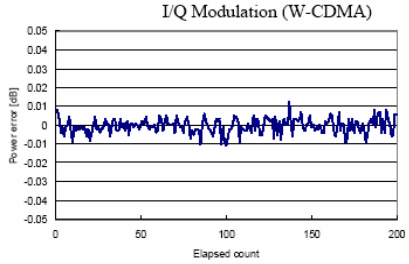
- **CW → I/Q Modulation (Mod off [on] off [on] off ...)**
  - 2 GHz, -11 dBm, W-CDMA



  » Difference ≤ 0.023 dB
  -0.011 ~ 0.012 dB

Typical Level stability

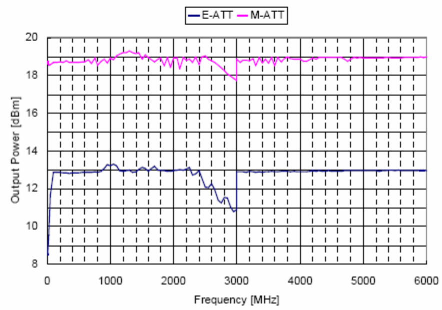
- **Random level [-140 ~ -1 dBm] → -11 dBm (any level [-11] any level [-11] ...)**
  - 2 GHz, I/Q Modulation (W-CDMA)



  » Difference ≤ 0.023 dB
  -0.011 ~ 0.012 dB

Typical Maximum available output level

- **Electronic step attenuator (Standard): +13 dBm setting**
  - E-ATT
- **Mechanical step attenuator (Option): +19 dBm setting**
  - M-ATT



Specifications for High Spectral Purity

- Spurious Response:
  - Harmonics:
    - ✓ 2 f_c
    - ✓ 3 f_c
  - Non-harmonics
  - Local oscillator leakage: f_{LO}
  - Image Signal: f_{img}
    - ✓ IF signal leakage: f_{IF}
    - ✓ Maximum signal of harmonic IF and LO: $2f_{IF}-f_{LO}$
  - Sub-harmonic
    - ✓ ½ f_c, 3/2 f_c
  - Power line and Fan Rotation (Hum)
    - ✓ f_c±Harmonics of AC frequency (especially 3rd order)
- Phase Noise:
  - Phase noise of reference oscillator
  - Loop bandwidth of PLL
  - Phase noise of YTO
  - Noise floor

Adjacent Channel Leakage Power Ratio (ACLR)

- In wireless communication, the ACLR requirements of a signal source is critical in order to utilize limited radio resources effectively.
- It is a critical specification for reference sources evaluating transmitter components/devices and for interference sources testing receivers.
- Adjacent channel leakage power ratio of modulated signals is caused by inter-modulation distortion produced by nonlinear signal generator elements.
- Alternate channel leakage power ratio is caused by phase noise.

MG3700A-001 Rubidium Reference Oscillator

- **Exchangeable for long-term stable internal reference oscillator**

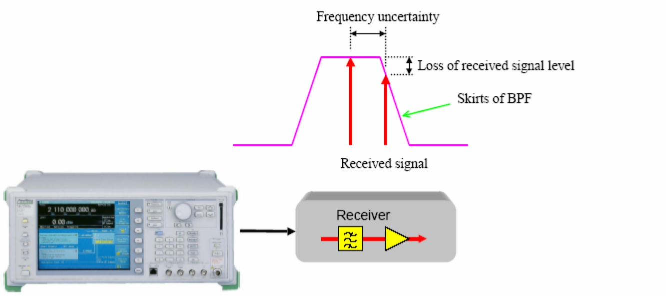
		Standard	Option
Aging rate		$\pm 1 \times 10^{-7}$ /year ($\pm 1 \times 10^{-8}$ /day)	$\pm 1 \times 10^{-10}$ /month
Warm-up stability	(after power-on 2 minutes)	($\pm 5 \times 10^{-7}$)	
(23 °C)	(after power-on 5 minutes)	$\pm 5 \times 10^{-8}$	($\pm 1 \times 10^{-9}$)
	(after power-on 7 minutes)		$\pm 1 \times 10^{-9}$
Temperature stability (0 ~ 50 °C)		$\pm 2 \times 10^{-8}$	$\pm 1 \times 10^{-9}$

* Warm-up stability: Reference after 24 hours

» Frequency accuracy is specified by the reference oscillator.
  - By the indoor use with the almost fixed temperature
- Frequency accuracy
  = ± (Output frequency × Aging rate × Time since last calibrated)
  e.g. 2 GHz, 1 year
  = ± 200 Hz * Standard
  ≈ ± 2 Hz * Option

Effect of frequency accuracy on receiver sensitivity test

- **In case of greater frequency uncertainty (poor frequency accuracy), receiver is tested with deteriorated sensitivity rather than true value.**
  - » The level of the signal is lost when the received signal is located in the skirt of BPF in a receiver by frequency uncertainty.



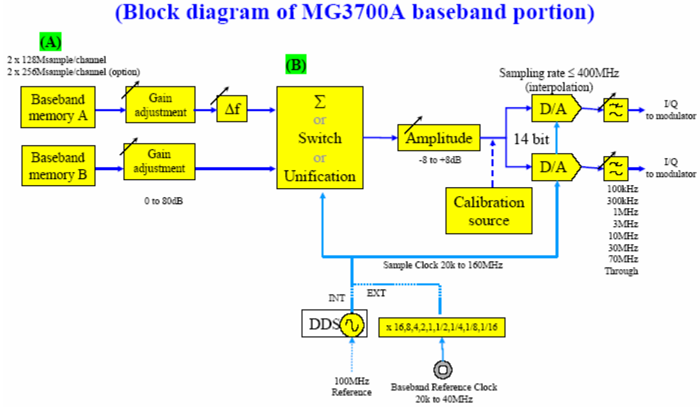
Calibration Requirements for Digital Modulation

- Many Waveform Definitions: e.g., WCDMA
- Vector Modulation (EVM) Uncertainty
- ACPR Uncertainty
- BER Uncertainty

- The receiver characteristic evaluation in various communication systems requires the measurement of characteristics while adding a modulated signal to a wanted signal.
- Therefore, two signal generators and one combiner are required for testing [Wanted signal + Modulated interfere signal].
- The standard MG 3700A configuration has three advantages:
  - A single set with two output signals
  - Built-in combiner
  - No level ratio adjustment required.

Waveform combining function principles

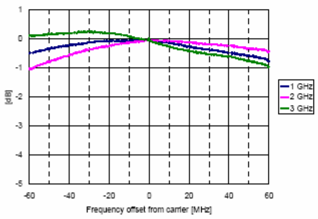
(Block diagram of MG3700A baseband portion)

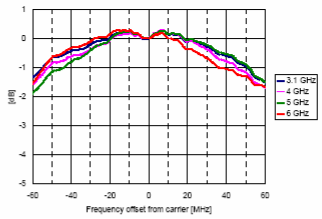


Wideband I/Q modulation

Modulation bandwidth using internal I/Q

Bandwidth	Flatness ≤ 3 GHz	> 3 GHz
• **20 MHz (±10 MHz)**	**< ±0.5 dB (≥0.2 GHz)**	**< ±1 dB**
• **120 MHz (±60 MHz)**	**< ±2 dB (≥1 GHz)**	**< ±3 dB**

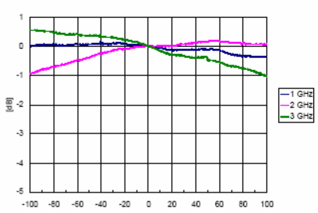


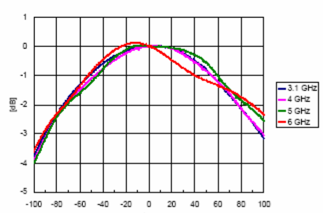


Wideband I/Q modulation

Modulation bandwidth using external I/Q

Bandwidth	Flatness ≤ 3GHz	> 3GHz
• **20 MHz (±10 MHz)**	**< ±0.5 dB (≥0.2 GHz)**	**< ±1 dB**
• **150 MHz (±75 MHz)**	**< ±3 dB (≥1 GHz)**	**< ±5 dB**
• **200 MHz (±100 MHz)**	**< ±6 dB (≥1 GHz)**	**< ±9 dB**





Measurements of "Wanted Signal + Modulated Interfering Signal"

W-CDMA

DUT	Measurement Items	MG3700A
BS	ACS	√
	IM *	√
	Blocking *	√
UE	ACS	√
	IM *	√
	Blocking *	√

TD-SCDMA

DUT	Measurement Items	MG3700A
BS	ACS	√
	IM *	√
	Blocking *	√
UE	ACS	√
	IM *	√
	Blocking *	√

ARIB STD-T61/T79/T86

DUT	Measurement Items	MG3700A
BS	ACS	√

PHS

DUT	Measurement Items	MG3700A
UE	ACS	√

*: In the measurement of IM/Blocking, the signal source of CW is needed.

W-CDMA Standard Definitions

W-CDMA UE

3GPP TS25.101		Wanted Signal *2 [dBm/1.28MHz]	Interfere Signal [dBm]	Offset Frequency [MHz]
7.5	ACS	-92.7 to -90.7	-52 (Mod)	+/-5.0
7.6	Blocking	-103.7 to -101.7 *1	-56 (Mod)	+/-10.0
7.6	Blocking	-103.7 to -101.7 *1	-44 (Mod)	+/-15.0
7.8	IM	-103.7 to -101.7 *1	-46 (Mod) -46 (CW)	+/-20.0 +/-10.0

*1: It depends on operating band.
*2: All the parameteres defined using the DL reference measurement channel (12.2kbps).
==> Preinstalled waveform pattern
Wanted signal 7.5 ACS "DL_RMC_12_2kbps_ACS"
Wanted signal 7.6-7.8 "DL_RMC_12_2kbps_RX"
Interfere signal "DL_Interfere" or "DL_Interfere_ov3"
*3: Supurious response frequencies

W-CDMA BS

3GPP TS25.141		Wanted Signal *2 [dBm/1.28MHz]	Interfere Signal [dBm]	Offset Frequency [MHz]
7.4	ACS	-105	-42 (Mod)	+/-5.0
7.5	Blocking	-115/-105/-101 *1	-40/-35/-30 (Mod)	+/-10.0
7.6	IM	-104	-48 (Mod) -48 (CW)	+/-6.4 +/-3.2

*1: Wide area BS/ Medium Range BS/ Local area BS
*2: All the parameteres defined using theUL reference measurement channel (12.2kbps).
==> Preinstalled waveform pattern
Wanted signal "UL_RMC_12_2kbps"
Interfere signal "UL_Interfere" or "UL_Interfere_ov3"
*3: Supurious response frequencies

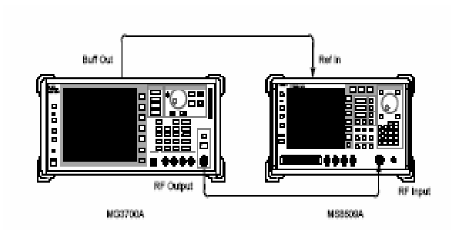
Red texts indicate the names of waveform patterns used in MG 3700A.

Various Waveforms

- WLAN (IEEE 802.11a/b/g)
- W-CDMA
- GSM
- CDMA 2000 1xEV-DO
- Bluetooth
- Digital Broadcast
- GPS
- PHS
- TD-SCDMA
- ARIB Standard
- …

Vector Modulation Performance Test

- This test consists of generating a baseband signal from the internal waveform pattern, and performance the vector modulation with the MG 3700A. The vector error of the modulated RF signal is measured with the transmitter tester (MS 8609A) to which signal analysis software has been installed.



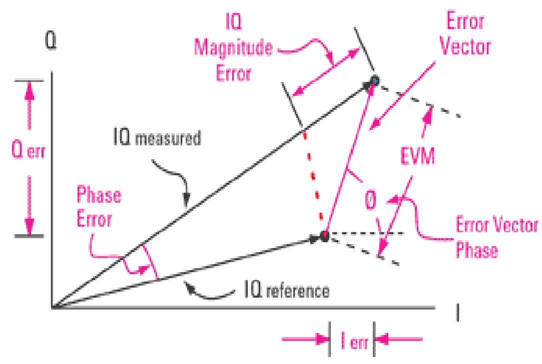
EVM

$$EVM\,[n] = \sqrt{I\,err[n]^2 + Q\,err[n]^2}$$

where [n] = measurement at the symbol time

I err = I Ref - I Meas

Q err = Q Ref - Q Meas



Vector Accuracy (section 5.4.1)

Settings: Frequency In Mhz	Settings: Output Lvl	Maximum Rating	Results	Uncertainty
800			.23 %	
1000		WCDMA	.22 %	
1800	-1 dbm	1code	.12 %	+/- 0.0%
2000	(+3 dbm	2% rms	.08 %	
2200			.24 %	
2400			.24 %	
2400			.11 %	
2497	-4 dBm	802.11a	.08 %	
4900	(0 dBm)	1% rms	.02 %	+/- 0.0%
5400			.03 %	
5925			.07 %	
2400	-4 dBm	802.11g	.13 %	
2497	(0 dBm)	1% rms	.14 %	+/- 0.0%
2400	-4 dBm	802.11b	2.28 %	
2497	(0 dBm)	5% peak	3.03 %	+/- 0.0%

* 4900 MHz to 5925 MHZ are available only when the Upper limit frequency 6 GHz option is installed

* Values in parentheses indicate the values when the Mechanical Attenuator option is installed

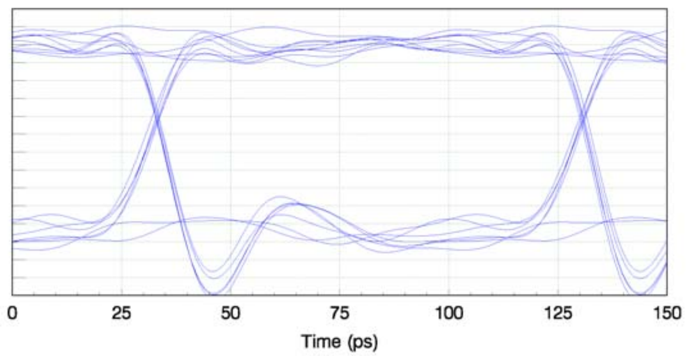
References

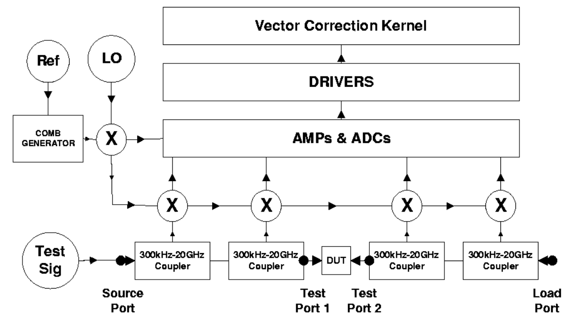
- MG 3700A_EF1100
- MG 3700A_EF2100
- MG 3700A_EI1600

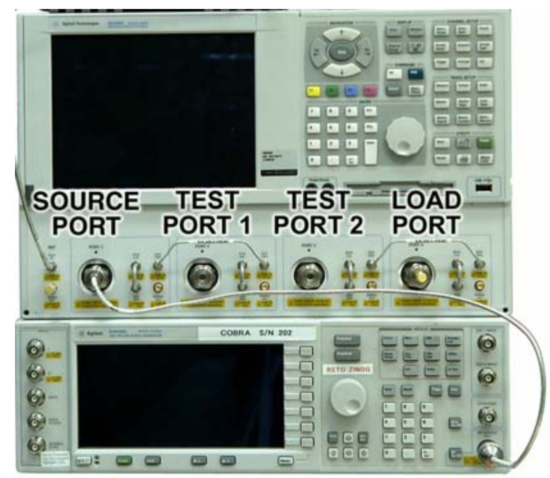
Phaser: Applications in…
Precision Time-Domain Measurement

Scope Implementation Possible

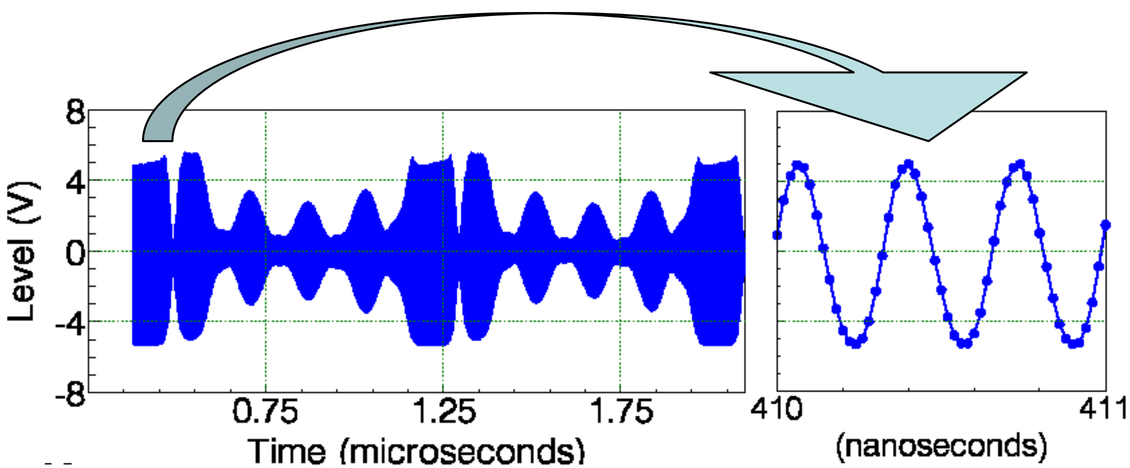
Jitter-free Bitstream Data

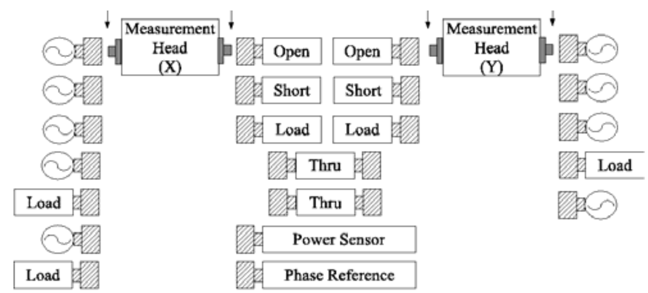






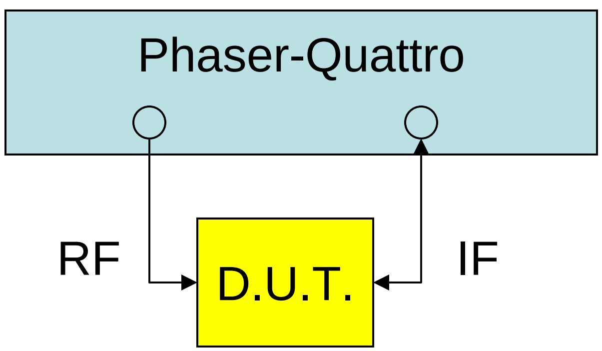
Optimum Spectral Analysis of Gated Signals



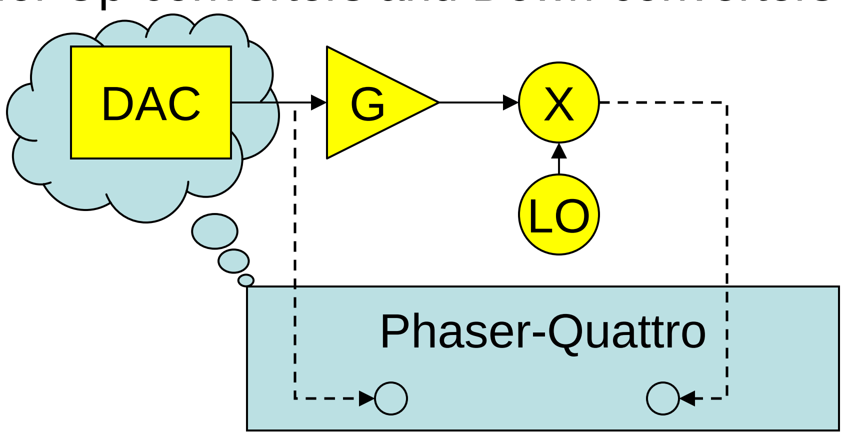


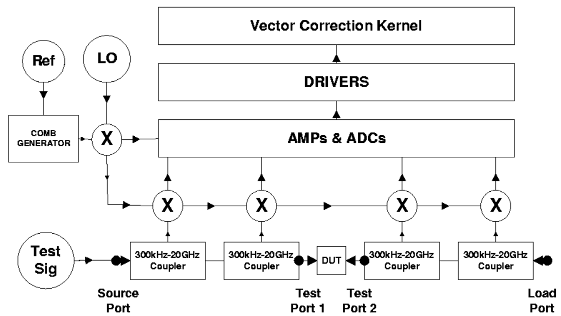
Phaser: Applications in…
Frequency Translating Systems

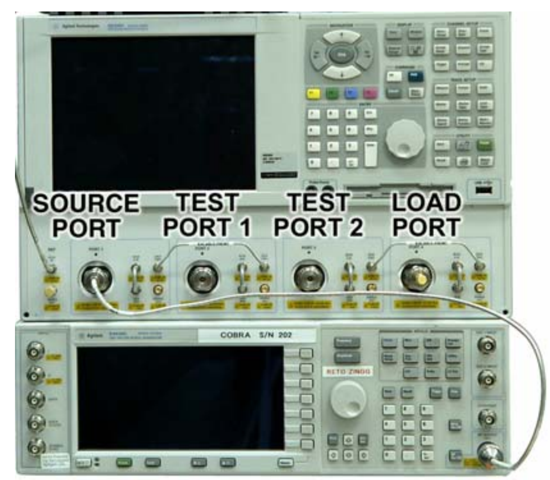
Group Delay Measurement of
Mixers, Receivers, and Transponders
(Satellite Channels)

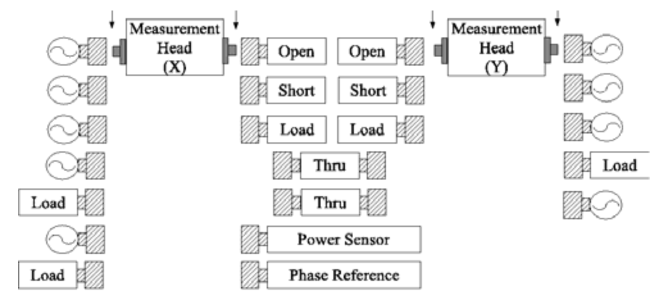


Phase Calibration and Pre-distortion
for Up-converters and Down-converters

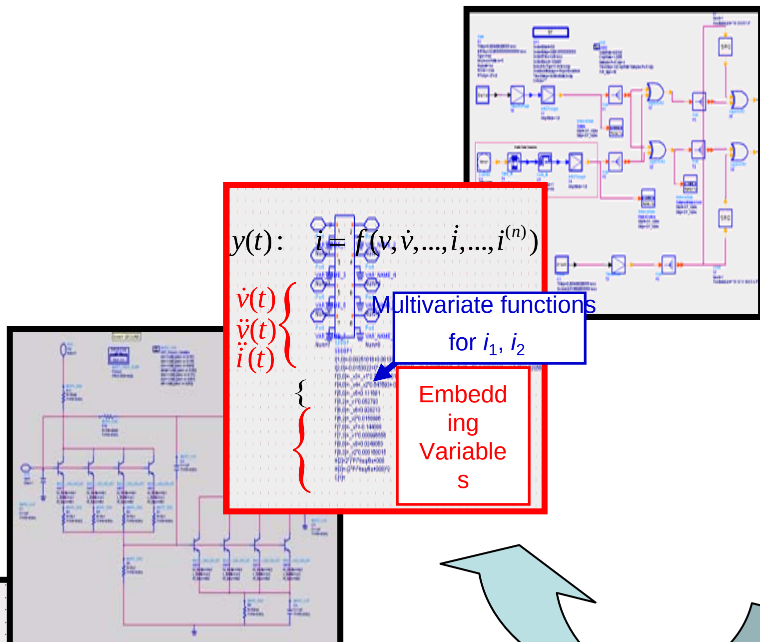


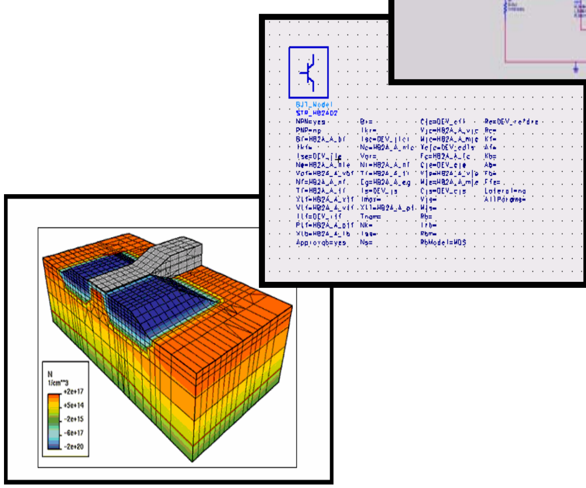




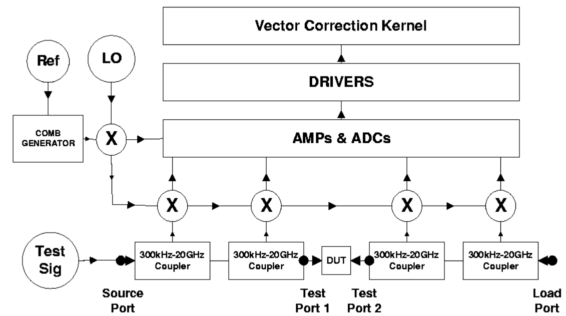


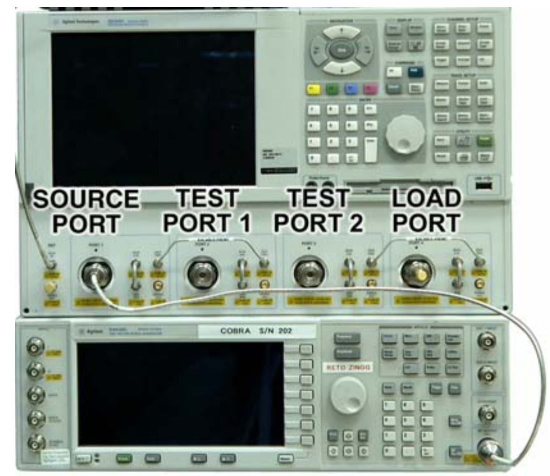
Phaser: Applications in…
Behavioural Modeling

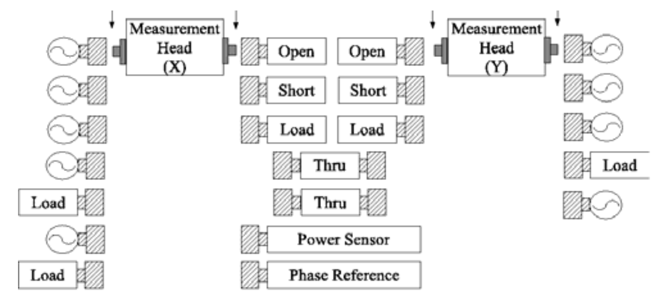




Characterize
DUT to extract
Black-box Model







Bandwidth Extension using “Stitching Approach”

Dominique Schreurs and Kate Remley*

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*NIST, USA (e-mail: remley@boulder.nist.gov)

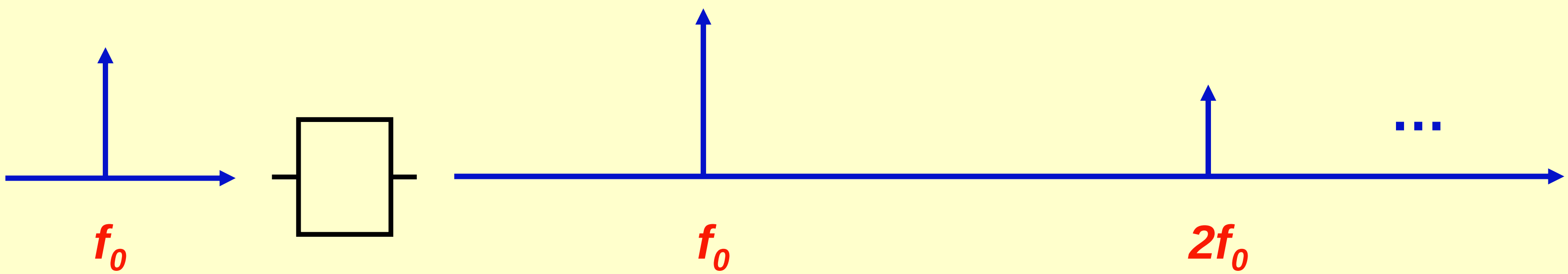
Outline

- Motivation
- Principle
- LSNA results
- VSA results
- Conclusions

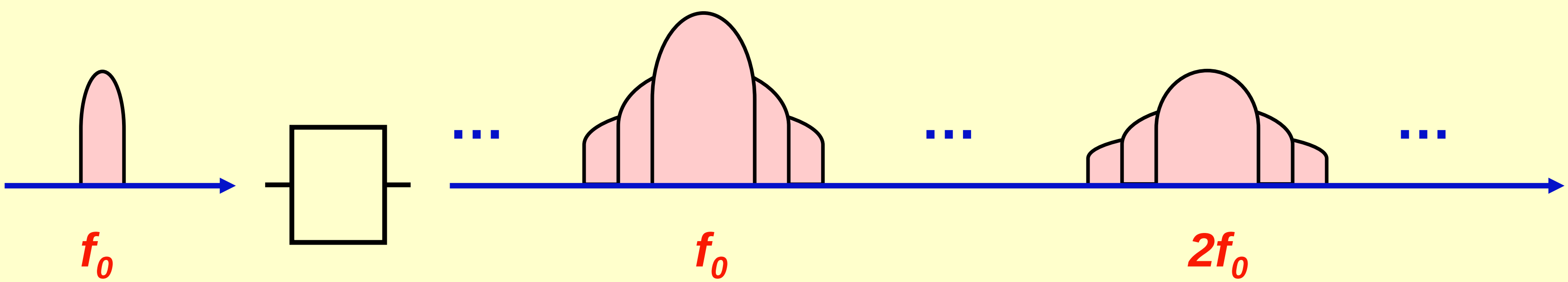
Motivation

Measurement based behavioural modelling

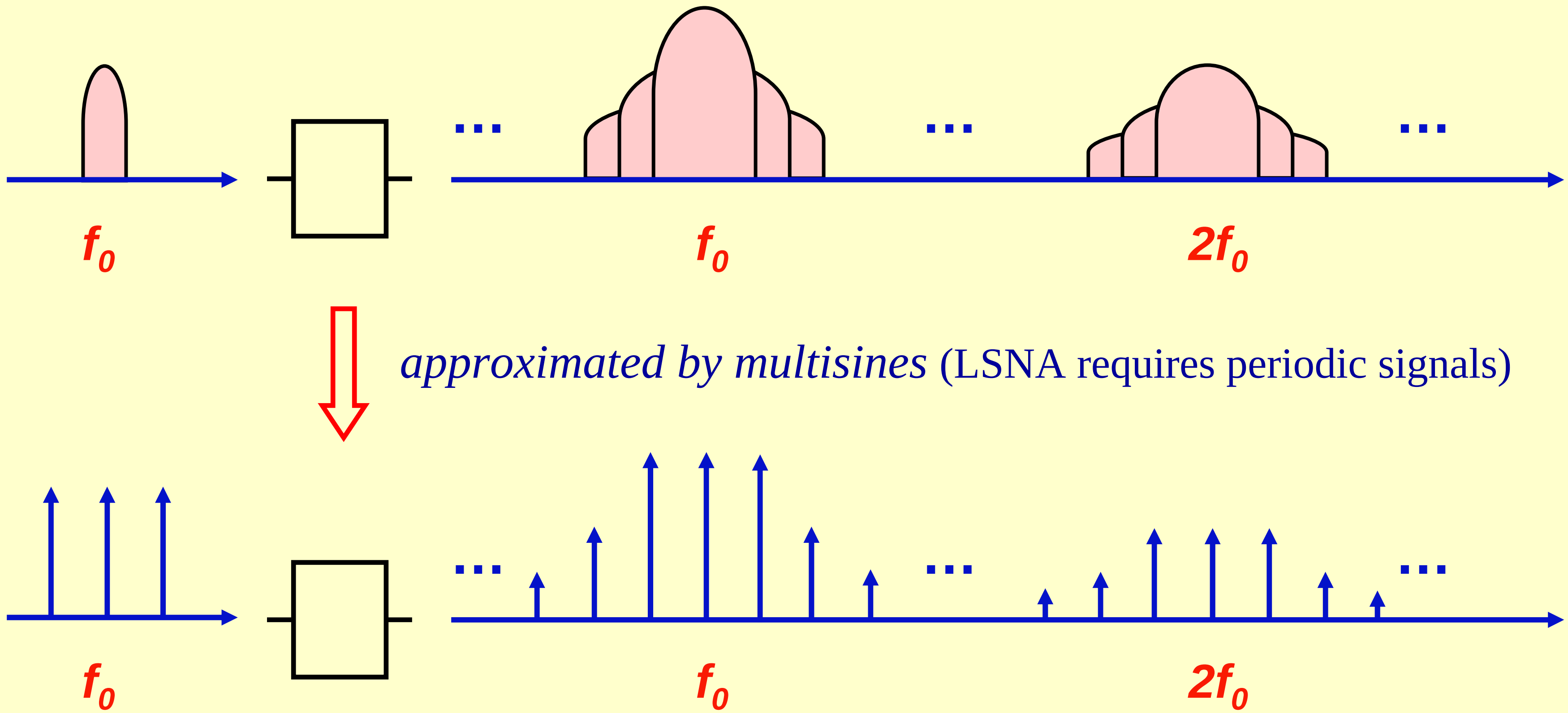
- Traditionally: *single-tone* measurement based models



- Reality: models used under *modulated excitation* conditions



Measurement Limitations



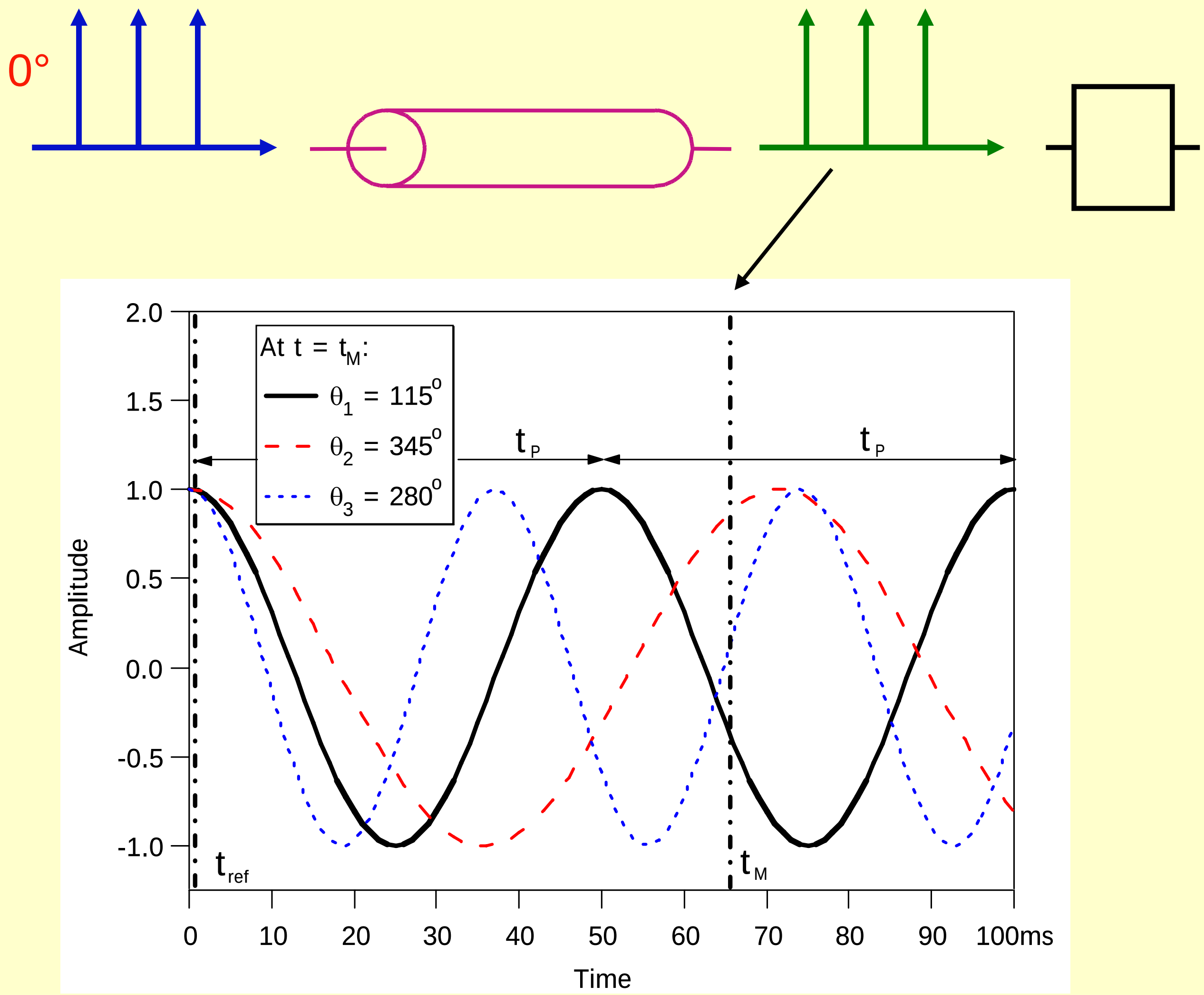
BW modulated signals: > 10 MHz

→ required measurement BW: ~100 MHz (to measure ACPR)

↔ BW LSNA: 8 MHz

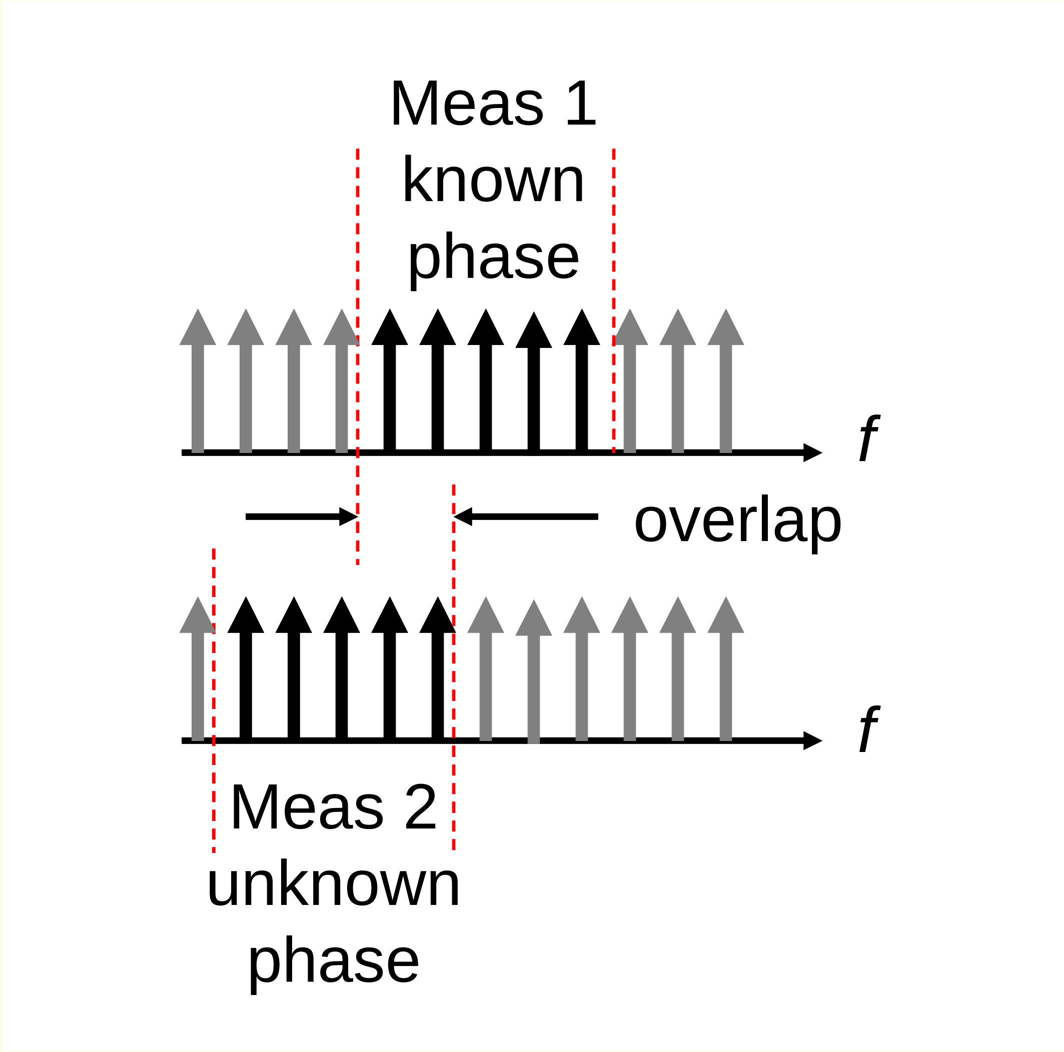
↔ BW VSA: 36 MHz

Phase Detrending



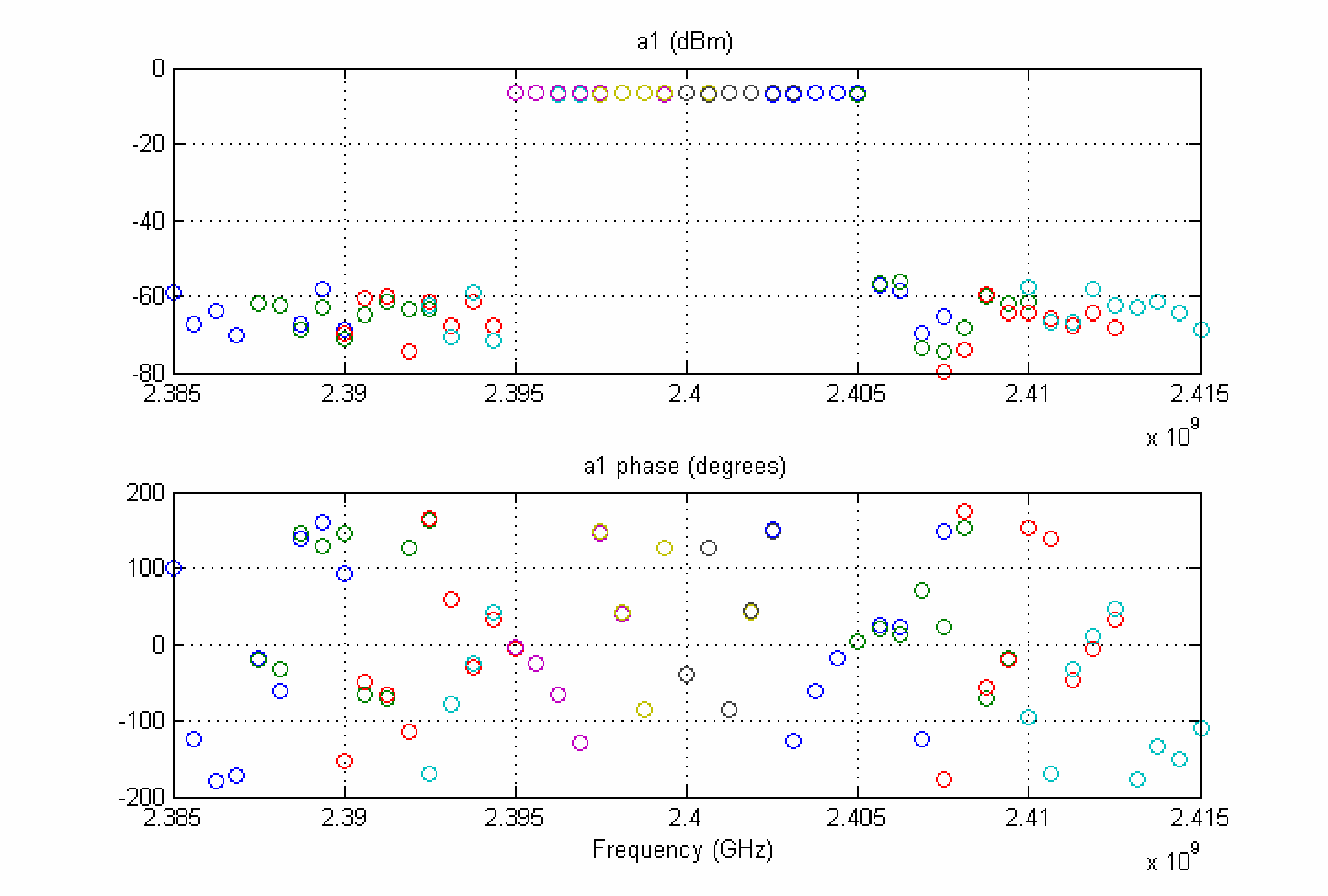
K. Remley *et al.*, "Phase Detrending for Measured Multisine Signals," ARFTG, 2003

Stitching Method: Principle One-Port

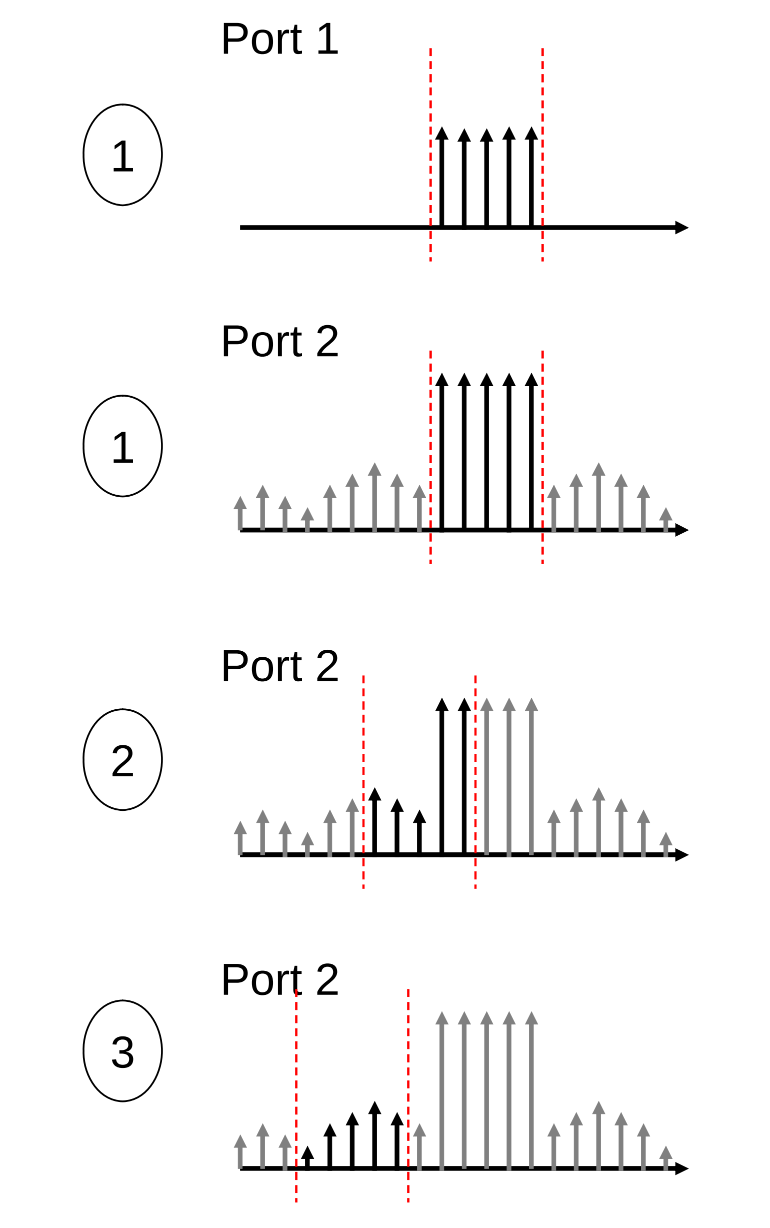


LSNA Results: a_1

- excitation: 10 MHz 17-tone Schroeder multisine
- stitching 13 IF blocks: Δf= 2.5 MHz, 9 tones of which 5 overlapping

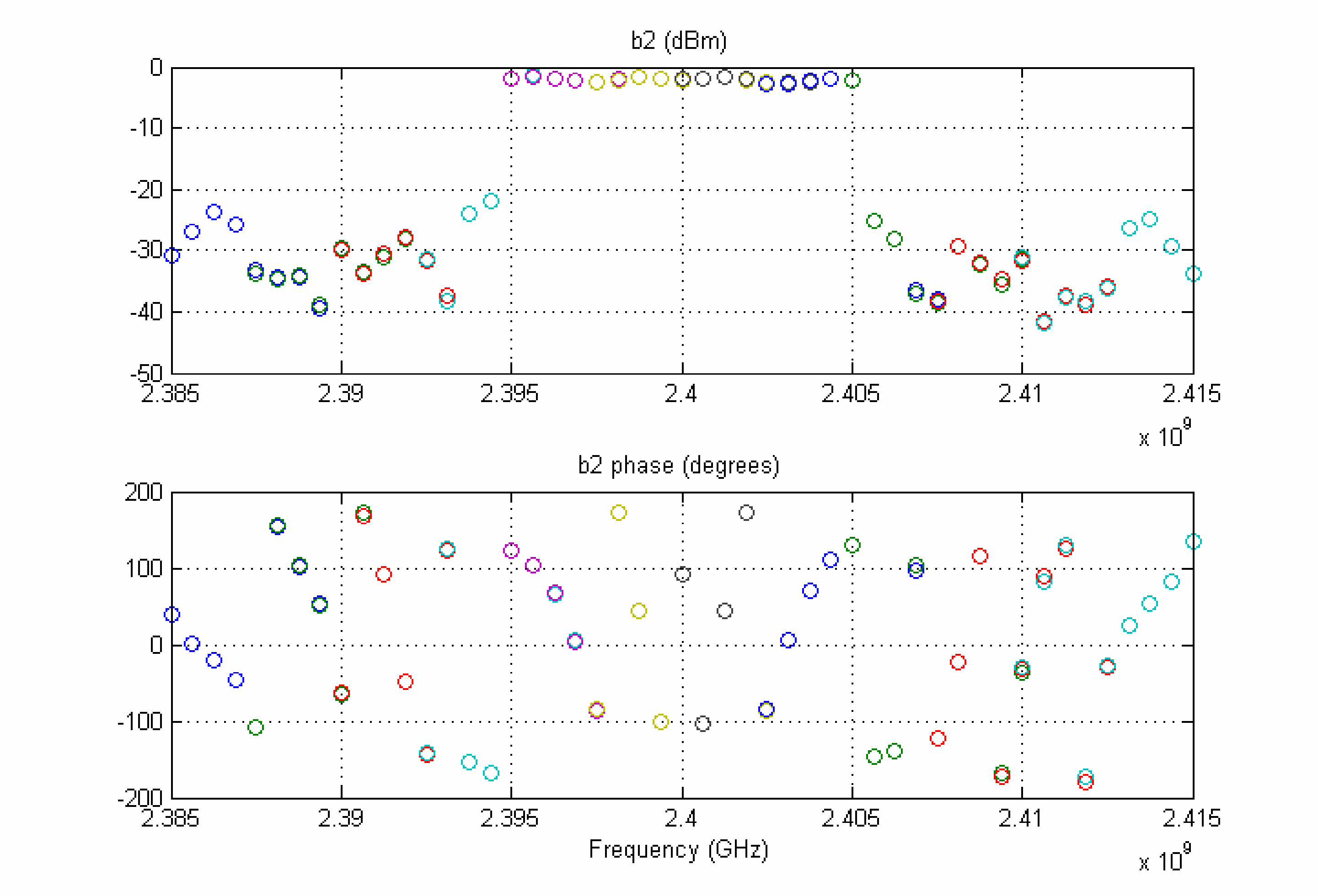


Stitching Method: Principle Two-Port



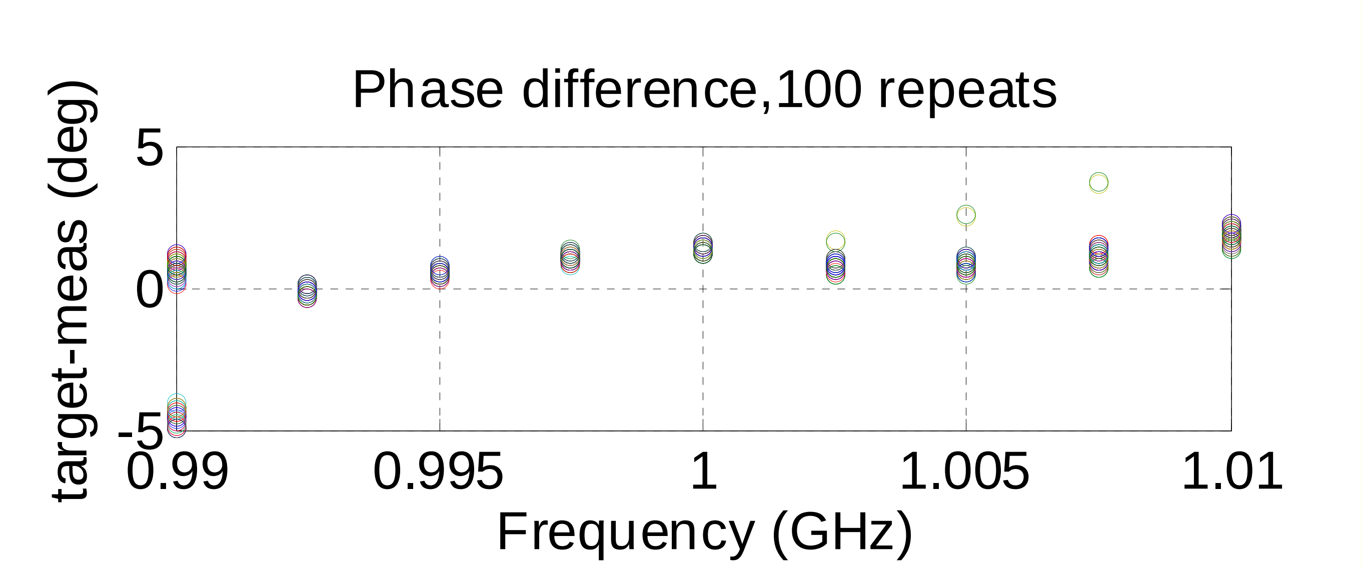
LSNA Results: b_2

- stitching 13 IF blocks: Δf= 2.5 MHz, 9 tones of which 5 overlapping
- spectral regrowth can be measured!



VSA Results

- excitation: 20 MHz 9-tone Schroeder multisine
- stitching 5 IF blocks: Δf= 5 MHz, 8 overlapping tones
- 100 repeats



Conclusions

- BW extension by stitching several IF measurement blocks

  = post-processing technique, requiring no hardware changes!

- Demonstrated on LSNA and VSA

- Next steps
  - Apply in behavioural modelling

66th Microwave Measurements Symposium
"Measurements of High Performance Devices and Applications"

Workshop on Nonlinear Measurements

WIDEBAND TIME-DOMAIN MEASUREMENT/MODELING: MOTIVATION, ISSUES, SUCCESSES

Dr. Christopher P. Silva

The Aerospace Corporation
El Segundo, California

Washington Marriott Hotel
Washington, DC

30 November 2005

Outline

- *Why Wideband, Baseband, and Time-Domain Measurements/Models?*
- *Aerospace Time-Domain Measurement System (ATDMS)*
  - Basis and technique description
  - System configuration and application
- *Blackbox Modeling of Nonlinear Components and Systems*
  - Fidelity quantification and requirements
  - *n*-box models and polyspectral method
  - Sample applications to high-power amplifiers (HPAs)
- *Conclusions*

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Why Nonlinear Measurement & Modeling?

- *Several classical/emerging factors in commercial and military arenas motivate need for state-of-the-art measurement and modeling.*
  - Performance/feature demands in challenging user and communications environments.
    - » *Requires broadband channels, increased power or bandwidth efficiencies.*
  - Power efficiency demands typically require nonlinear operation of HPAs.
    - » *Induces nonlinear distortion (deterministic or stochastic) that must be characterized accurately for effective mitigation design.*
  - Simultaneous data throughput and bandwidth efficiency demands require multilevel *amplitude phase-keying* (APK) modulations, making characterization/ mitigation even more challenging.
  - Similar set of challenges encountered for emerging multi-carrier systems.
  - Accurate measurements needed for several purposes:
    - » *Construction and validation of nonlinear HPA and system-level simulation models.*
    - » *System diagnosis and specification testing.*

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Frequency- vs. Time-Domain Measurements

- *Frequency-domain measurements are most widely used and accepted form of component/system characterization.*
  - Performed primarily with VNA, resulting in very accurate calibrated gain and phase measurements.
  - Excellent for linear case, less so for nonlinear case due to basic limitations.
    - » *Stimulus signals limited to single sinusoids swept in power/frequency.*
    - » *Cannot capture classical and unique nonlinear effects (intermodulation, harmonics, noise).*
  - Spectrum analyzer can capture nonlinear effects, but much less accurately and with no important phase information.
- *Time-domain measurements are typically less accurate but have no nonlinear application limitations.*
  - Classical approaches record RF waveform directly with digital storage oscilloscope (DSO) or Microwave Transition Analyzer (MTA).
  - Captures all nonlinearity effects, whether deterministic or stochastic.
    - » *Especially useful for nonlinearities with memory exhibiting frequency-dependent effects.*
  - Allow for use of operational signals as stimuli instead of simple single CW tones.
    - » *In principle, can formally identify nonlinearities using appropriate stimuli.*
  - Aerospace baseband approach overcame traditional limitation on measurement accuracy.

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Why Baseband Time-Domain Measurements?

- *Measurements of time-domain waveforms at lower frequencies offers several important advantages:*
  - Recording instrument accuracy greatly improves.
  - Coherent downconversion eliminates carrier phase noise.
  - Large reduction in sampling requirements implies longer time records or higher time resolution possible for measured data.
  - Accuracy of measurement is independent of carrier frequency.
  - Downconversion to baseband maximizes accuracy and results in complex *lowpass equivalent* (LPE) envelope of waveform.
  - Baseband data can be used to directly construct LPE model compatible with standard communication system simulation tools.
- *Approach is only possible if downconverter response (amplitude and phase) can be calibrated out of the measurement.*

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Aerospace Measurement Developments

- *Two novel and critical innovations enabled very accurate measurement of wideband time-domain signals.*
  - *Frequency-translating device (FTD) characterization (1996)* — Solved classical problem of obtaining amplitude and phase transmission response using a VNA.
    - » *Applicable from frequency converters to whole communication segments with frequency offset between input and output.*
    - » *Accurately determines converter phase distortion that can impact modern digital modulation performance.*
  - *Baseband time-domain measurement technique (1998)* — Developed means for extremely accurate measurement of communication signals.
    - » *Basic strategy: Downconvert signals to baseband and use FTD method to remove downconverter distortions.*
    - » *Enabled successful application of time-domain-based modeling approaches.*
    - » *Remaining important issues to address: FTD reciprocity characterization and development of time-domain traceable standard.*

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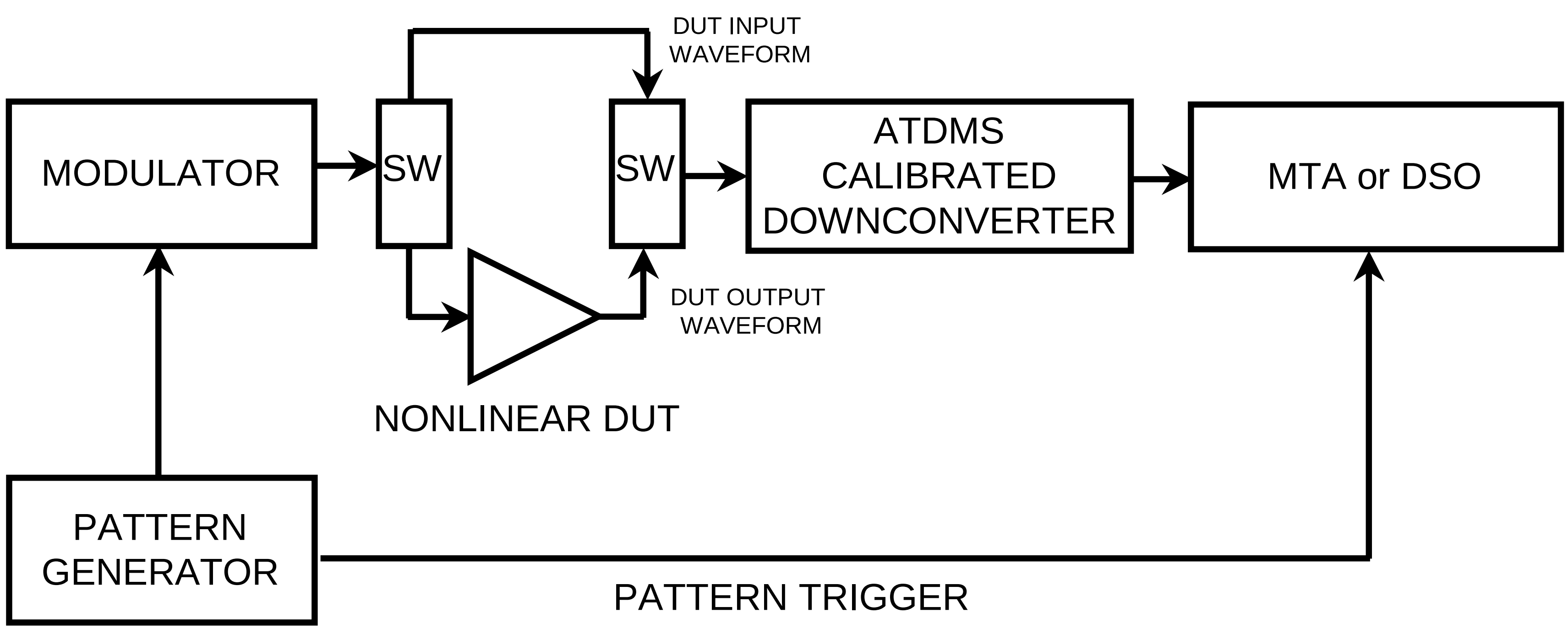
Basic Measurement Configuration

- *Following ATDMS setup used to make time-domain measurements with digitally modulated signals for model construction and validation.*
  - MTA or DSO as baseband recording instrument (MTA superior).
  - Fully automated via LabVIEW™ control (calibration and input/output time-domain recording).
  - Accommodates periodic, but otherwise arbitrary signals.
    - » *Periodicity required by separate I/Q waveform recording.*



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ATDMS Implementation

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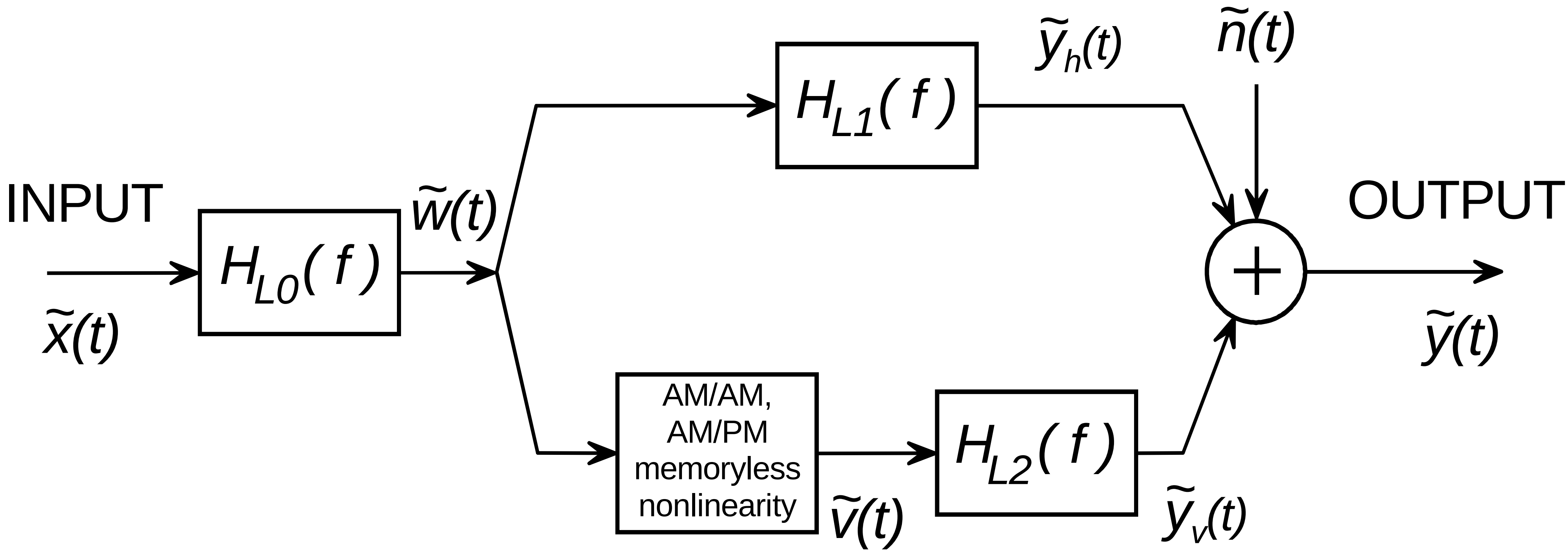
NMSE Waveform Metric/Fidelity Requirements

- *Waveform metric devised to quantify matching and repeatability of time-domain measurements, as well as model predictive fidelity.*
- *Error calculated on point-by-point basis using general normalized mean square error (NMSE) metric.*
  - Qualitatively, NMSE is average error power between two time-domain waveforms normalized to signal power of one of them (–10 dB NMSE = 10% relative error).
- *Important issues of required model fidelity and validation not yet adequately addressed.*
  - Models need to be evaluated for operational signals.
    - » *Need becomes more critical with increasing bandwidths, data rates, and modulation complexity — caused by inherent nature of nonlinear input/output operators.*
    - » *Makes sufficiently accurate time-domain measurements crucial to model validation.*
      - Current ATDMS has repeatability below –55 dB NMSE, constituting the model fidelity floor.
  - Required NMSE fidelity can be systematically determined from BER performance curves and system requirements.

Aerospace Model Developments

- *Developed both n-box (n = 1,2,3) and more sophisticated polyspectral HPA models, the latter especially accurate for wideband HPAs.*
  - Simplified, practical baseband version of general formal Volterra series identification.
    - » $H_{L0}(f)$ *derived from small- or large-signal VNA sweep of HPA.*
    - » $H_{Li}(f)$ (i = 1,2) *are calculated baseband equivalent model parameter filters.*
  - Approach provides several important benefits that also impact nonlinear distortion compensation analysis/design.



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Nonlinear HPA Modeling I

- *1-box and 2-box model constructed/validated for commercial 20-GHz SSA over several different operating conditions.*
  - Small-signal response measured over 8 GHz with VNA.
  - Two types of digitally modulated signals used with ATDMS.
    - BPSK signal with bit rate from 150 Mbps to 2.4 Gbps and 5-GHz bandlimiting pre-filter.
    - 16-QAM signal with fixed 9.6 Gbps rate using either no pre-filter or a 3-, 4-, and 5-GHz bandlimiting pre-filter.

BPSK Signals

Data Rate (Mbps)	1-Box Model NMSE (dB)	2-Box Model NMSE (dB)
150	*–27.92*	*–33.69*
600	*–22.64*	*–28.34*
1200	*–19.84*	*–26.24*
2400	*–18.72*	*–24.31*

16-QAM Signals

Bandlimiting Filter BW (GHz)	1-Box Model NMSE (dB)	2-Box Model NMSE (dB)
3	*–20.04*	*–24.30*
4	*–19.86*	*–23.61*
5	*–19.31*	*–23.19*
None	*–15.62*	*–19.44*

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Nonlinear HPA Modeling II

- *Polyspectral approach provided highest-fidelity, system-level model for both 20-GHz SSAs and TWTAs — NMSE results over 3-GHz BW:*

HPA	**Box Model** Average NMSE (dB) (Relative Error,%)	**Polyspectral Model** Average NMSE (dB) (Relative Error,%)	**NMSE Improvement (dB)**
JCA SSA	***2-Box*** *–21.5 to –24.6* *(0.35 to 0.71)*	***Version I*** *–26.9 to –28.6* *(0.14 to 0.20)*	*2.6 to 6.0*
Helix TWTA	***3-Box*** *–27.2 to –32.8* *(0.052 to 0.19)*	***Version II*** *–32.8 to –34.7* *(0.034 to 0.052)*	*1.7 to 6.1*

– Several important observations:

» *Version II TWTA model consistently better than SSA Version I model via superior pre-filter.*

» *NMSE improvements highest at saturation (construction basis), lowest for 6 dB IBO.*

» *Model superiority maintained for all subsequent TWTAs over similar data sets.*

» *Results indicate true local identification of HPA.*

– SSA (TWTA) polyspectral model just (comfortably) adequate for 16-QAM simulations.

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Conclusions I

- *Both commercial and military communication systems demanding high power and bandwidth efficiencies, broadband capabilities.*
  - Motivates need for accurate measurements and nonlinear system models.
- *Time-domain measurements provide several advantages for capturing nonlinear effects.*
  - Needed for construction/validation of models, system diagnosis, and specification testing.
- *State-of-the-art automated time-domain measurement system developed at Aerospace.*
  - Based on distortion-free conversion to baseband where recording instruments are much more accurate.
  - Provides convenient envelope measurement data for LPE simulation models in common usage.
  - Includes several accuracy enhancement features/procedures, giving rise to better than –55 dB NMSE waveform repeatabilities.

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Conclusions II

- *Several issues remain to be addressed for ATDMS.*
  - Fundamental reciprocity assumption for FTD characterization basis.
  - Traceability of time-domain recording (DSO or MTA) to national standard.
- *Accurate nonlinear system models provide critical basis for meaningful performance trades and effective compensation design.*
  - Model choice should be guided by NMSE fidelity required for operational context.
  - *n*-box models will likely provide adequate fidelity for most wireless applications.
  - Polyspectral model provides state-of-the-art fidelity for challenging wideband, multilevel modulation, and multi-carrier contexts found in military satellite communication applications.
    - » *Exhibits flexibility, practicality, and many analytical/application benefits.*
    - » *Construction based on time-domain input/output measurements and spectral analysis.*
    - » *Best HPA system model fidelity to date for wideband digitally modulated signals.*
    - » *Method also provides set of analysis/design tools for application to current compensators and development of novel new ones.*

Broadband Measurements for Wireless Telecommunication Systems

ARFTG66th Nonlinear Measurements workshop

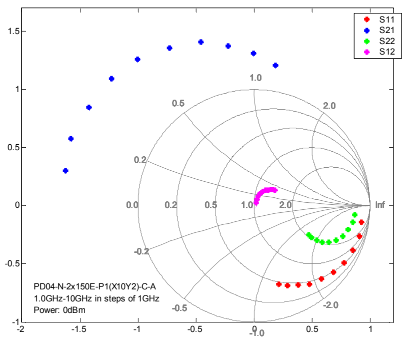
Organized by Kate Remley, NIST

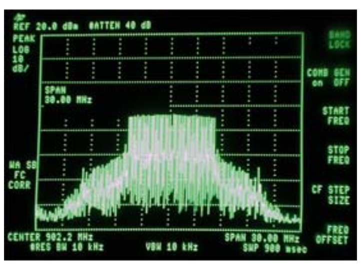
Needs & Prospective for Broader Bandwidth Non-Linear Measurements with the LSNA

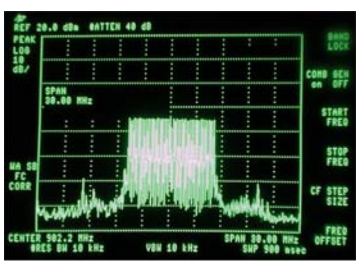
Patrick Roblin

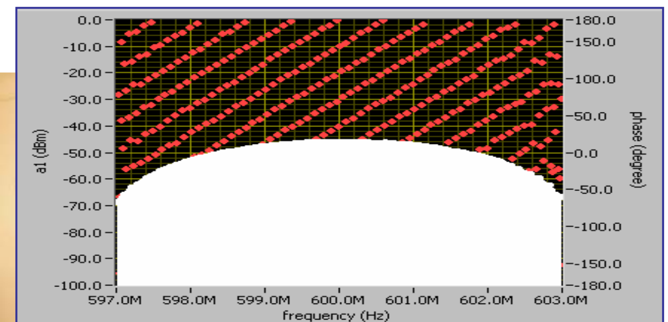
The Ohio State University

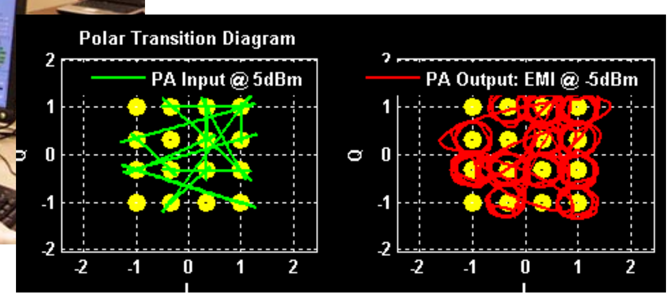
November 30, 2005



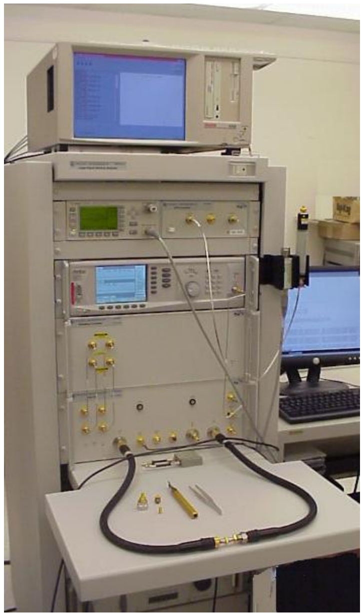


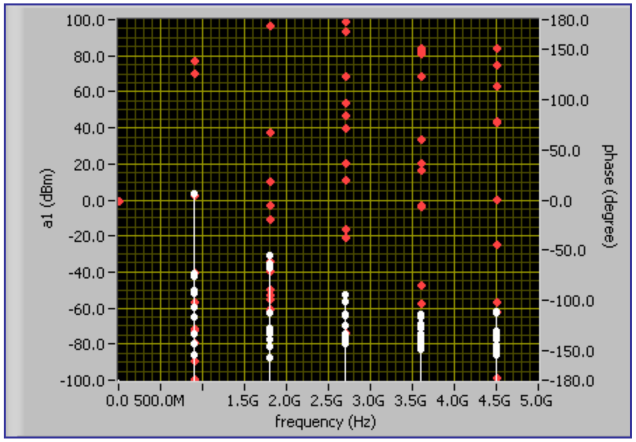


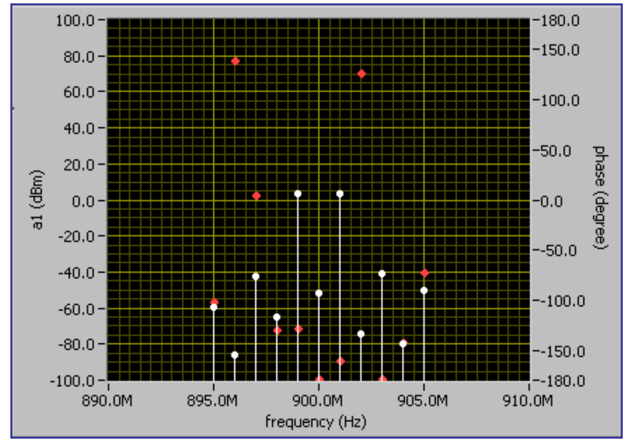




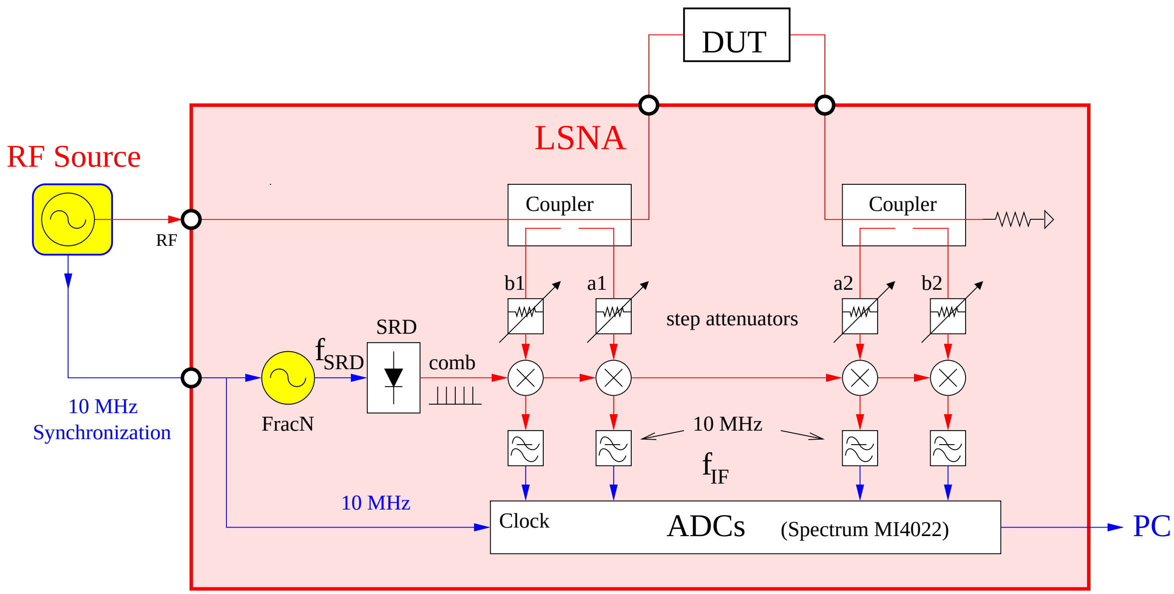
Features of the Large Signal Network Analyzer





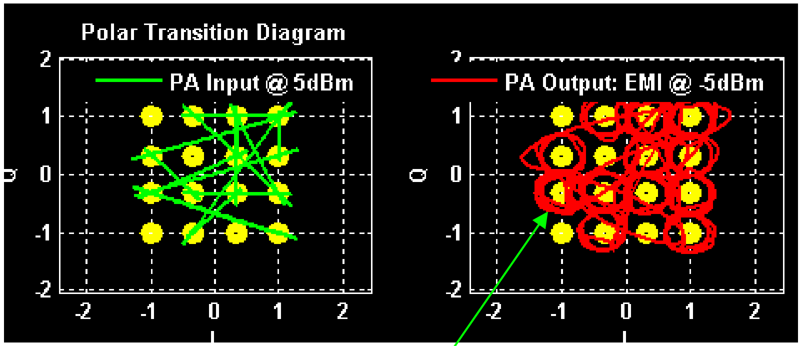


- Acquire amplitude & phase of harmonics up to 50 GHz
- Vectorial measurement of periodically modulated RF signals
- Modulation bandwidth is limited to 20MHz



Applications of LSNA needing Wider Bandwidth

- LSNA as a vector signal analyser (transition and constellation diagrams)
- Characterization of memory effects in PA non-linearities
- Pulsed RF S-parameters for shorter pulses
- Multi-port measurements with triggered LSNA

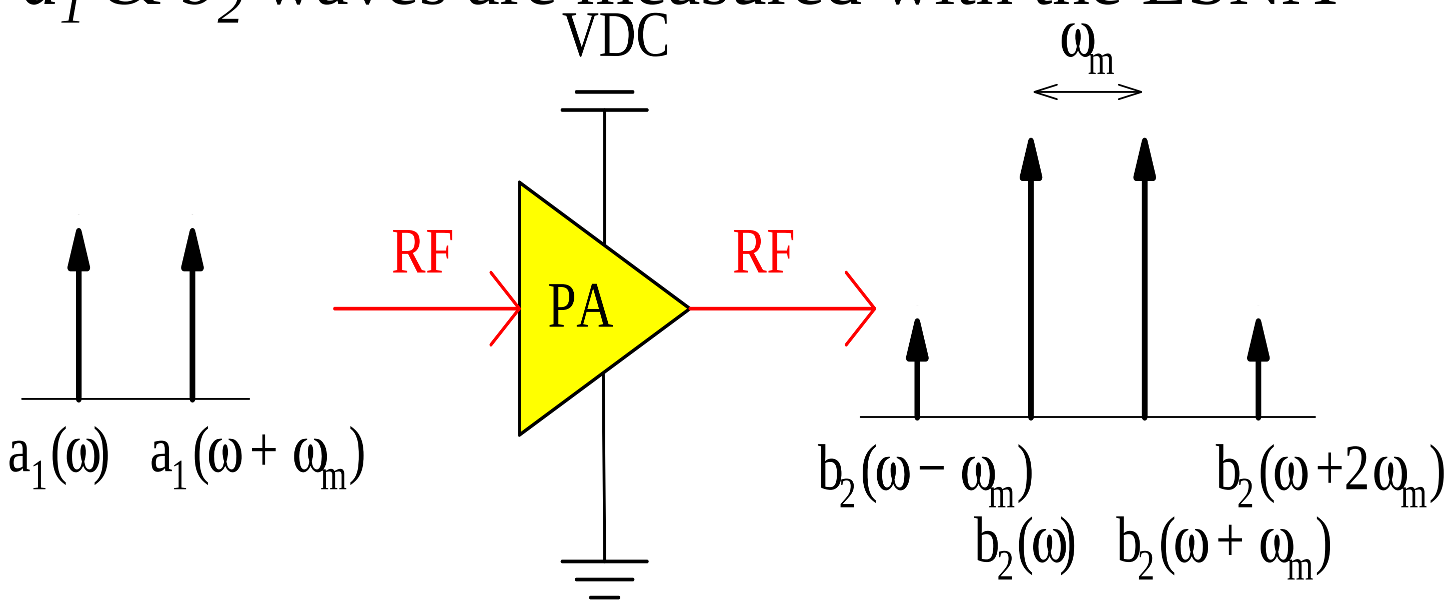


Constellation diagram recovered from LSNA multitone measurements on periodic QAM 16 signals

Effect of an interferer

Extraction of Y_{m3-}&Y_{m3+} using a 2-tone Signal

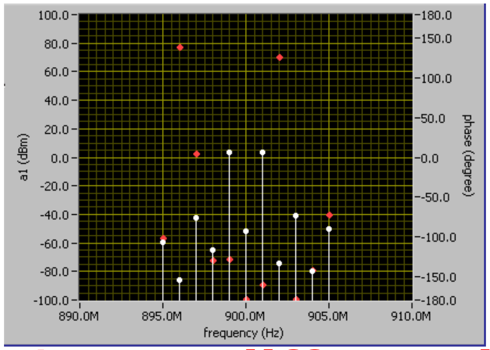
- The a_1 & b_2 waves are measured with the LSNA



- Generalized Volterra coefficients Y_{m3-} and Y_{m3+} for IMD3:

$$Y_{m3-} = \frac{b_2(\omega-\omega_m)}{a^2{}_1(\omega)a^*{}_1(\omega+\omega_m)} \qquad Y_{m3+} = \frac{b_2(\omega+2\omega_m)}{a^*{}_1(\omega)a^2{}_1(\omega+\omega_m)}$$

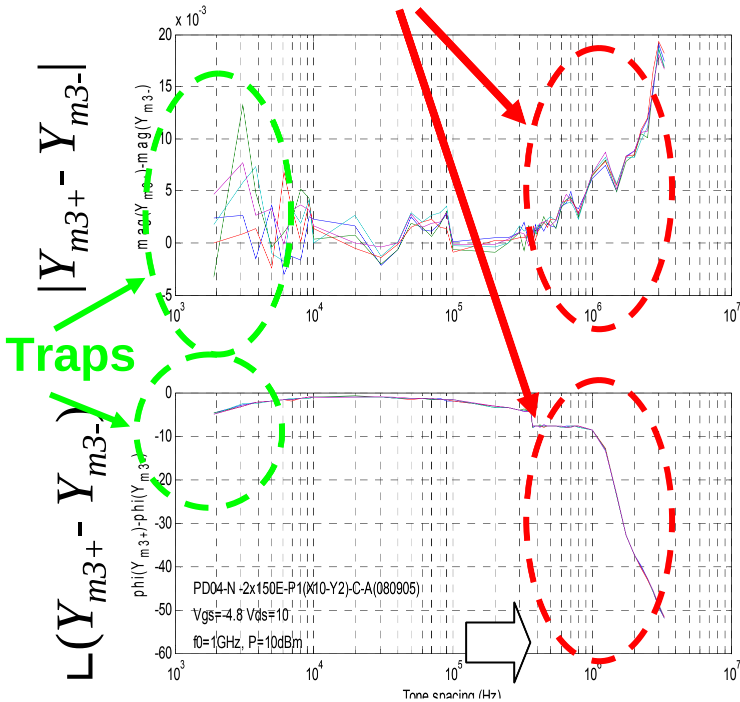
Differential memory effects: $Y_{m3-} \neq Y_{m3+}$

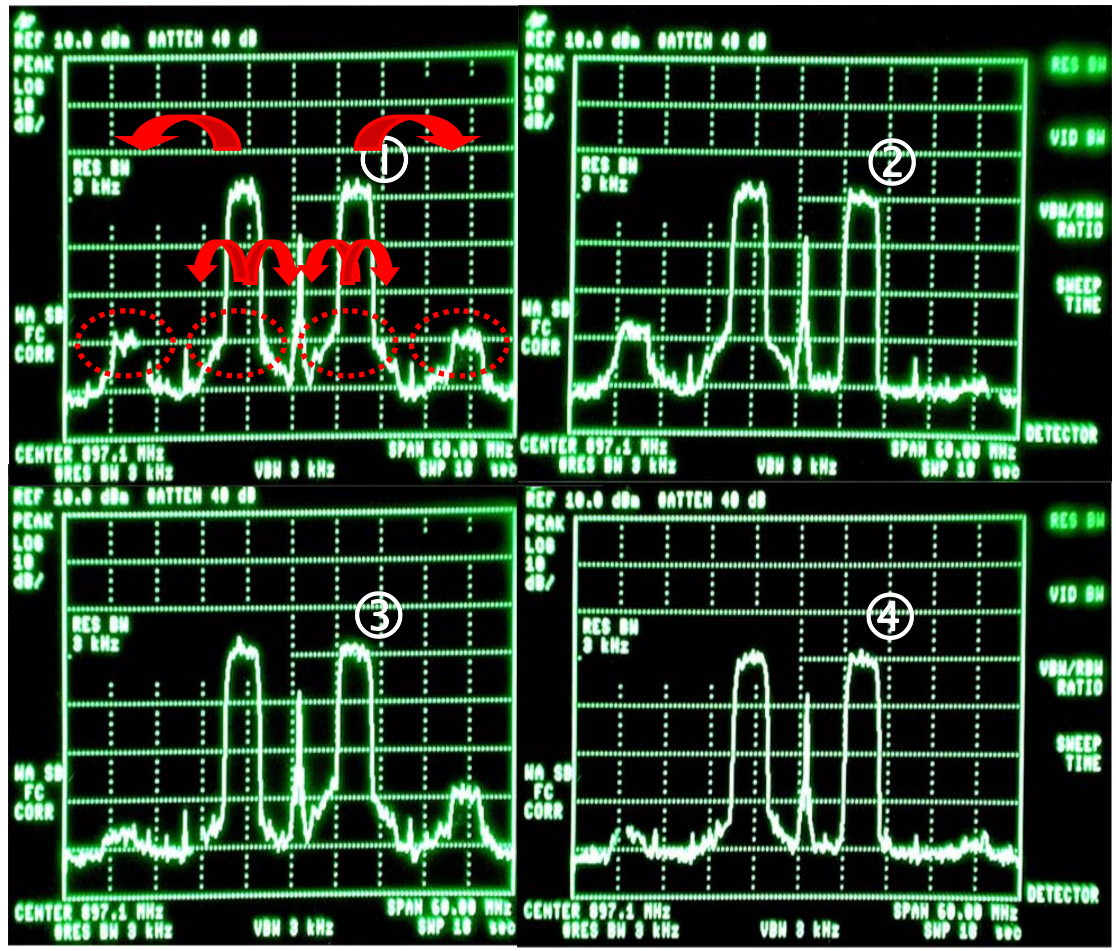


Multi-Carrier Linearization
2-Carrier WCDMA Results

Independent control of 6 bands (U&LSB)

Large ***differential*** memory effect above 1 MHz





Modulation Frequency ω_m

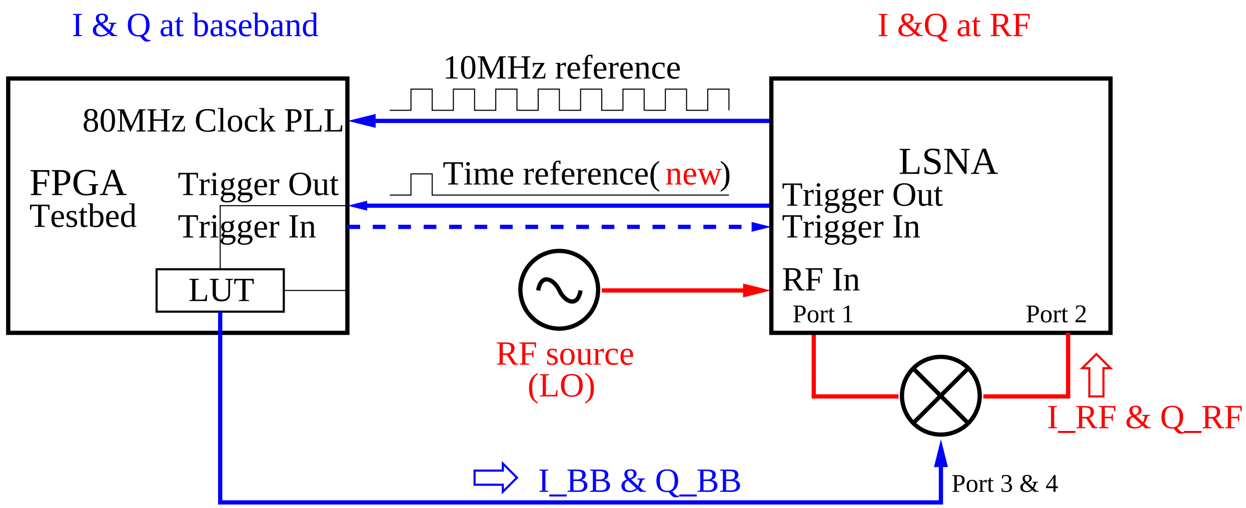
Data acquired with LSNA

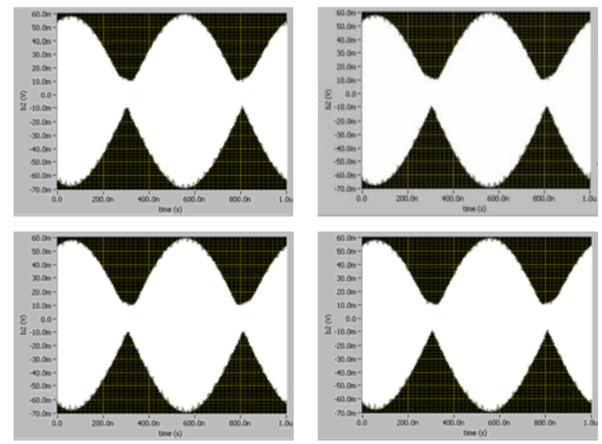
Need for larger bandwidth for OFDM & UWB

After linearization

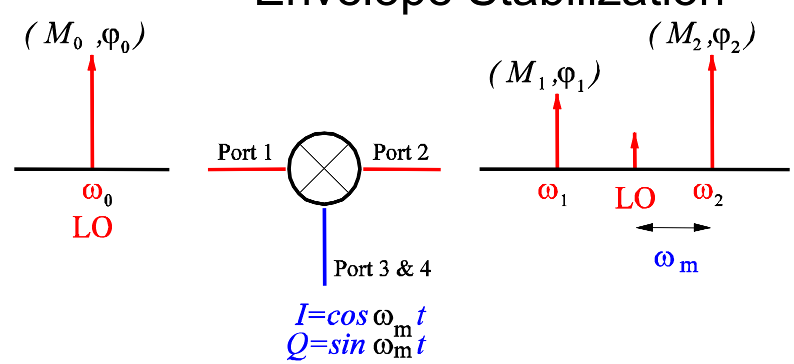
Multiport IF with triggered LSNA

Example: IQ Modulator Characterization

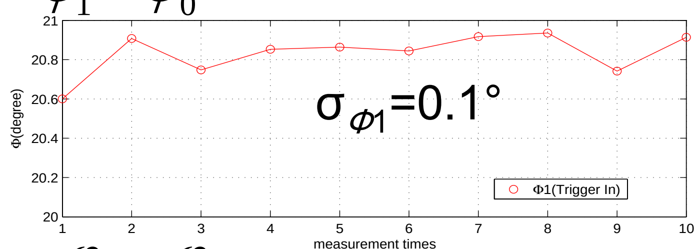




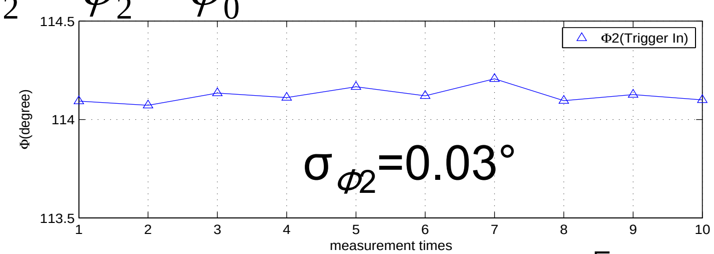
Envelope Stabilization



$$\Phi_1 = \varphi_1 - \varphi_0$$



$$\Phi_2 = \varphi_2 - \varphi_0$$



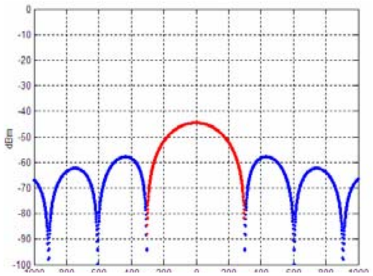
time

Need for larger bandwidth

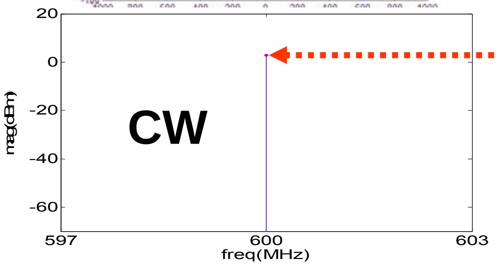
Phase error : $\Delta\phi = \omega_m \tau_{\text{rising}} / 2 = 0.36^\circ$

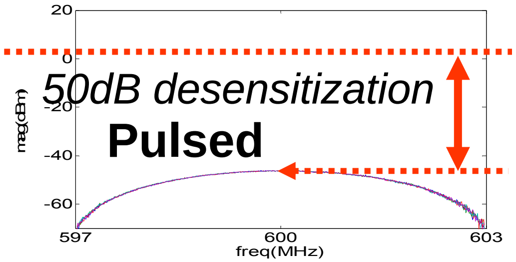
$$\begin{bmatrix} I_{RF}(t) \\ Q_{RF}(t) \end{bmatrix} = \left\{ M_1 \begin{bmatrix} \cos\Phi_1 & \sin\Phi_1 \\ \sin\Phi_1 & -\cos\Phi_1 \end{bmatrix} + M_2 \begin{bmatrix} \cos\Phi_2 & -\sin\Phi_2 \\ \sin\Phi_2 & \cos\Phi_2 \end{bmatrix} \right\} \begin{bmatrix} I_{BB}(t) \\ Q_{BB}(t) \end{bmatrix}$$

Pulsed RF Measurements with LSNA

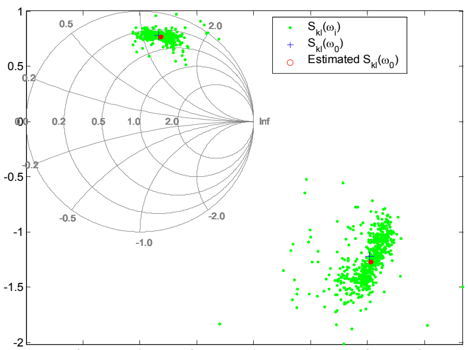


RF pulse width=0.33μs
10 kHz repetition rate
601 tones acquired

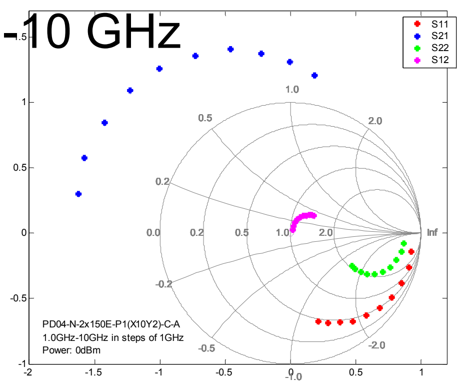


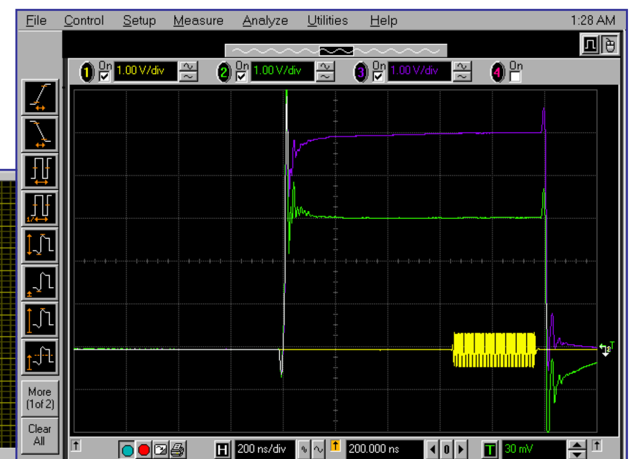


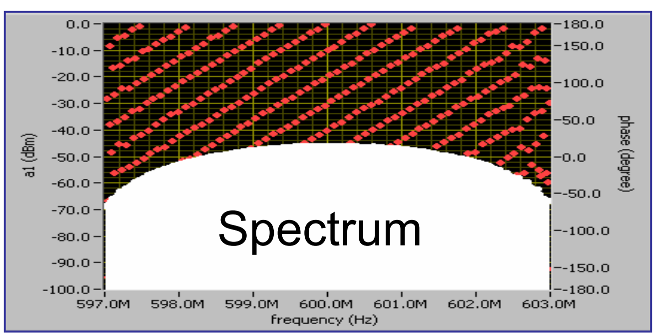
Wider bandwidth is required for RF pulsed below 100 ns

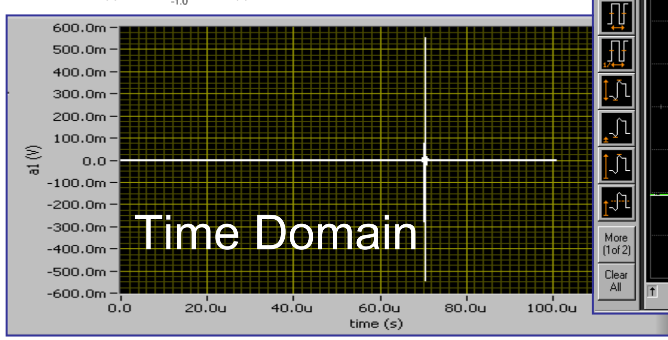


1-10 GHz







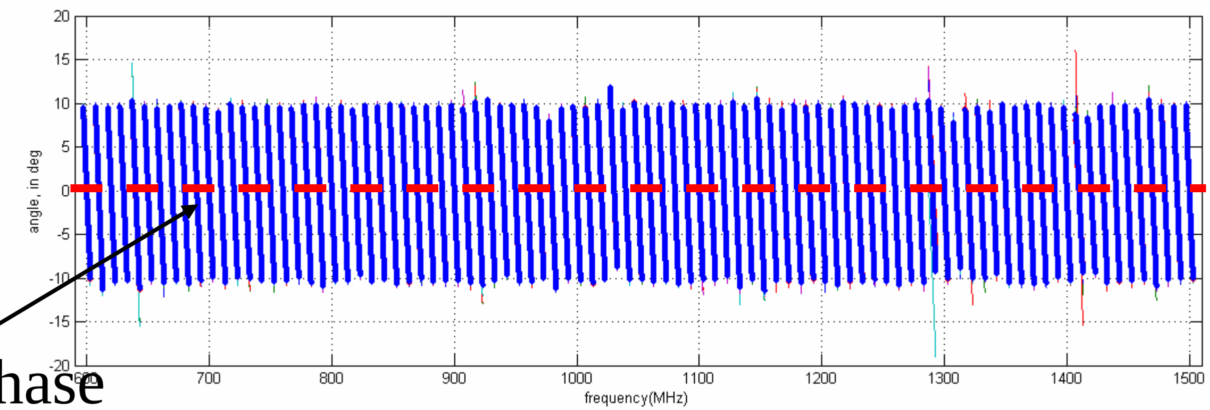


Pulsed IV/RF

IF Calibration

- Residual linear dispersion in IF calibration
- Can be characterized using a Thru (b_2=a_1) and Shorts (b_1=-a_1 and b_2=-a_2)
- These linear relative dispersions can be removed using 3 time constants: $\Delta\varphi = \Delta\omega\,\tau$

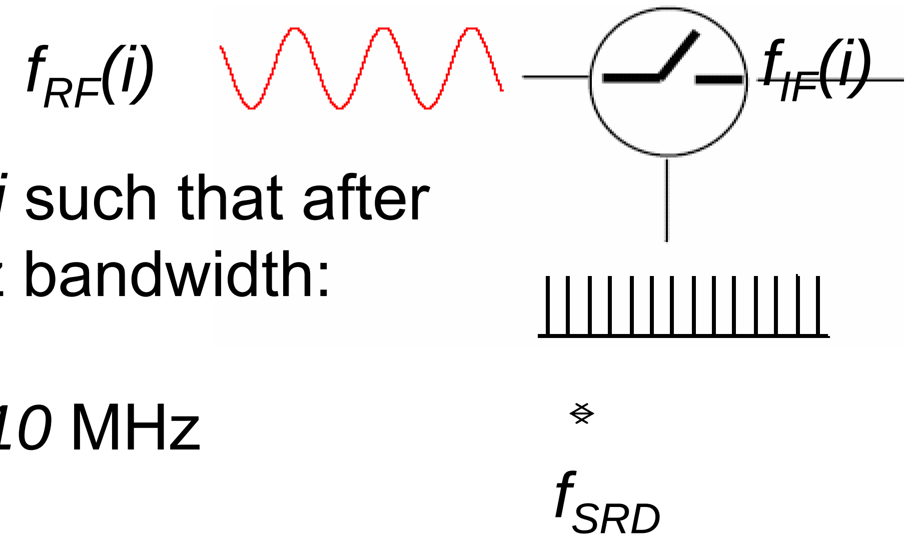
Dispersion in Thru when using 10 MHz Bandwidth Modulation



Expected phase

Alternative solution: calibrate at all tones measured.

Extension of LSNA up to GHz IF Bandwidth for UWB



Select f_{SRD} for each input tone *i* such that after downconversion in the 10 MHz bandwidth:

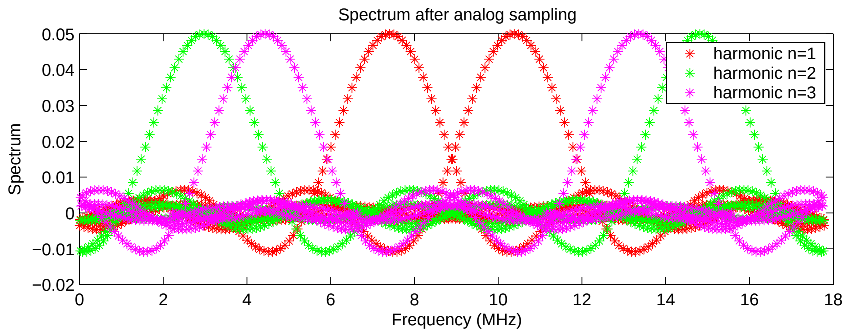
$$0 < f_{IF}(i) = f_{RF}(i) - m(i)\, f_{SRD} < 10 \text{ MHz}$$

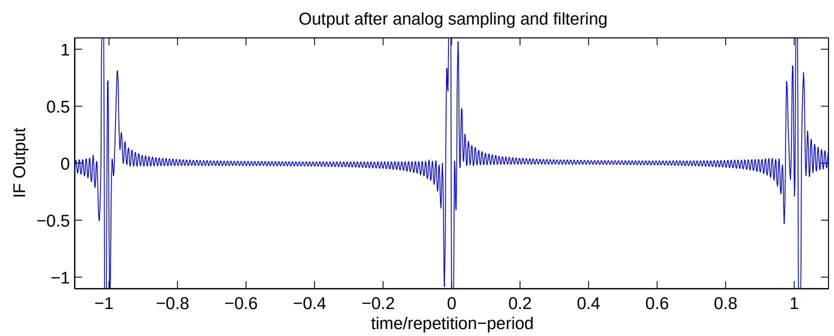
no overlap of the frequencies $f_{IF}(i)$ occurs.

- Present ADCs permit to resolve 10,000 RF tones with 100 Hz resolution.
- 280 MHz bandwidth was demonstrated by Jan Verspecht at *ARFTG62* Dec. 2003.
- New broadband calibration needed: simplest is to calibrate for all tones used. However using the IF calibration would be more efficient: For 1 GHz bandwidth we need 1 GHz/20 MHz= 50 IF bands and could use then any modulation.

Ideal Signals at the LSNA ADCs

Spectrum

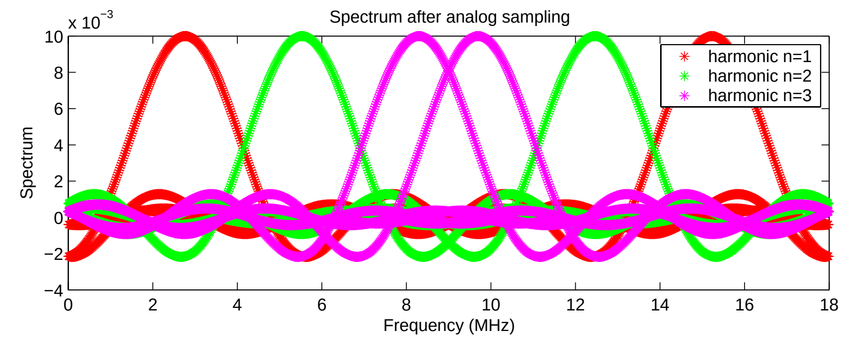


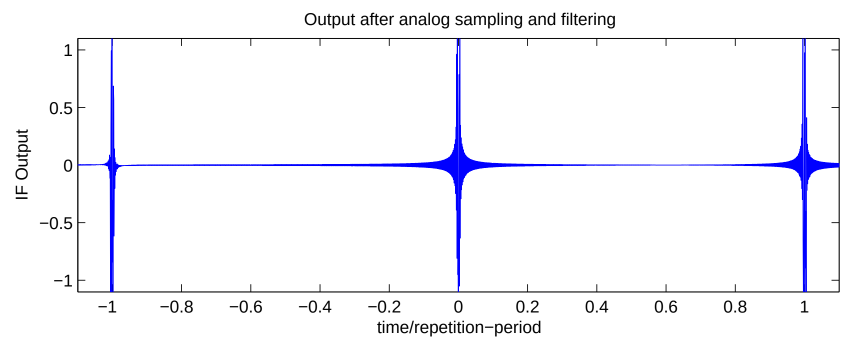


Time-domain

5% Duty Rate

Spectrum





Time-domain

1% Duty Rate

Conclusion

- The LSNA is intrinsically broad-band
- The same hardware/architecture can be used except for low duty rate pulsed-RF signals
- New RF/IF calibration is required to make use of its bandwidth compression
- Good tone accounting is required to map the IF tones measured at the ADCs to the correct RF tones

Measuring Broadband Modulated Signals Using Sampling Frequency Convertors

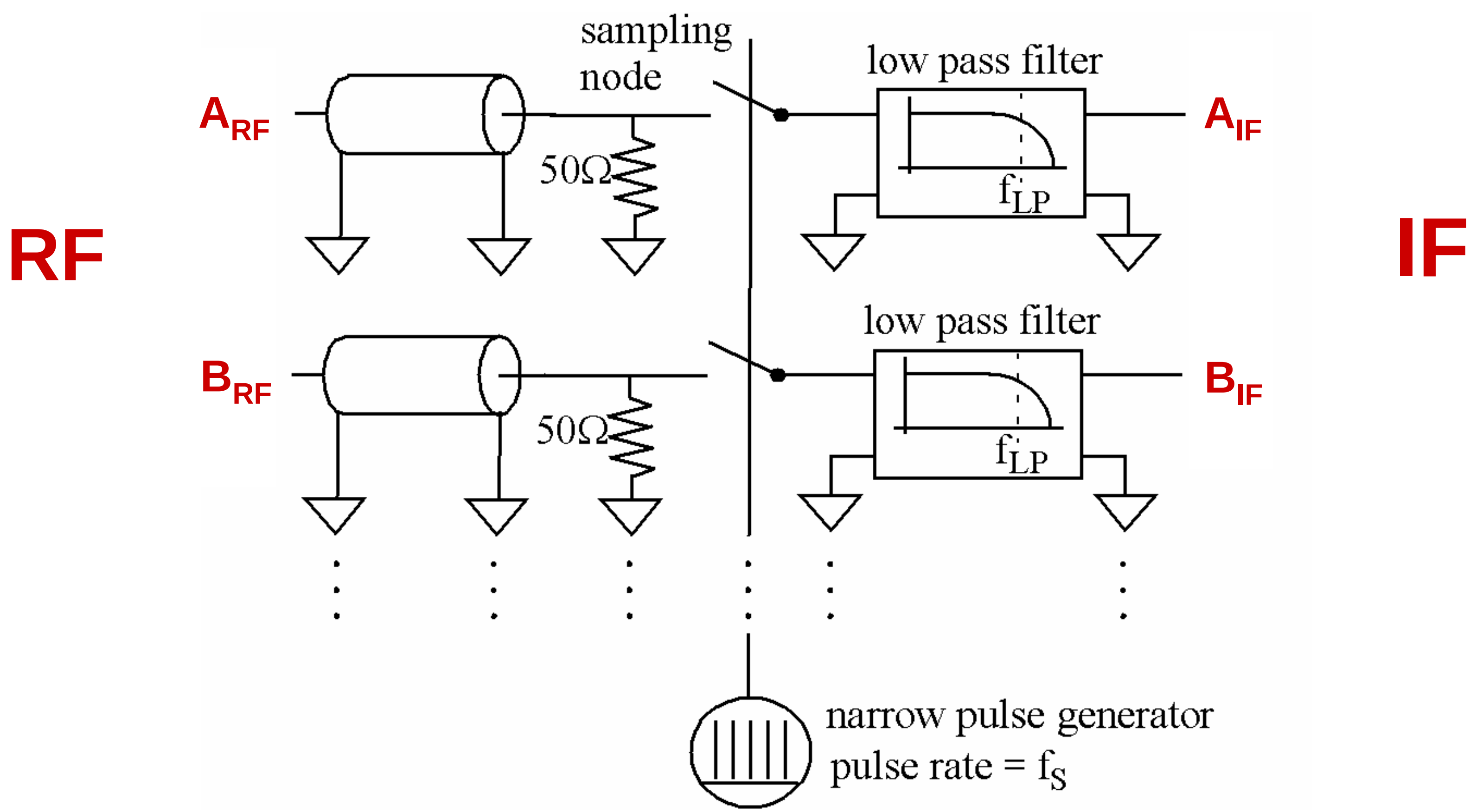
Jan Verspecht

"Jan Verspecht bvba"

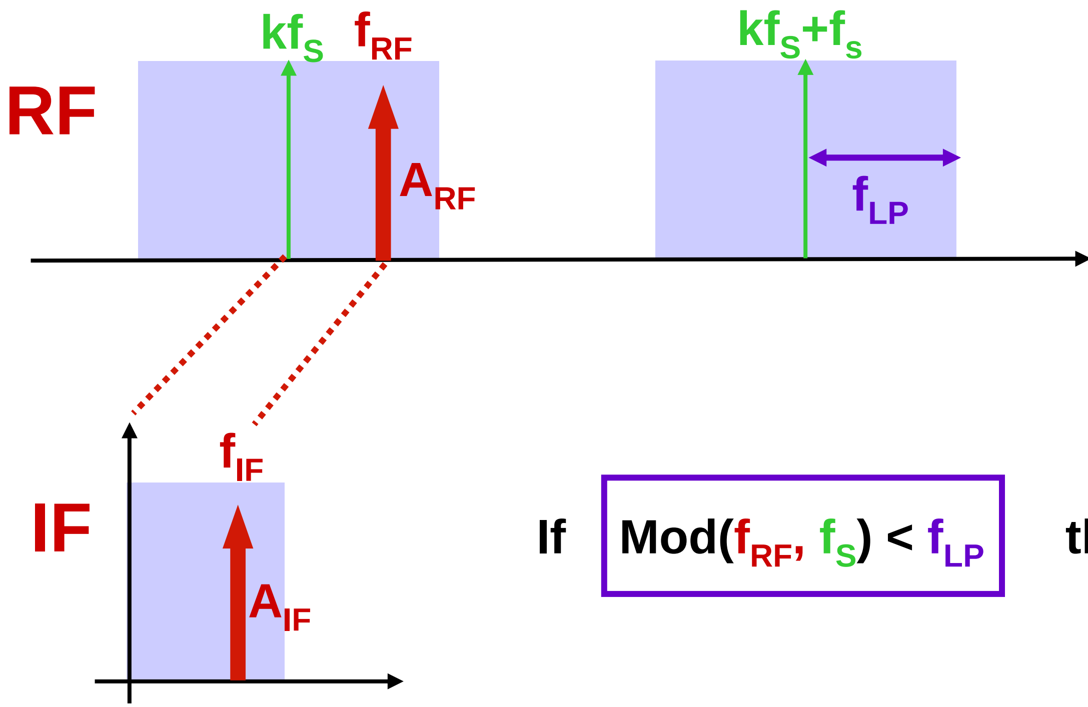
URL: http://www.janverspecht.com

This presentation contains several slides which are used with the permission of Agilent Technologies, Inc.

Sampling Convertor Basics



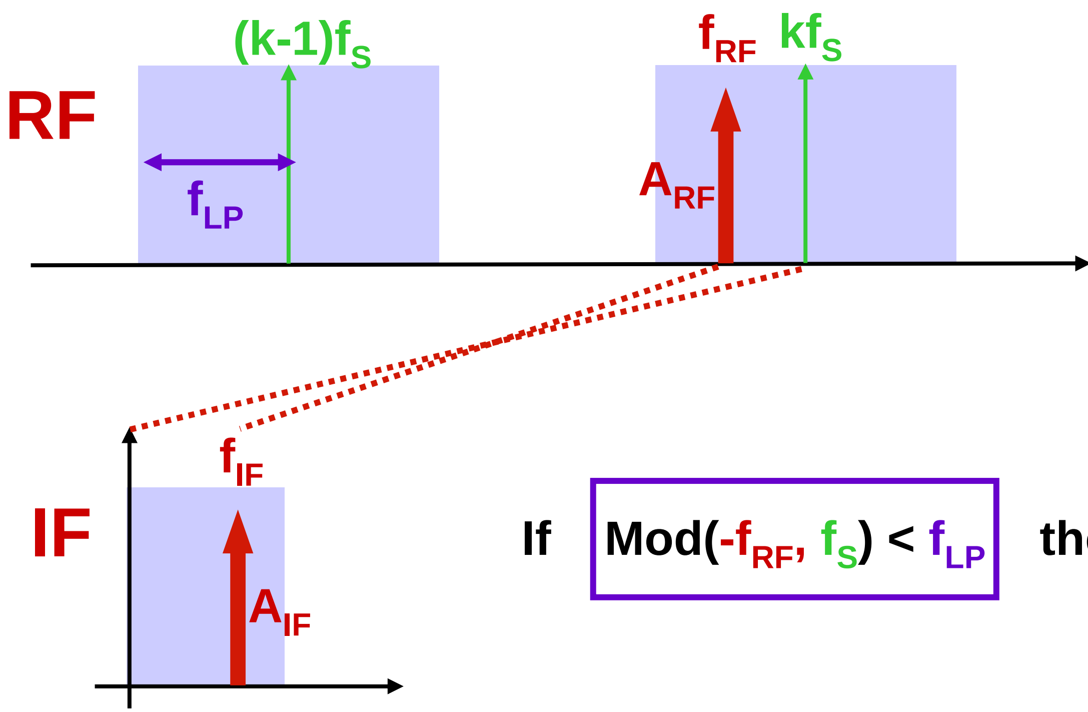
Frequency Mapping: Direct Mixing Product



If $\mathrm{Mod}(f_{RF}, f_S) < f_{LP}$ then

$$f_{IF} = \mathrm{Mod}(f_{RF}, f_S)$$
$$A_{IF} = A_{RF}$$

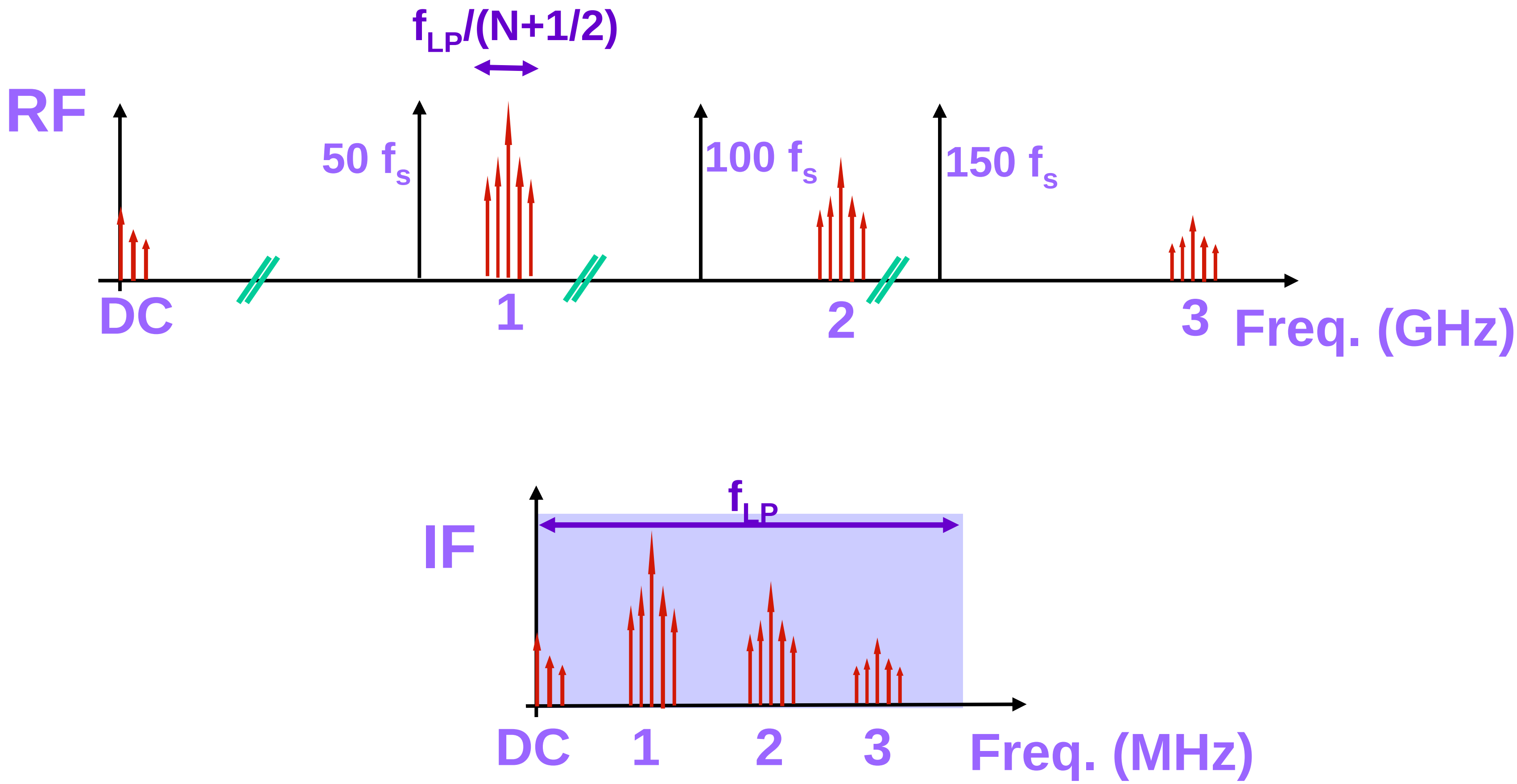
Frequency Mapping: Image Mixing Product



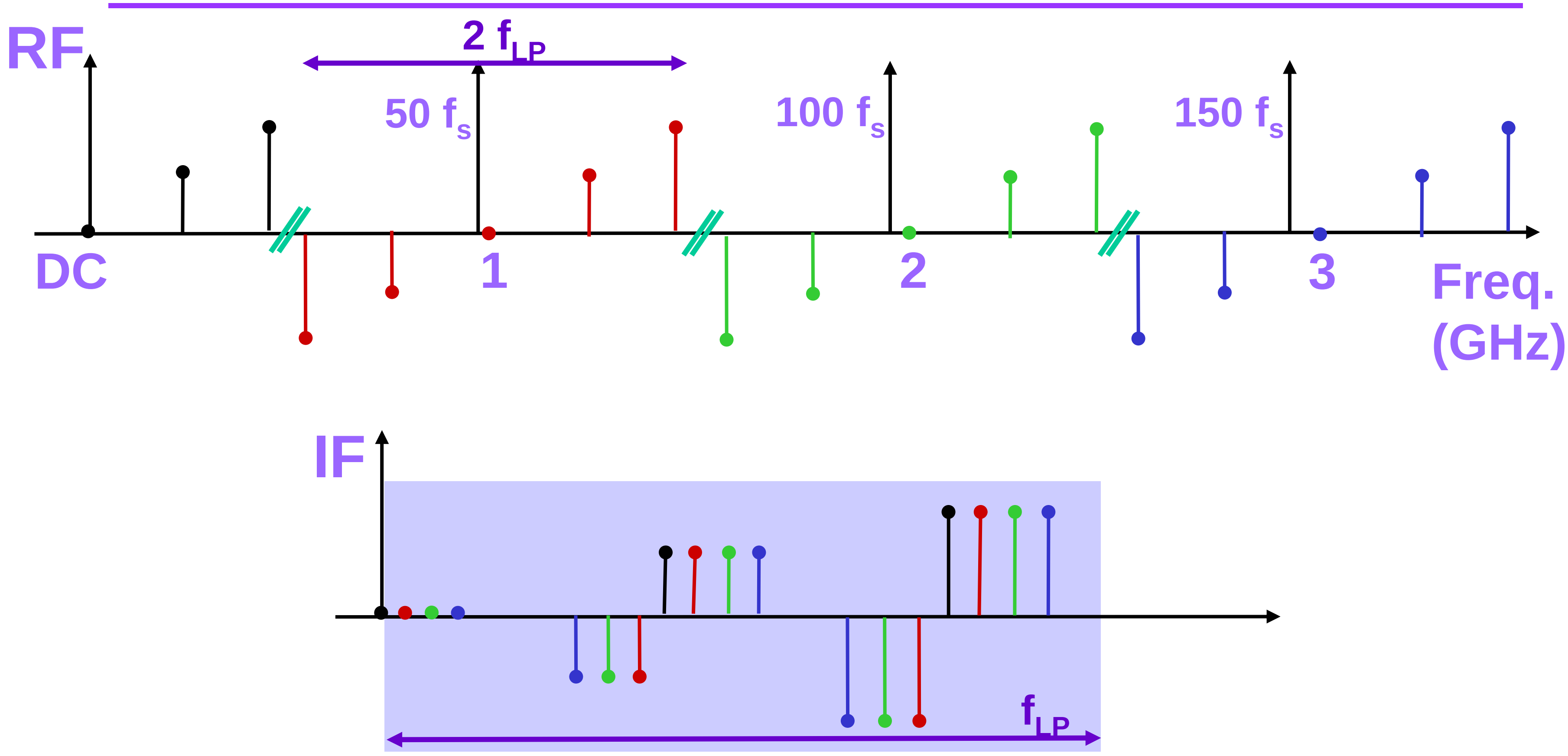
If $Mod(-f_{RF}, f_S) < f_{LP}$ **then**

$$f_{IF} = Mod(-f_{RF}, f_S)$$
$$A_{IF} = conj(A_{RF})$$

Modulation: Narrowband

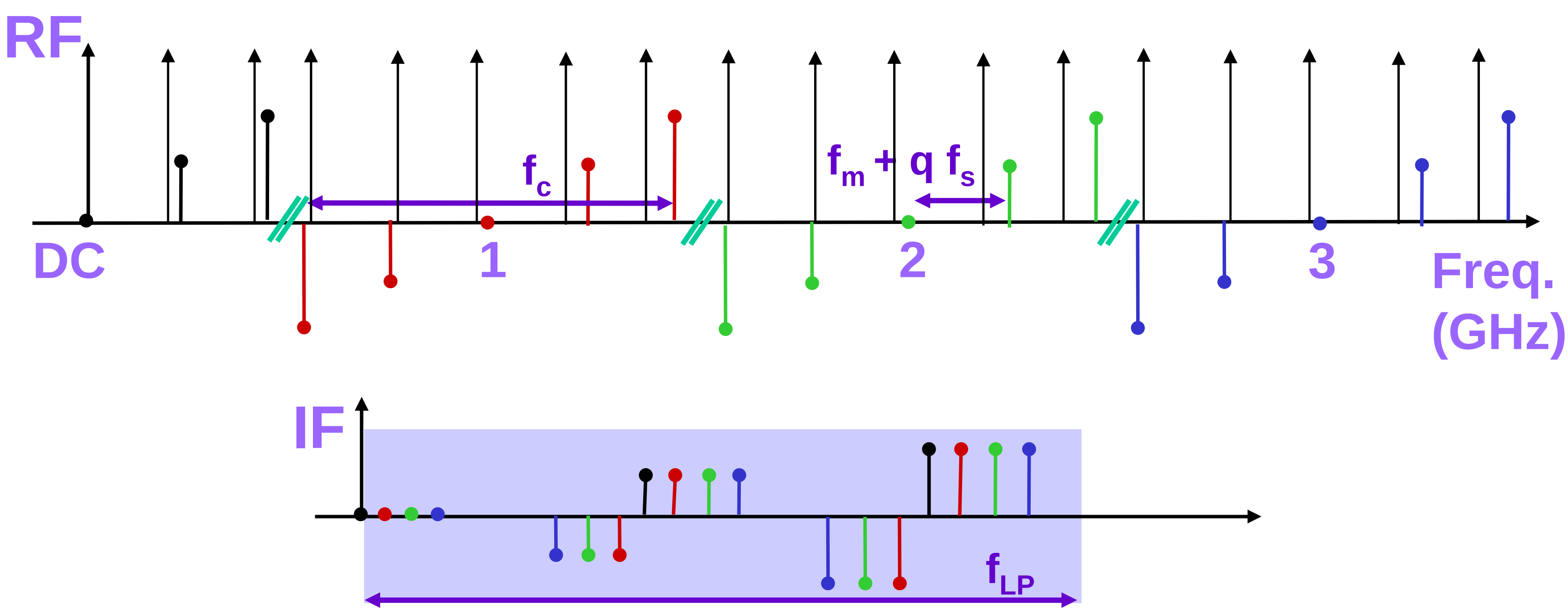


Modulation: Broadband



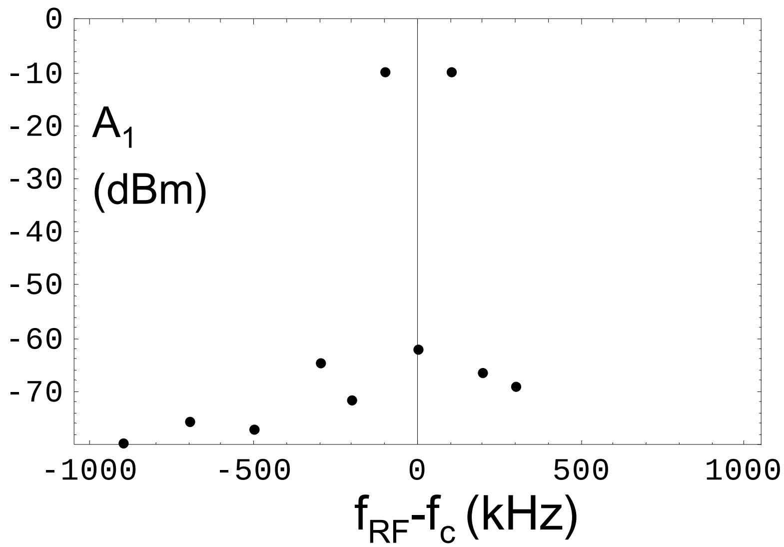
Modulation: “Even Broader”-band

Add an integer times f_s to the modulation frequency

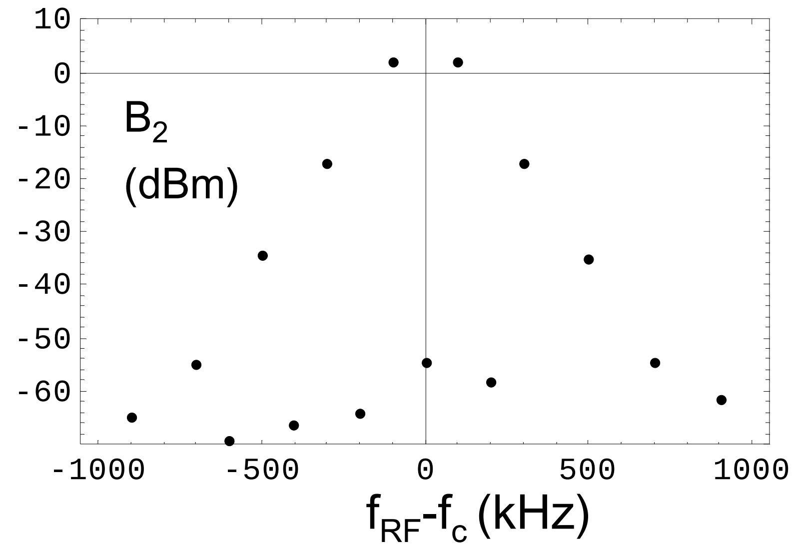


Measurement Application
LSNA with 2-tone excitation

Fundamental of A_1 (gate input signal)



Fundamental of B_2 (drain output signal)

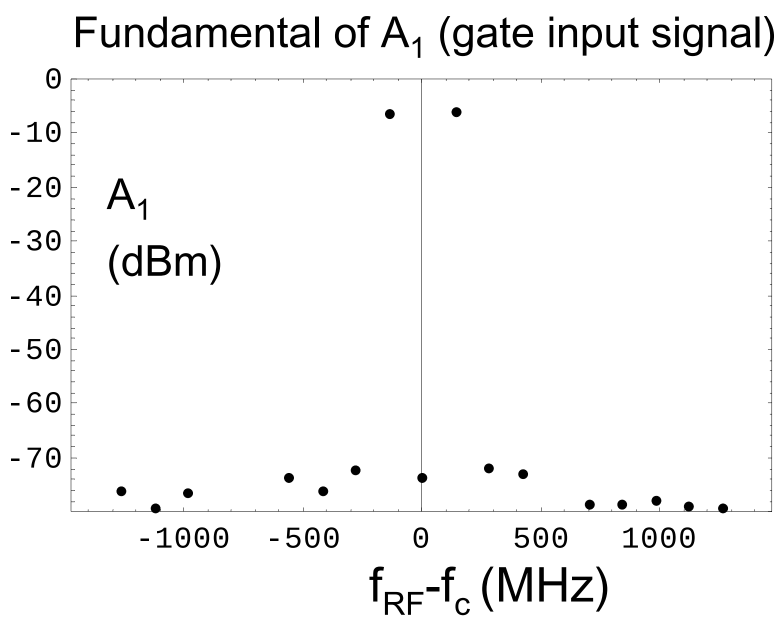


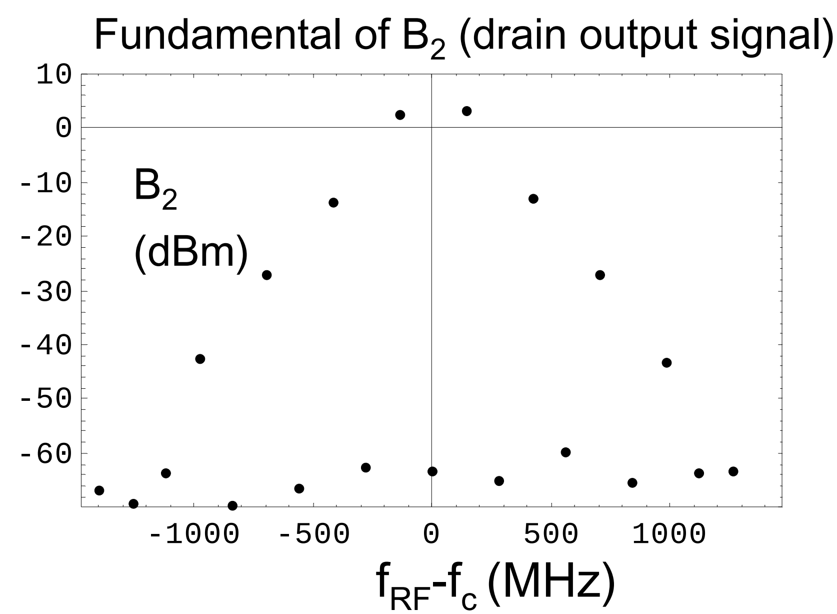
Tone spacing = $2f_M$ = +/- 200 kHz f_C = 3 GHz

D.U.T. = .2µm x 100µm metamorphic HEMT on GaAs provided by IMEC (Belgium)

LSNA courtesy of Prof. Dr. D. Schreurs (Catholic University Leuven, Belgium)

Measurement Application
LSNA with 2-tone excitation



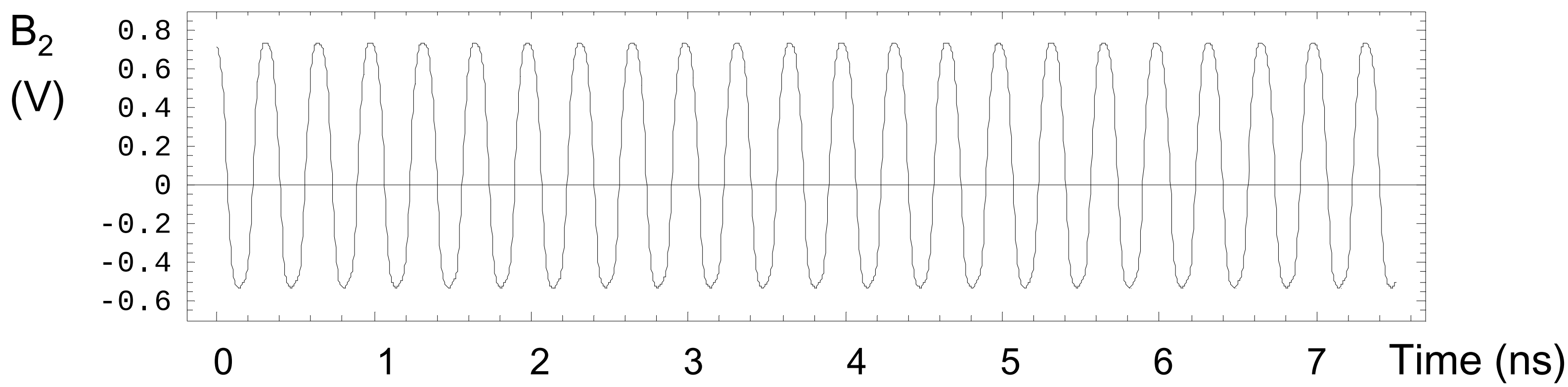


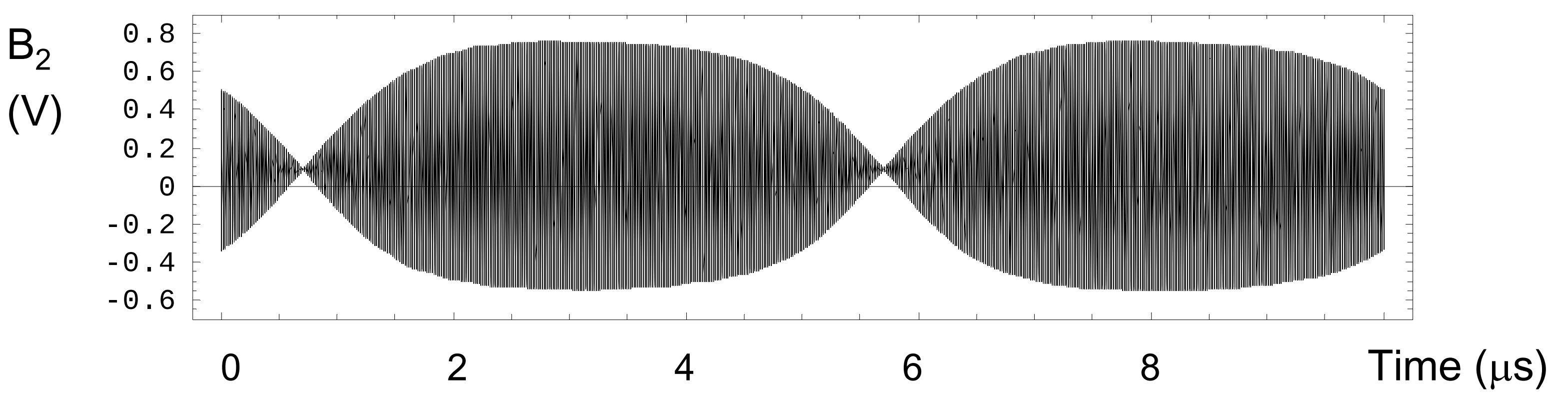
Tone spacing = $2f_M$ = +/- 280 MHz f_C = 3 GHz

D.U.T. = .2µm x 100µm metamorphic HEMT on GaAs provided by IMEC (Belgium)

LSNA courtesy of Prof. Dr. D. Schreurs (Catholic University Leuven, Belgium)

Time Domain B_2 ($2f_M$ = +/- 200 kHz)





Time Domain B_2 ($2f_M$ = +/- 280 MHz)