Spectrum Analysis Back to Basics
Agenda

• Introduction
• Overview:
  – What is Signal Analysis?
  – What Measurements are available?
• Theory of Operation
• Specifications
• Modern spectrum analyzer designs & capabilities
  » Wide Bandwidth Vector Measurements
Overview

What is Signal, Vector and Spectrum Analysis?

Spectrum Analysis
• Display and measure amplitude versus frequency for RF & MW signals
• Separate or demodulate complex signals into their base components (sine waves)
Overview
Frequency versus Time Domain

Amplitude (power)

Time domain Measurements (Oscilloscope)

Frequency Domain Measurements (Spectrum Analyzer)
Overview
Types of Measurements Available

- Frequency, power, modulation, distortion & noise
  - Spectrum monitoring
  - Spurious emissions
  - Scalar network analysis
  - Noise figure & phase noise
  - Harmonic & intermodulation distortion
  - Analog, digital, burst & pulsed RF Modulation
  - Wide bandwidth vector analysis
  - Electromagnetic interference

- Measurement range (-168 dBm to +30 dBm)
- Frequency range (3 Hz to 325 GHz)
Overview
Different Types of Analyzers

FFT Analyzer

Parallel filters measured simultaneously

LCD shows full spectral display

\[ A \]

\[ f_1 \quad f_2 \quad f \]
Overview
Different Types of Analyzers

**Swept Analyzer**

Filter 'sweeps' over range of interest

LCD shows full spectral display
Agenda

- Introduction
- Overview
- **Theory of Operation:**
  - Swept Spectrum Analyzer Hardware
- Specifications
- Modern spectrum analyzer designs & capabilities
  - Wide Bandwidth Vector Measurements
Theory of Operation
Swept Spectrum Analyzer Block Diagram

Input signal

RF input attenuator

Pre-selector or Low Pass Input Filter

Mixer

IF gain

IF filter (RBW)

Envelope detector

Log Amp

Video filter

Local oscillator

Crystal Reference Oscillator

Sweep generator

ADC, Display & Video Processing
Theory of Operation
Display terminology

- Reference Level
- Amplitude
- Start Freq.
- Stop Freq.
- Freq. Span
- Center Freq.
Theory of Operation
Mixer

MIXER

LO

f

sig

1.5 GHz

3.6 GHz

f_LO

6.5 GHz

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Theory of Operation
IF Filter (Resolution Bandwidth – RBW)

Input Spectrum

IF Bandwidth (RBW)

Display

A

B

C

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Theory of Operation
Envelope Detector

Before detector

After detector

Envelope Detector

Envelop Detector

Beyond S-Parameters

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Theory of Operation
Envelope Detector and Detection Types

Digitally Implemented Detection Types

- Positive detection: largest value in bin displayed
- Negative detection: smallest value in bin displayed
- Sample detection: middle value in bin displayed

Other Detectors: Normal (Rosenfell), Average (RMS Power)

* Sweep points

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Power Average Detection (rms) = Square root of the sum of the squares of ALL of the voltage data values in the bin /50Ω
Theory of Operation
Video Filter (Video Bandwidth – VBW)

Beyond S-Parameters

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**Theory of Operation**

**Video Filter vs. Trace/Video averaging**

- **Video Filter** operates as the sweep progresses, sweep time may be required to slow down by the transient response of the VBW filter.

- **Trace/Video Average** takes multiple sweeps, sweep time for each sweep is not affected.

- Many signals give the same results with either video filtering or trace averaging.

Trace averaging for 1, 5, 20, and 100 sweeps, top to bottom (trace position offset for each set of sweeps).
Theory of Operation
How it All Works Together - 3 GHz spectrum analyzer

Input signal is fed into a mixer, where it is combined with a local oscillator (LO) signal. The mixer produces an intermediate frequency (IF) signal, which is then filtered to isolate a specific frequency band of interest. The filtered IF signal is further processed and displayed on an LCD screen.
Agenda

• Overview
• Theory of Operation
• Specifications:
  – Which are important and why?
• Modern spectrum analyzer designs & capabilities
  » Wide Bandwidth Vector Measurements
Key Specifications

- Safe spectrum analysis
- Frequency Range
- Accuracy: Frequency & Amplitude
- Resolution
- Sensitivity
- Distortion
- Dynamic Range
Specifications? A Definition

- **Specifications** describe the performance of parameters covered by the product warranty (temperature = 0 to 55°C, unless otherwise noted).

- **Typical** values describe additional product performance information that is not covered by the product warranty. It is performance beyond specification that 80% of the units exhibit with a 95% confidence level over the temperature range 20 to 30°C. Typical performance does not include measurement uncertainty.

- **Nominal** values indicate expected performance, or describe product performance that is useful in the application of the product, but is not covered by the product warranty.
• Use best practices to eliminate static discharge to the RF input!
• Do not exceed the Damage Level on the RF Input!
• Do not input signals with DC bias!

0 V DC MAX
+30dBm (1W) MAX
### Specifications

**Frequency Range**

<table>
<thead>
<tr>
<th>Description</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal Mixing</strong></td>
<td></td>
</tr>
<tr>
<td>Bands</td>
<td></td>
</tr>
<tr>
<td>• 0</td>
<td>3 Hz to 3.0 GHz</td>
</tr>
<tr>
<td>• 1</td>
<td>2.85 to 6.6 GHz</td>
</tr>
<tr>
<td>• 2</td>
<td>6.2 to 13.2 GHz</td>
</tr>
<tr>
<td>• 3</td>
<td>12.8 to 19.2 GHz</td>
</tr>
<tr>
<td>• 4</td>
<td>18.7 to 26.8 GHz</td>
</tr>
<tr>
<td>• 5</td>
<td>26.4 to 31.15 GHz</td>
</tr>
<tr>
<td>• 6</td>
<td>31.0 to 50.0 GHz</td>
</tr>
<tr>
<td><strong>External mixing</strong></td>
<td>18 to 325 GHz</td>
</tr>
</tbody>
</table>
Components which contribute to uncertainty are:

- Input mismatch (VSWR)
- RF Input attenuator (Atten. switching uncertainty)
- Mixer and input filter (frequency response)
- IF gain/attenuation (reference level accuracy)
- RBW filters (RBW switching uncertainty)
- Log amp (display scale fidelity)
- Reference oscillator (frequency accuracy)
- Calibrator (amplitude accuracy)
Specifications
Absolute and relative Accuracy: Frequency & amplitude

Note: Absolute accuracy is also “relative” to the calibrator reference point
Specifications

Accuracy: Frequency Readout Accuracy

- From the PSA Data Sheet:

\[ \pm \left( \text{freq readout} \times \text{freq reference error } + 0.25\% \times \text{span} + 5\% \times \text{RBW} + 2\text{Hz} + 0.5 \times \text{Horiz. Res.} \right) \]

**RBW Error**
IF filter center frequency error

**Span Accuracy**

**Residual Error**

*Horizontal resolution is span/(sweep points – 1)*
Specifications

Accuracy: Frequency Readout Accuracy Example

**Frequency:** 1 GHz  
**Span:** 400 kHz  
**RBW:** 3 kHz  
**Sweep points:** 1000

\[
\text{Calculation :} \quad (1 \times 10^9 \text{Hz}) \times (\pm 1.8 \times 10^{-7}/\text{Year ref. Error}) = 180 \text{Hz} \\
400 \text{kHz Span} \times 0.25\% = 1000 \text{Hz} \\
3 \text{kHz RBW} \times 5\% = 150 \text{Hz} \\
2 \text{Hz} + 0.5 \times 400 \text{kHz}/1000-1 = 202 \text{Hz} \\
\text{Total uncertainty} = \pm 1532 \text{Hz}
\]

Utilizing internal frequency counter improves accuracy to ±180Hz
### Specifications

**Accuracy: Key amplitude uncertainty contributions**

<table>
<thead>
<tr>
<th>Relative and absolute:</th>
<th>Sample Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Input impedance mismatch</td>
<td>(±0.13 dB)</td>
</tr>
<tr>
<td>• Input attenuator switching uncertainty</td>
<td>(±0.6 dB)</td>
</tr>
<tr>
<td>• Frequency response</td>
<td>(±1.8 dB)</td>
</tr>
<tr>
<td>• Reference level accuracy</td>
<td>(±1.0 dB)</td>
</tr>
<tr>
<td>• RBW switching uncertainty</td>
<td>(±0.5 dB)</td>
</tr>
<tr>
<td>• Display scale fidelity</td>
<td>(±0.85 dB)</td>
</tr>
</tbody>
</table>

**Absolute only:**

• Calibrator accuracy                         | (±0.34 dB)           |
Specifications
Accuracy: Frequency Response

Signals in the Same Harmonic Band

Absolute amplitude accuracy – Specification: ± 1 dB
Relative amplitude accuracy – Specification: ± 2 dB
Specifications
Accuracy: Display Fidelity

Display Fidelity includes:
- Log Amp Fidelity
- Envelope Detector Linearity
- Digitizing Circuit Linearity

Display fidelity error applies when signals are not at the same reference level amplitude when measured.

In the past, technique for best accuracy was to move each measured signal to the reference line, eliminating display fidelity error.
Specifications
Amplitude Accuracy: Reference Level Switching

- Uncertainty applies when changing the Ref. Level
- Also called IF Gain Uncertainty
- Decision: Do I change the reference level or live with the display fidelity uncertainty in my measurements?
Optimize measurement setup & techniques for best accuracy

- Minimize changes to uncertainty contributors
  - Or change contributor with least error impact
  - Or stay within the optimum accuracy envelope parameters that modern auto-alignment calibration techniques provide

- Traditionally, one technique for best accuracy was to move each measured signal to the reference line, eliminating display fidelity error. However, in today’s designs, display fidelity has improved to the point where there is generally less error just to leave the signals where they occur on the display.

- Except for freq. response, uncertainty contributors that impact both signals equally in a relative measurement can be ignored.

- In the absence of specified relative freq. response, the relative response uncertainty is assumed to be 2x specified absolute error.
What Determines Resolution?

- Resolution Bandwidth
- RBW Type and Selectivity
- Noise Sidebands
Specifications
Resolution: Resolution Bandwidth

- Input Spectrum
- Mixer
- 3 dB BW
- IF Filter/
Resolution Bandwidth Filter (RBW)
- LO
- Sweep
- Display
- Envelope
Detector

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Specifications
Resolution: Resolution BW

Determines resolvability of **equal** amplitude signals
Specifications
Resolution BW Selectivity or Shape Factor

Selectivity = \frac{60 \text{ dB BW}}{3 \text{ dB BW}}

Determines resolvability of **unequal** amplitude signals
Specifications
Resolution BW Selectivity or Shape Factor

RBW = 1 kHz
Selectivity 15:1

RBW = 10 kHz

3 dB

60 dB

7.5 kHz

60 dB BW = 15 kHz

10 kHz

distortion products

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Specifications
Resolution: RBW Type and Selectivity

Typical Selectivity
Analog  15:1
Digital  ≤5:1
Noise Sidebands can prevent resolution of unequal signals
Penalty For Sweeping Too Fast
Is An Uncalibrated Display
Specifications

Resolution: RBW Type Determines Sweep Time

8563E Analog RBW

PSA Digital RBW

PSA FFT RBW

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280 sec

134 sec

13.5 sec
A Spectrum Analyzer Generates and Amplifies Noise Just Like Any Active Circuit
Sensitivity is the Smallest Signal That Can Be Measured

\[ \text{Signal} = \text{Noise} \]

\[ \sim 2.2 \text{ dB} \]
Effective Level of Displayed Noise is a Function of RF Input Attenuation

Signal To Noise Ratio Decreases as RF Input Attenuation is Increased
Specifications
Sensitivity/DANL: IF Filter(RBW)

Displayed Noise is a Function of IF Filter Bandwidth

Decreased BW = Decreased Noise
Specifications

Sensitivity/DANL: Video BW filter (or Trace Averaging)

Video BW or Trace Averaging Smoothes Noise for Easier Identification of Low Level Signals
Specifications

Sensitivity/DANL:

Signal-to-Noise Ratio Can Be Graphed

Displayed Noise in a 1 kHz RBW

Displayed Noise in a 100 Hz RBW

POWER AT MIXER = INPUT - ATTENUATOR SETTING dBm
For Best Sensitivity Use:

- Narrowest Resolution BW
- Minimum RF Input Attenuation
- Sufficient Averaging (video or trace)
Mixers Generate Distortion

Signal To BeMeasured

Frequency Translated Signals

Mixer Generated Distortion

Resultant
Most Influential Distortion is the Second and Third Order

Two-Tone Intermod

Harmonic Distortion

< -50 dBc

< -40 dBc

< -50 dBc
Distortion Products Increase as a Function of Fundamental's Power

Two-Tone Intermod

- Second Order: $\Delta 2 \text{ dB/dB of Fundamental}$
- Third Order: $\Delta 3 \text{ dB/dB of Fundamental}$

Harmonic Distortion

- Second-order distortion: $\Delta 2$ dB/dB of Fundamental
- Third-order distortion: $\Delta 3$ dB/dB of Fundamental

Power in dB
Distortion is a Function of Mixer Level

- Second Order
- Third Order

POWER AT MIXER = INPUT - ATTENUATOR SETTING dBm
Attenuator Test: Change power to the mixer

1. Change input attenuator by 10 dB
2. Watch distortion amplitude on screen

No change in amplitude: distortion is part of input signal (external)

Change in amplitude: at least some of the distortion is being generated inside the analyzer (internal)
The ratio, expressed in dB, of the largest to the smallest signals simultaneously present at the input of the spectrum analyzer that allows measurement of the smaller signal to a given degree of uncertainty.
Dynamic Range Can Be Presented Graphically

Specifications
Dynamic Range

Maximum 2nd Order Dynamic Range

Maximum 3rd Order Dynamic Range

Optimum Mixer Levels

POWER AT MIXER = INPUT - ATTENUATOR SETTING dBm
Dynamic Range for Spur Search Depends on Closeness to Carrier

- Dynamic Range Limited By Noise Sidebands dBc/Hz
- Noise Sidebands
- Dynamic Range Limited By Compression/Noise
- Displayed Average Noise Level
- 100 kHz to 1 MHz
Dynamic Range is actually:

**Maximum dynamic range calculation**

Calculated from distortion products and sensitivity/DANL

bounded by

- $-\text{dBc/Hz Phase Noise sidebands @ close-in offset frequencies}$

Determined by the phase noise specifications of the SA
• **What settings provide the best sensitivity?**
  • Narrowest resolution bandwidth
  • Minimal input attenuation
  • Sufficient averaging

• **How do you test for analyzer distortion?**
  • Increase the input attenuation and look for signal amplitude changes
  • Then set the attenuator at the lowest setting without amplitude change

• **What determines dynamic range?**
  • Analyzer distortion, noise level, and sideband/phase noise
Agenda

- Introduction
- Overview
- Theory of Operation
- Specifications
- Modern spectrum analyzer designs & capabilities
  - Wide Analysis Bandwidth Measurements
Modern Spectrum Analyzer Block Diagram

Auto Alignment
- Temp & time calibration

3 to 50 GHz Pre-amp
- Improve 1 GHz
- DANL -153dBm to -168dBm

Analog Pre-Filter (Single Pole)

Attenuation
- 2 dB step to 50 GHz

Digitally Synthesized LO
- Fast tuning
- Close-in phase noise
- Far-out phase noise

14 bit ADC
- Wider dynamic range with autoranging
- Dither on/off

Digital IF Filters
- 160 RBW filters
- 1 Hz to 8 MHz
- ±0.03 dB switching error

Digital Log Amp
- ±0.07 dB Scale Fidelity
- >100 dB Dynamic range
- ±0.0 dB reference level error

Digital Video Filters
- Power, voltage, log filtering

Digital Detectors
- Normal
- Peak
- Min
- Sample

FFT vs Swept RBW
- Faster Sweep w/Max DR

Digital Log Amp
- ±0.07 dB Scale Fidelity
- >100 dB Dynamic range
- ±0.0 dB reference level error

Frequency Counter
- Fast (0.1s)
- High resolution (mHz)

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## Modern Spectrum Analyzer - Specifications

Digital IF provides improved accuracy

<table>
<thead>
<tr>
<th>Specification</th>
<th>PSA</th>
<th>Traditional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input impedance mismatch</td>
<td>±0.13 dB</td>
<td>±0.29 dB</td>
</tr>
<tr>
<td>Input attenuator switching uncertainty</td>
<td>±0.18 dB</td>
<td>±0.0 dB</td>
</tr>
<tr>
<td>Frequency response</td>
<td>±0.38 dB</td>
<td>±1.8 dB</td>
</tr>
<tr>
<td>Reference level accuracy</td>
<td>±0.0 dB</td>
<td>±1.0 dB</td>
</tr>
<tr>
<td>RBW switching uncertainty</td>
<td>±0.03 dB</td>
<td>±0.5 dB</td>
</tr>
<tr>
<td>Display scale fidelity</td>
<td>±0.07 dB</td>
<td>±0.85 dB</td>
</tr>
<tr>
<td>Calibrator accuracy</td>
<td>±0.24 dB</td>
<td>±0.34 dB</td>
</tr>
</tbody>
</table>

Total accuracy (up to 3 GHz)  
95% Confidence  
Typical  

±0.62 dB vs. ±1.8 dB  
±0.24 dB  
±0.17 dB
Modern Spectrum Analyzer Features

Built-in One-Button Power Measurements

Power Measurements

- Occupied Bandwidth
- Channel Power
- Multi-Offset ACP – fast ACP
- Multi-carrier Power
- CCDF
- Harmonic Distortion
- Burst Power
- TOI
- Spurious Emissions
- Spectral Emissions Mask

Format Setups

- GSM/EDGE
- cdma2000
- W-CDMA
- cdmaOne
- NADC/PDC
- Bluetooth
- Tetra (Ch. Pwr, ACP)
- 802.11a/b (SEM)
- HiperLAN2 (SEM)
- DVB-T
- UWB
- S-DMB
## Modern Spectrum Analyzer Features

### Application Focused Internal Software (one-button measurements)

**General purpose applications**
- Phase noise
- Ext. source control
- Noise figure
- Code compatibility suite

**Flexible digital modulation analysis**
- Flexible demod
- W-CDMA, HSDPA, HSUPA
- GSM with EDGE
- Cdma2000 & 1xEV-DV
- 1xEV-DO
- cdmaOne
- NADC/PDC
- TD-SCDMA

**Beyond S-Parameters**
- ACPR, Multi-carrier Power
- Occupied Bandwidth (OBW)
- Spectral Emissions Mask
- Phase and Freq. (PFER)
- Mod Accuracy (Rho)
- Code Domain Power
- ORFS (GSM/EDGE)
- Spurious Emissions
- Power vs Time
- Channel power
- IM distortion
- CCDF
- ACPR
- EVM
- SEM

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Who needs wide analysis BW?

Modern designs demand more bandwidth for capturing high data rate signals and analyzing the quality of digitally modulated bandwidths

• Aerospace and Defense
  - Radar – Chirp errors & modulation quality
  - Satellite – Capture 36/72 MHz BW’s with high data rates
  - Military communications – Capture high data rate digital comms & measure EVM

• Emerging communications
  - W-LAN, 802.16 (wireless last mile), mesh networks
    - Measure EVM on broadband, high data rate signals

• Cellular Communications
  - W-CDMA ACPR & Multi-carrier Pre-Distortion
    - High dynamic range over 60 MHz BW to see low level 3rd order distortion for 4 carrier pre-distortion algorithms
PSA Wide Analysis Bandwidth

Existing Narrowband IF (10 MHz)

Swept and Stepped LO

14 bit 30 Msps

Pre-filter

Auto range

A/D

ASIC

Swept Results

CPU

Demod FFT

Display Proc

Display

Wideband IF/Digitizer (80 MHz)

14 bit 200 Msps

I/Q Detectors

Filters

Decimation

Resampling

Demod FFT

Memory

Calibration

A/D

ASIC & FPGA
The End

THANK YOU!