Cassini RF ATE System
Basic Training Seminar

Science of RF Measurements

Roos Instruments

Cassini Basic Seminar Outline

- Operation and Troubleshooting
- System Administration and Maintenance
- Basic Test Plan Concepts
- **Science of RF Measurement**
- Device Definitions
- Example Applications Development
- Test Fixture and Device Interface Design
- Test Design & Best Practices Test Optimization
- Application User Guides

RF Measurements Outline

- **Basic Measurements**
- Phase and Magnitude
- Scattering Parameters
- Conversion Gain/Loss Measurements
- RF Power Measurements
- Spectral Purity (Harmonics) Measurements
- Intermod Distortion Measurements
- Digitally Modulated RF Signal Measurements
- Error Vector Magnitude (EVM)
- Noise Figure Measurements

Cassini ATE System Basic Measurements

- S Parameters
- RF Power
- Noise Figure & Noise Power
- Spectral Purity & ACP
- Gain Compression
- S/N, SINAD, Distortion & BER
- Intermod Distortion
- 3rd Order Intercept (TOI)
- Isolation
- DC Voltage & DC Current
- DC to RF Efficiency
- I & Q Amplitude & Phase
- Rise/Fall, Duty Cycle, Period & Jitter

Verification

- System startup verifies major component functionality
- System receiver self calibration/verification every 20 minutes
- Full verification to calibration specifications automatically run on user schedule or on demand

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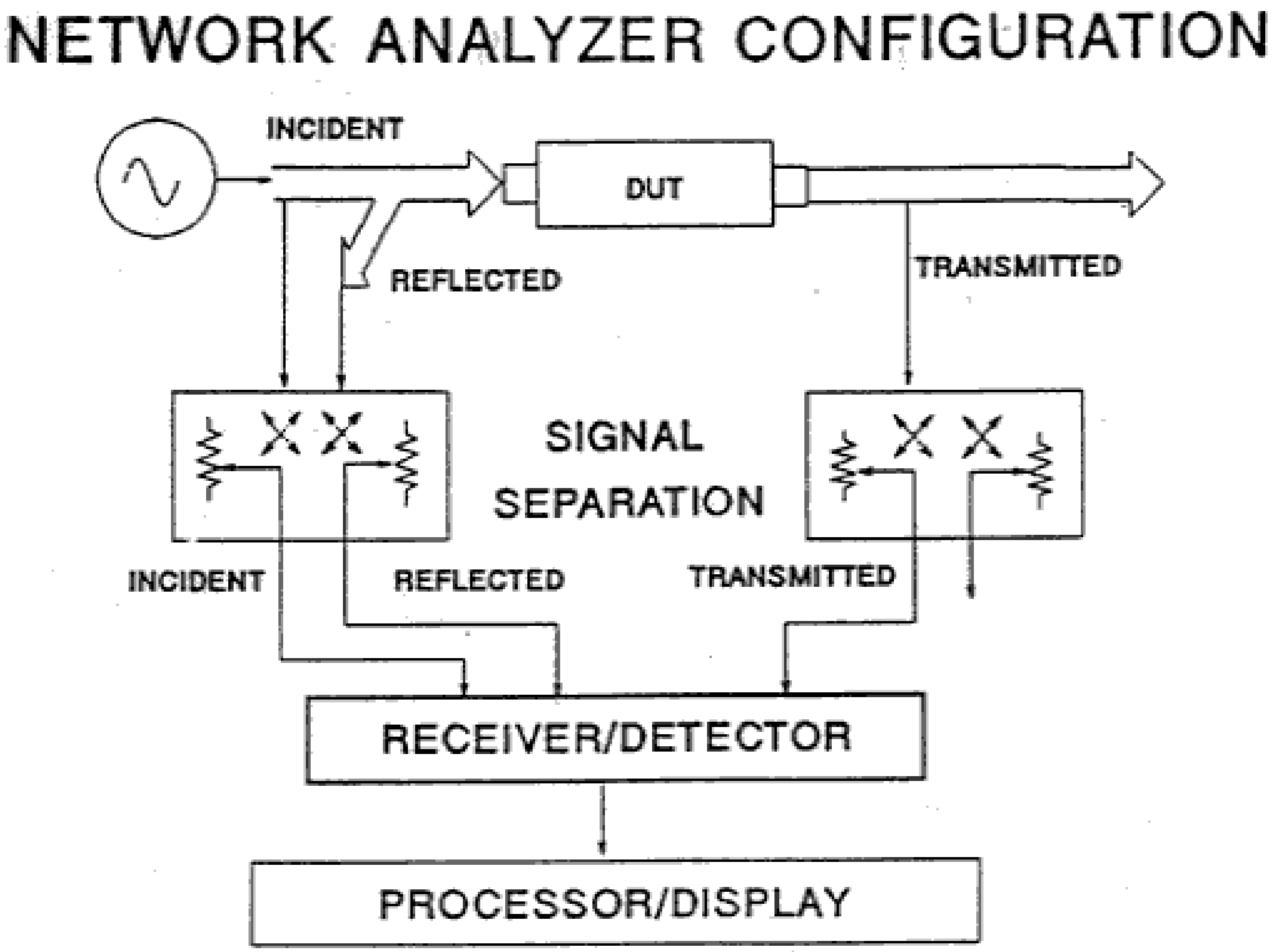
Why Measure Phase and Magnitude ?

- To Measure Complex Impedance
- Resistance with Capacitance & Inductive components Complete Characterization of Linear Networks Transmission Distortion Effects
- Deviation from Linear Phase
- Bandwidth
- Vector Accuracy Enhancement
- De-embedding of measurement results
- Characterization of Systematic Errors
- Time Domain Transforms

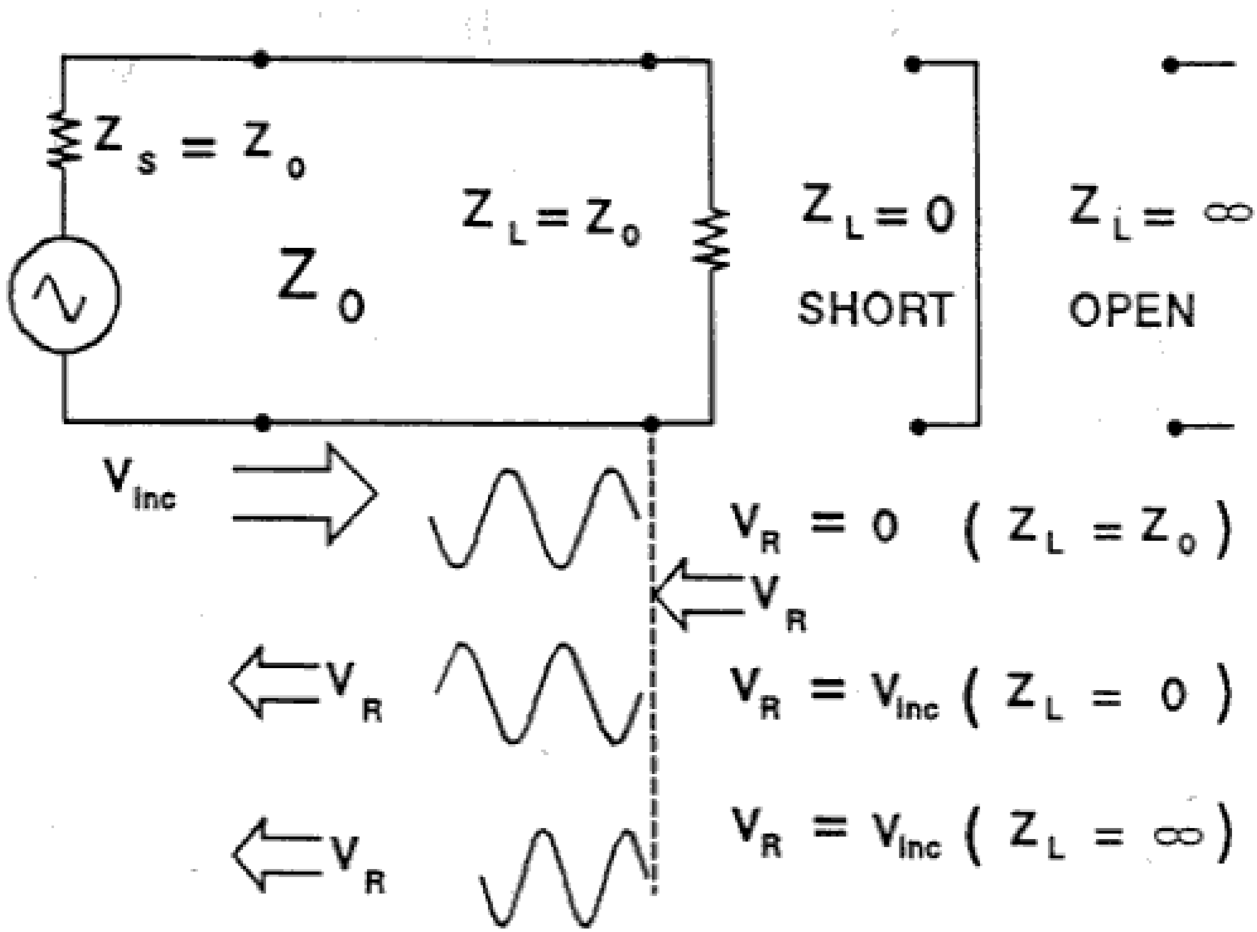
Vector Network Measurement

- Reflection Meas:
  - Input VSWR
  - Return Loss
  - Input Impedance
  - Reflection Coeff
  - S Parameters S_{11} S_{22}
- Transmission Meas:
  - Gain/Loss
  - Insertion Phase
  - Group Delay
  - S Parameters S_{21} S_{12}

Typical Network Analyzer



RF Reflected Signals



Reflection Coefficient, Return Loss and SWR

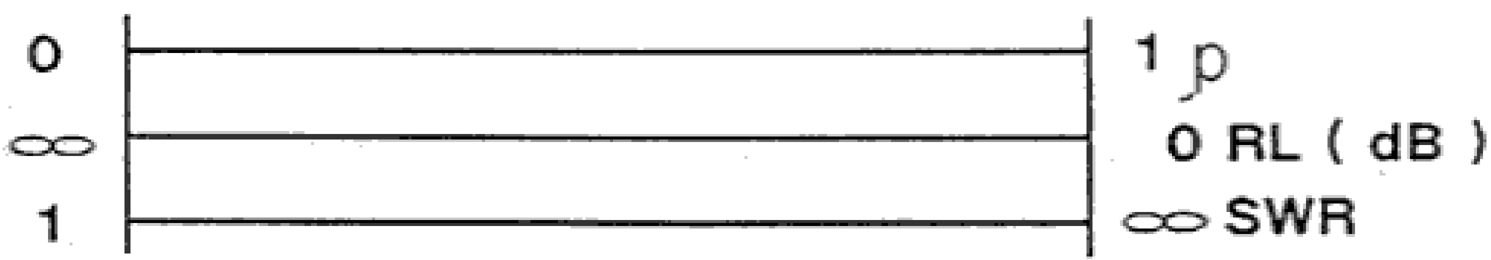
REFLECTION TERMINOLOGY

Reflection Coefficient $\Gamma = \frac{V_R}{V_{INC}} = \frac{Z_L - Z_O}{Z_L + Z_O} = \rho \angle \phi$

$$\rho = |\Gamma|$$

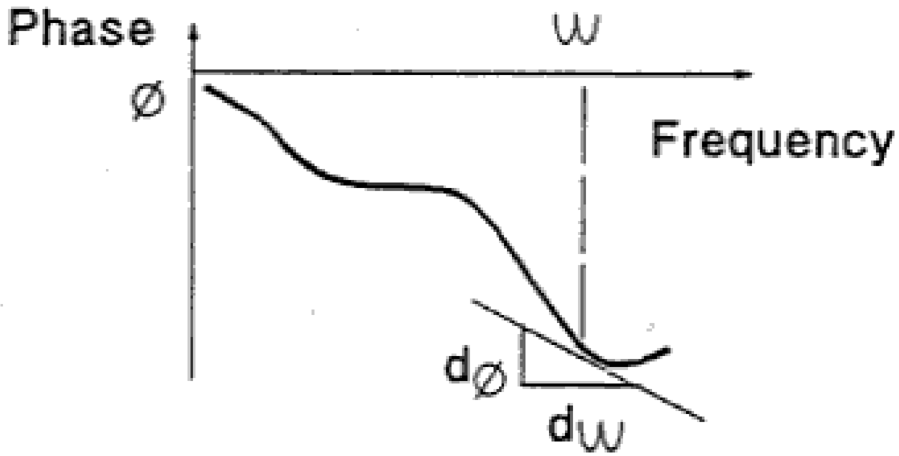
$$\text{Return Loss} = -20 \text{ Log } \rho$$

$$\text{SWR} = \frac{1+\rho}{1-\rho}$$



What is Group Delay?

GROUP DELAY



$$\text{Group Delay} = t_g = \frac{-d\phi}{d\omega}$$

ϕ In Radians

ω In Radians/Sec

$$= \frac{-1}{360^\circ} \cdot \frac{d\phi}{d_f}$$

ϕ In degrees

f In Hz ($\omega = 2\pi f$)

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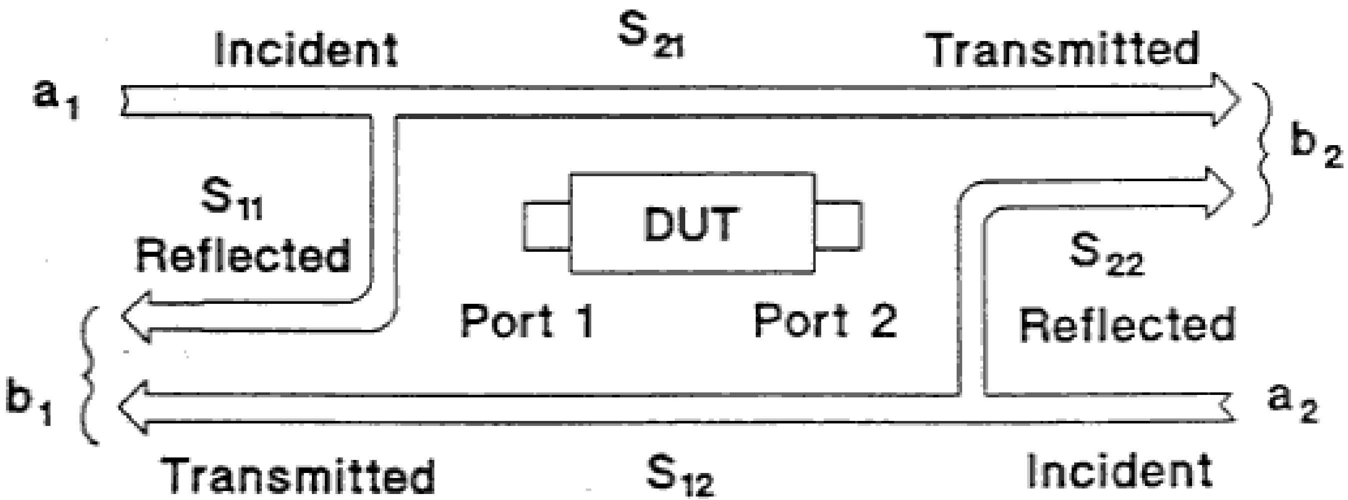
Basic Measurement Capability (S-Parameters)

- Definition of Scattering Parameters
- Measurement Concept
- Flow Graphs
- Cassini Measurement Hardware
- Error Correction
- Two Port Error Model

What is an S-Parameter?

SCATTERING PARAMETER DEFINITION

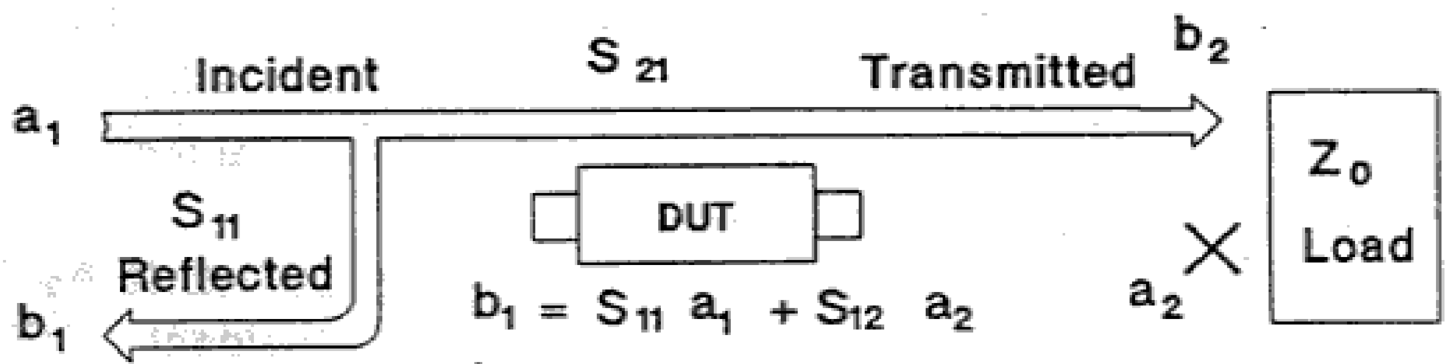


$$b_1 = S_{11}\,a_1 + S_{12}\,a_2$$

$$b_2 = S_{21}\,a_1 + S_{22}\,a_2$$

Measuring 2 port s-Parameters

SCATTERING PARAMETER MEASUREMENT



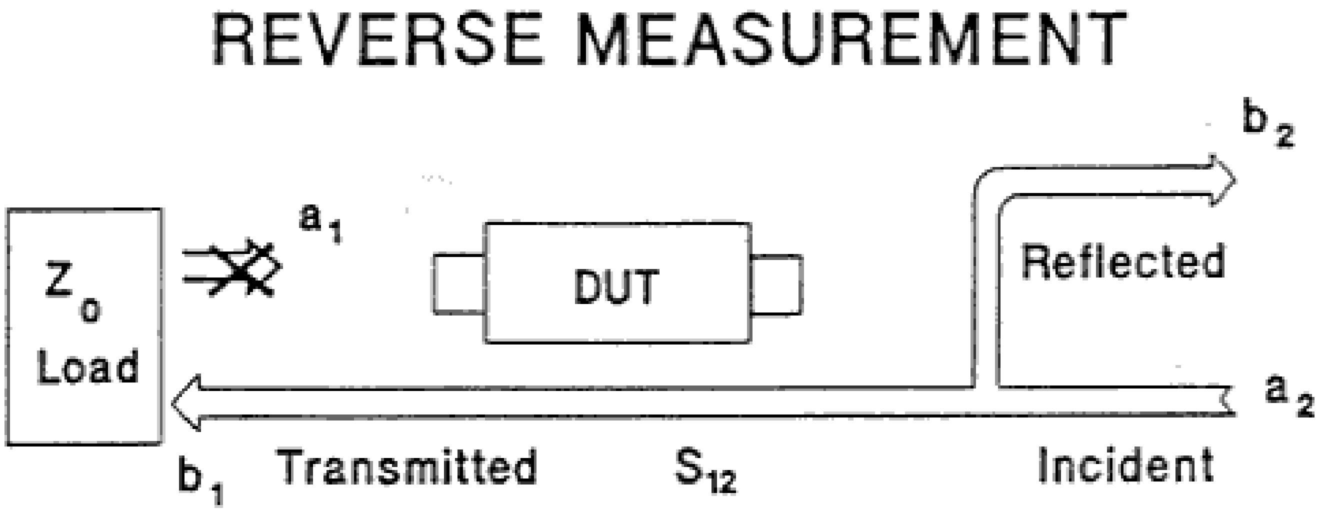
$$b_1 = S_{11}\,a_1 + S_{12}\,a_2$$

$$b_2 = S_{21}\,a_1 + S_{22}\,a_2$$

$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1} \Big|\; a_2 = 0$$

$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1} \Big|\; a_2 = 0$$

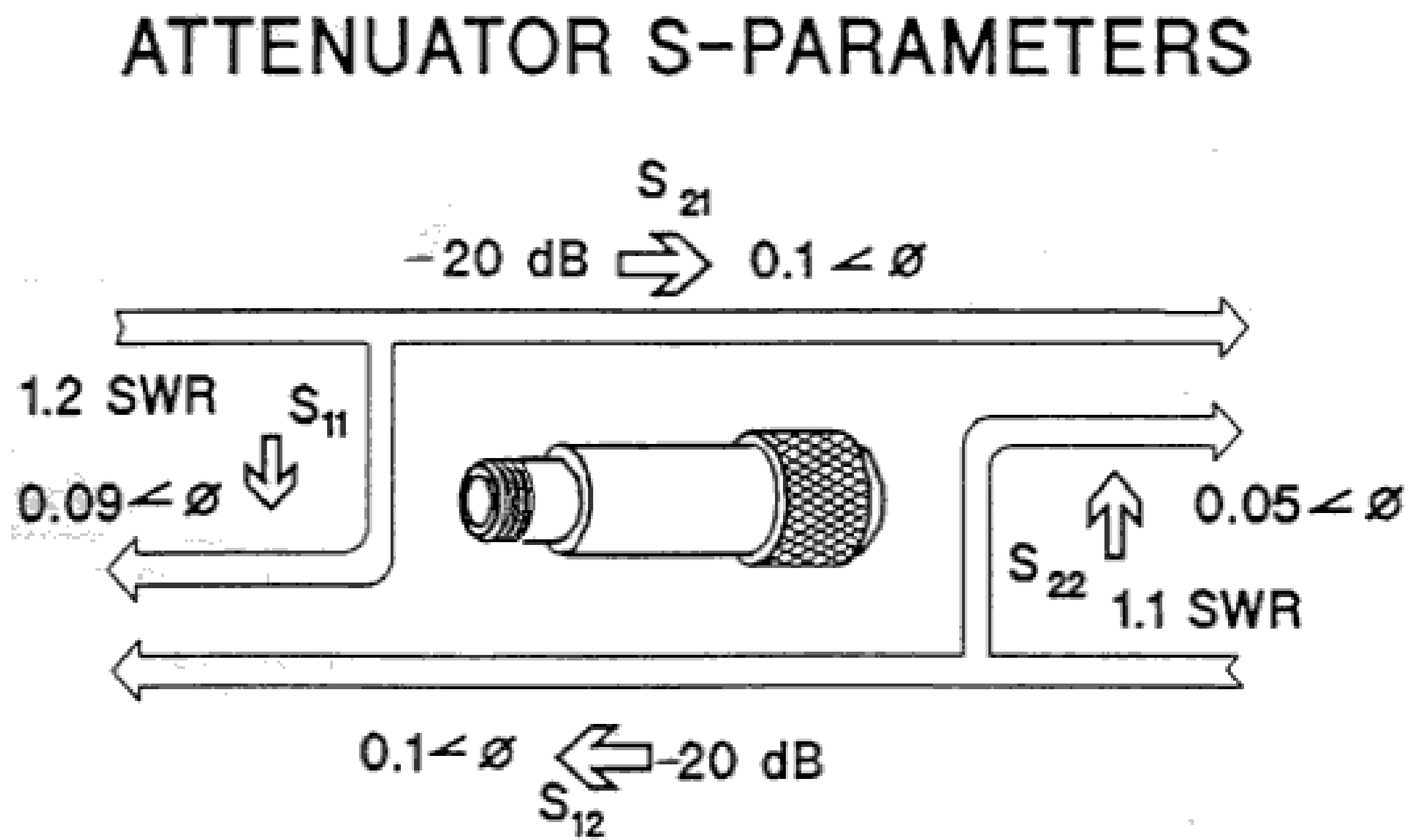
Second half of the S-Parameter Measurement Process



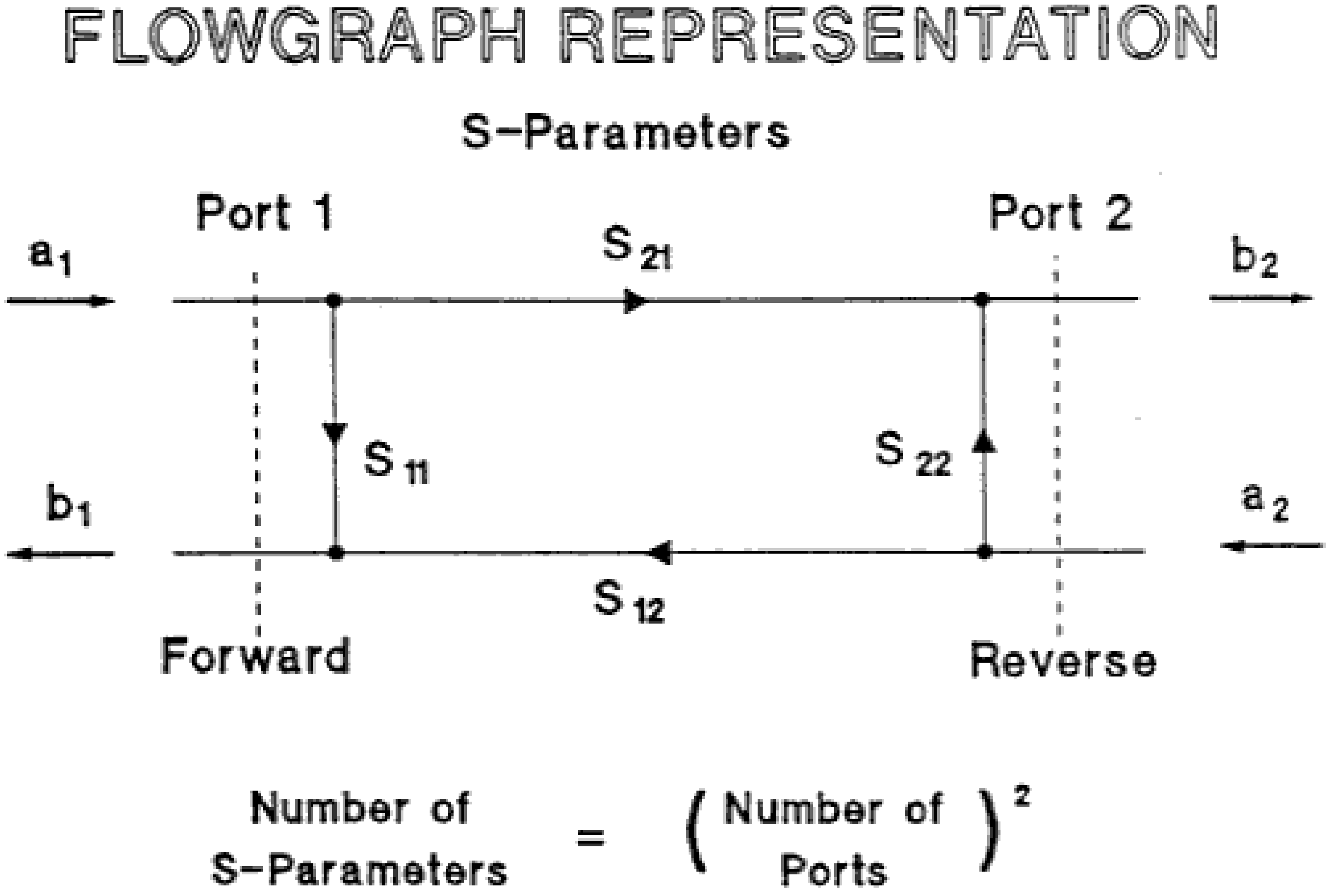
$$S_{22} = \frac{b_2}{a_2} \quad \Big| \quad a_1 = 0$$

$$S_{12} = \frac{b_1}{a_2} \quad \Big| \quad a_1 = 0$$

Testing an Attenuator

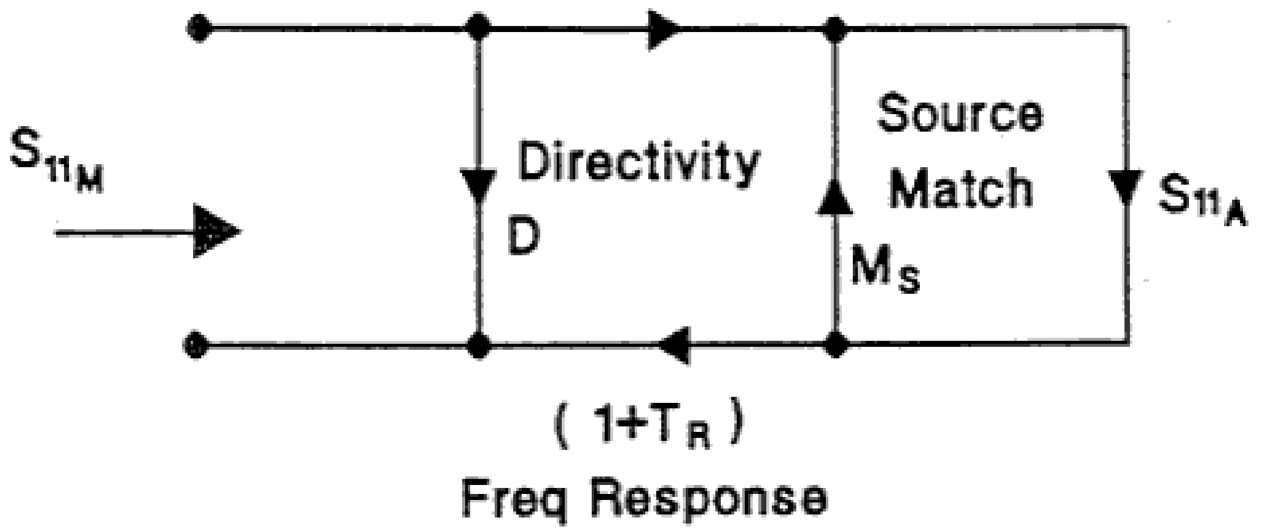


S-Parameter Flow Graphs



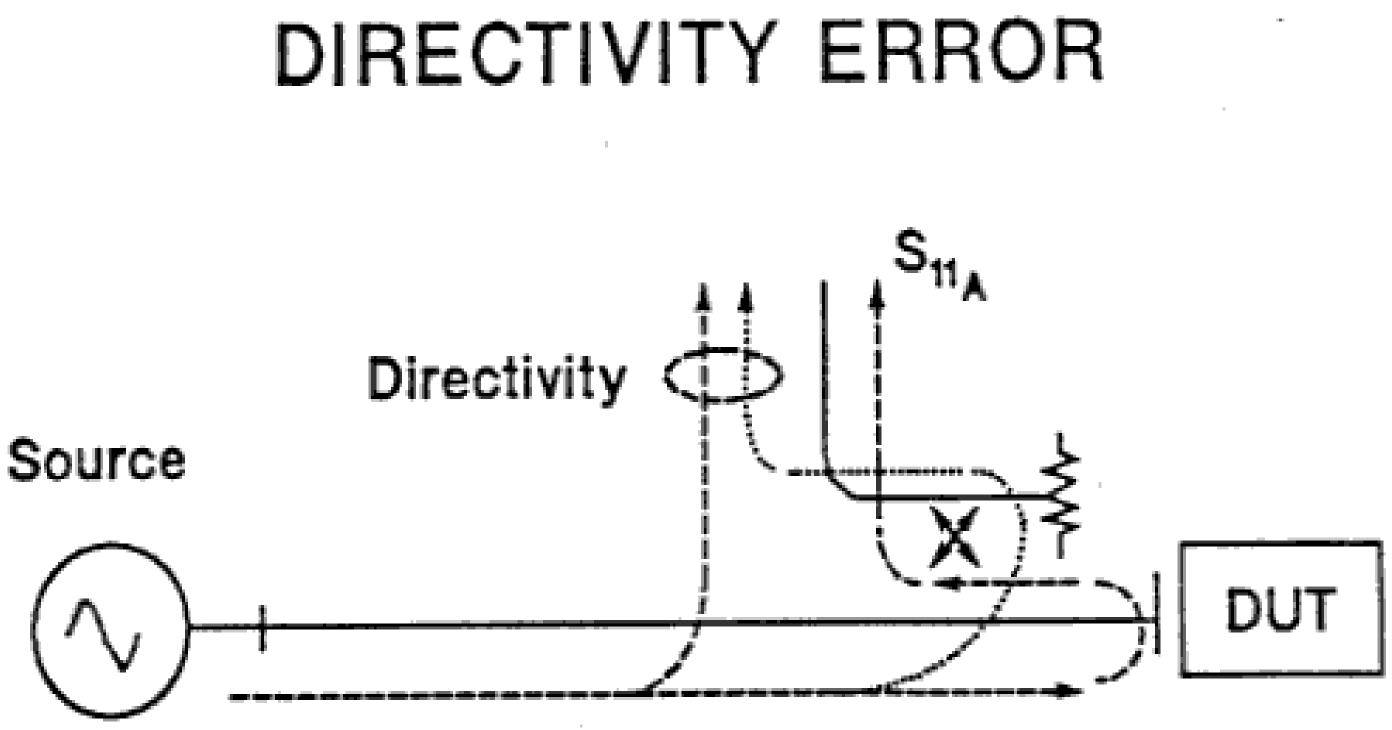
One Port S-Parameter Measurement Errors

"ONE PORT" MEASUREMENT MODEL



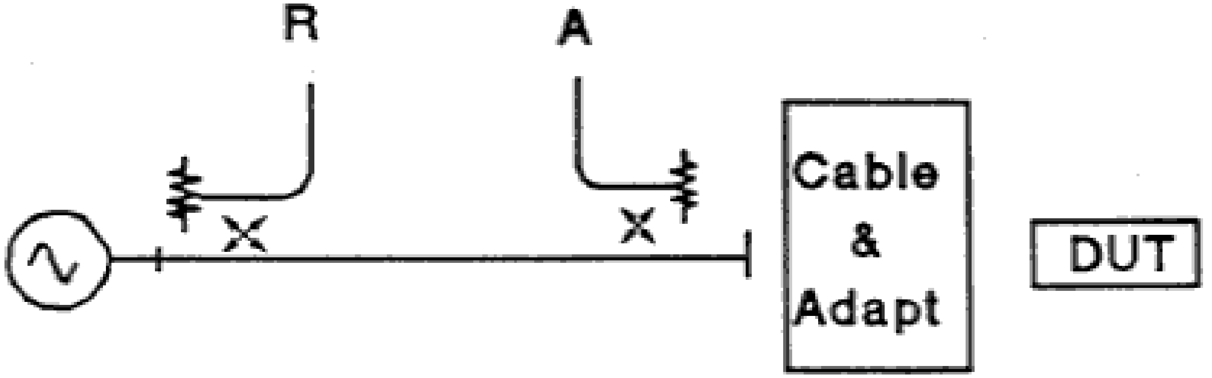
$$S_{11_M} = D + \frac{S_{11_A}\ (1+T_R)}{1 - M_S S_{11_A}}$$

Directivity (Directional) Errors



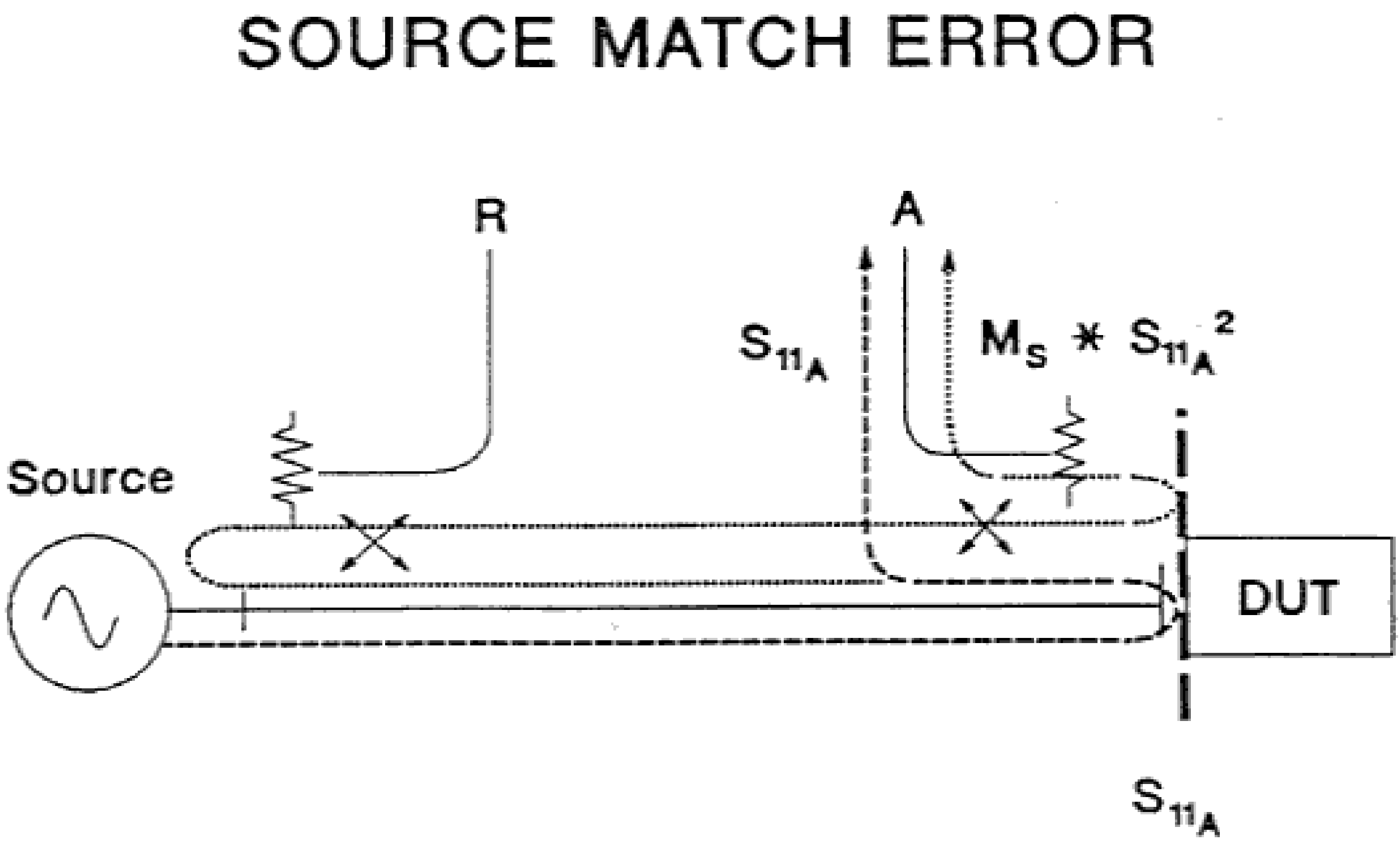
Reflection Tracking Errors

FREQUENCY RESPONSE ERROR



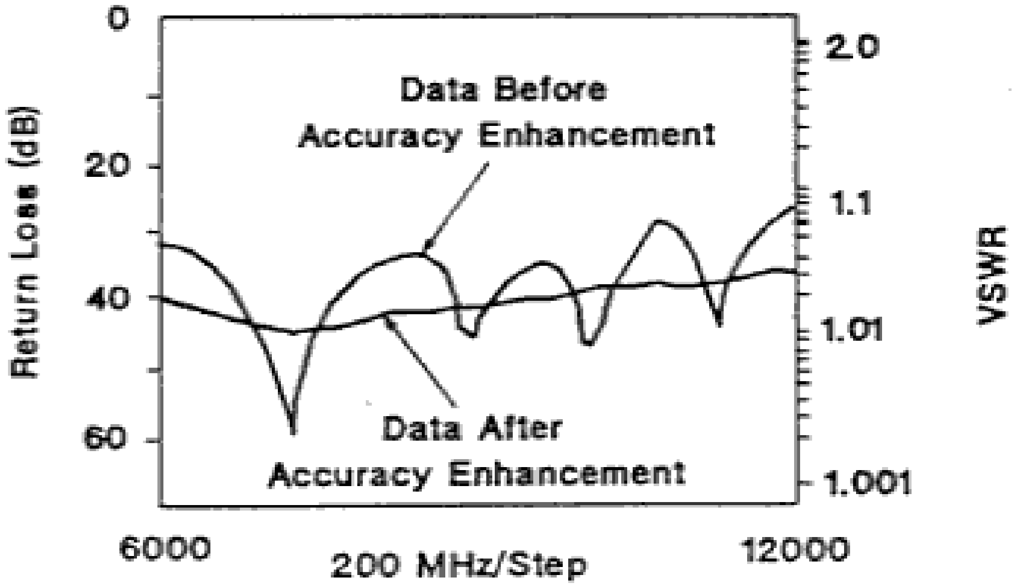
- Coupler Tracking
- Test Cable/Adapter Loss
- Test to Reference Mixer/Sampler Tracking

Test Source Mismatch Errors

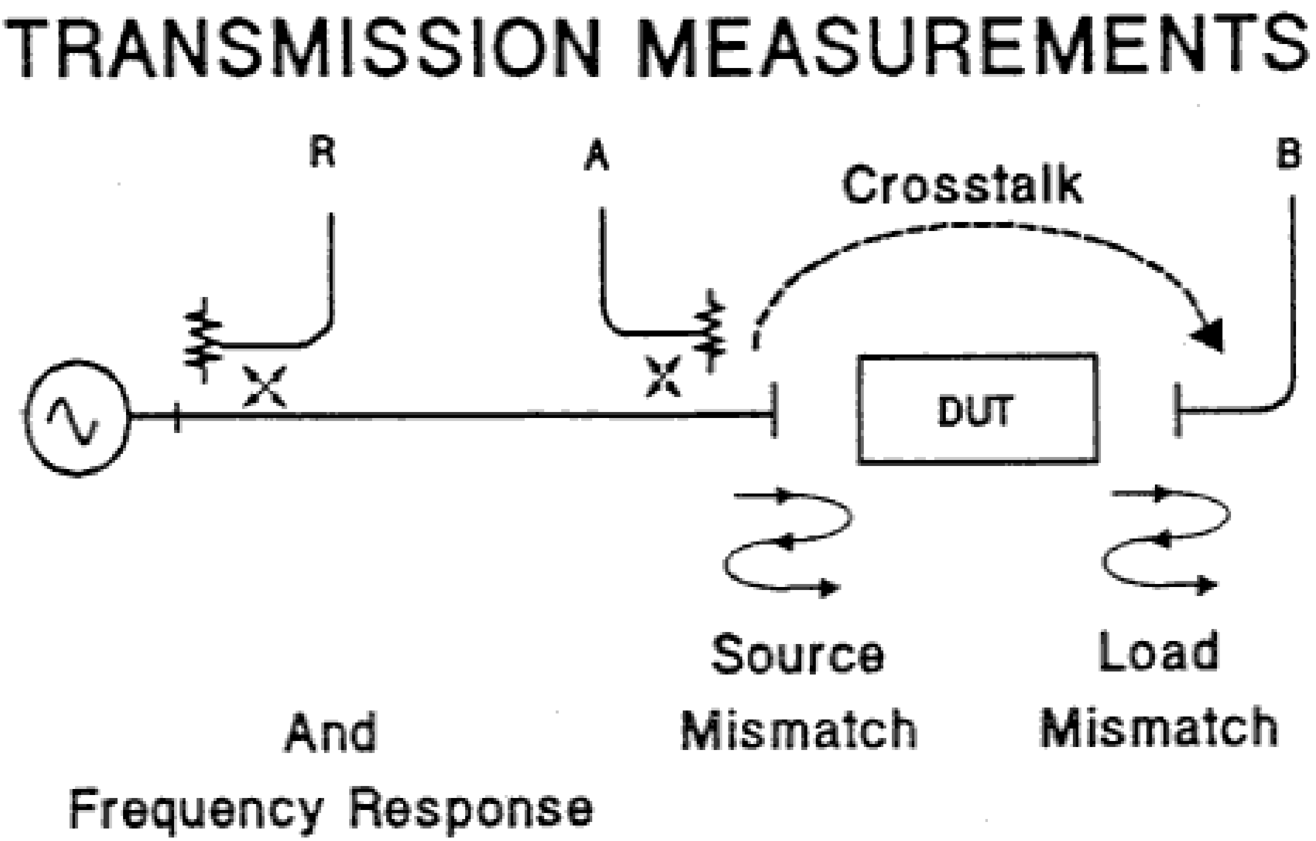


Why we use Error Correction!

BEFORE AND AFTER
ONE-PORT
MEASUREMENT CALIBRATION

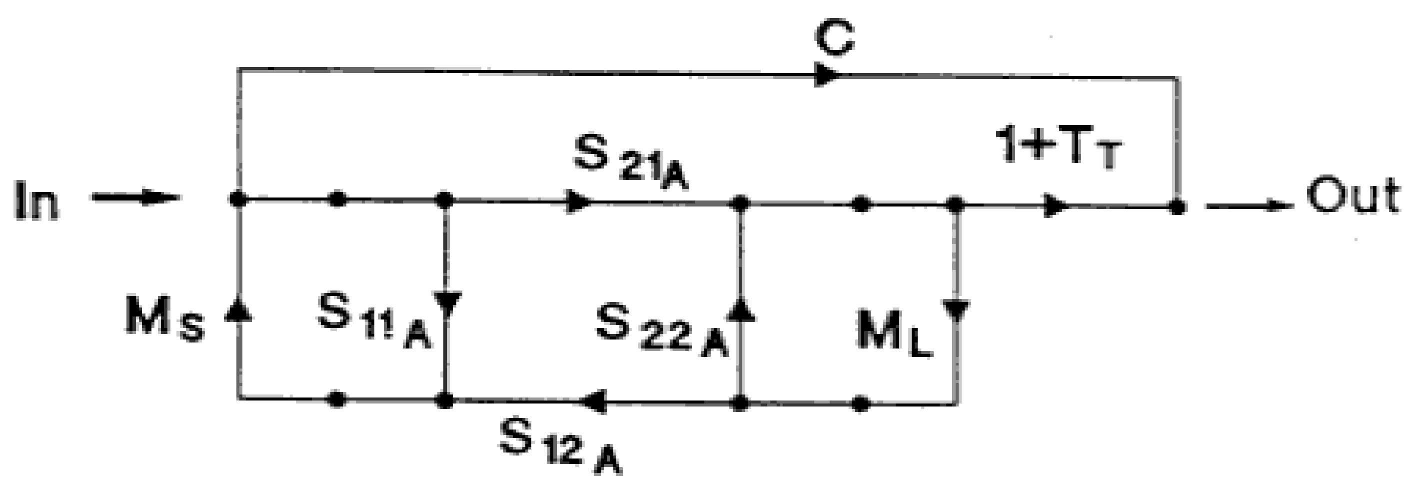


Expanded 2 Port Cals



Flow Diagram of 2 Port Errors

TRANSMISSION
MEASUREMENT MODEL

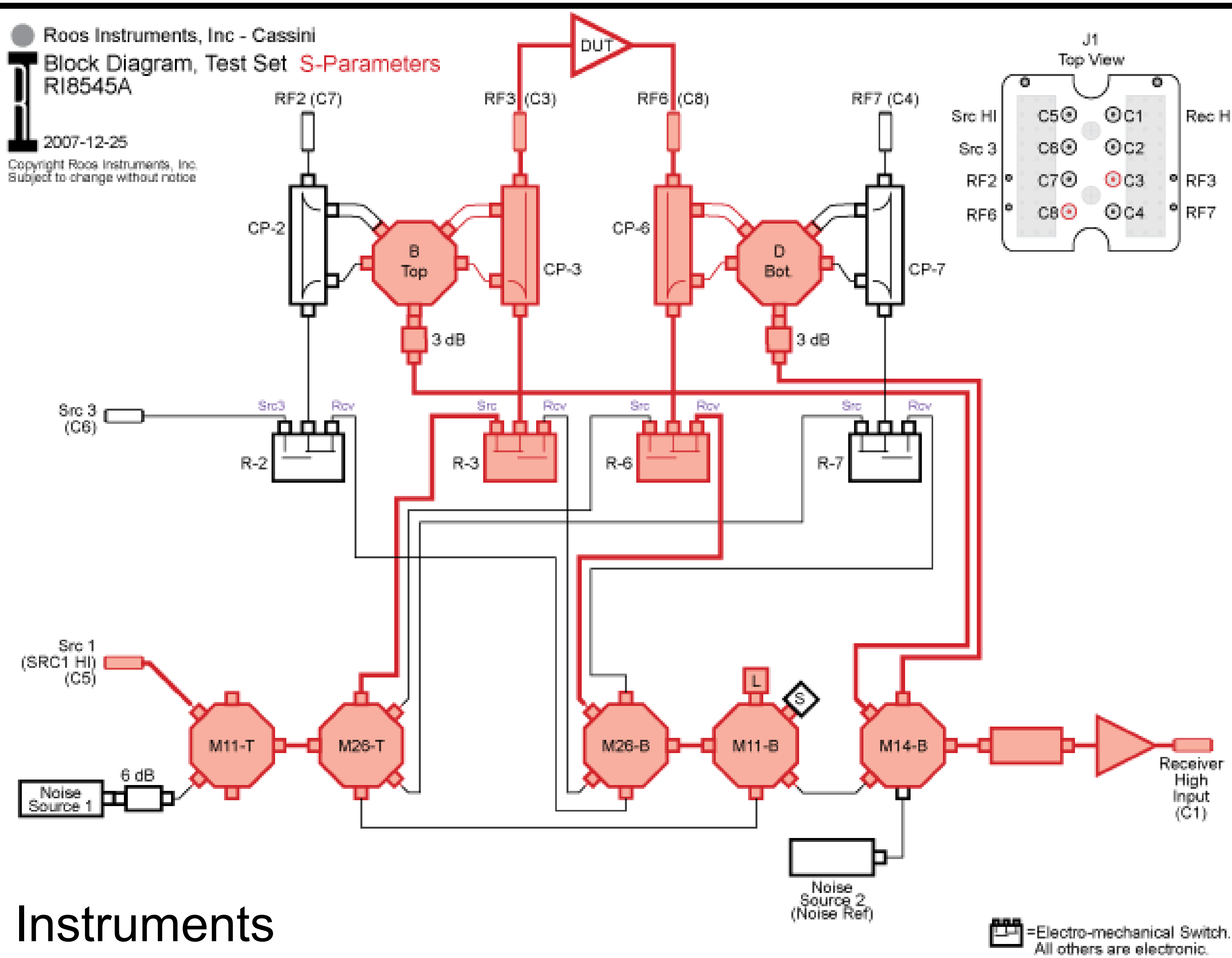


$$S_{21_M} = C + \frac{S_{21_A}\,(1 + T_T)}{1 - M_S S_{11_A} - M_L S_{22_A} - M_S M_L S_{21_A} S_{12_A}}$$

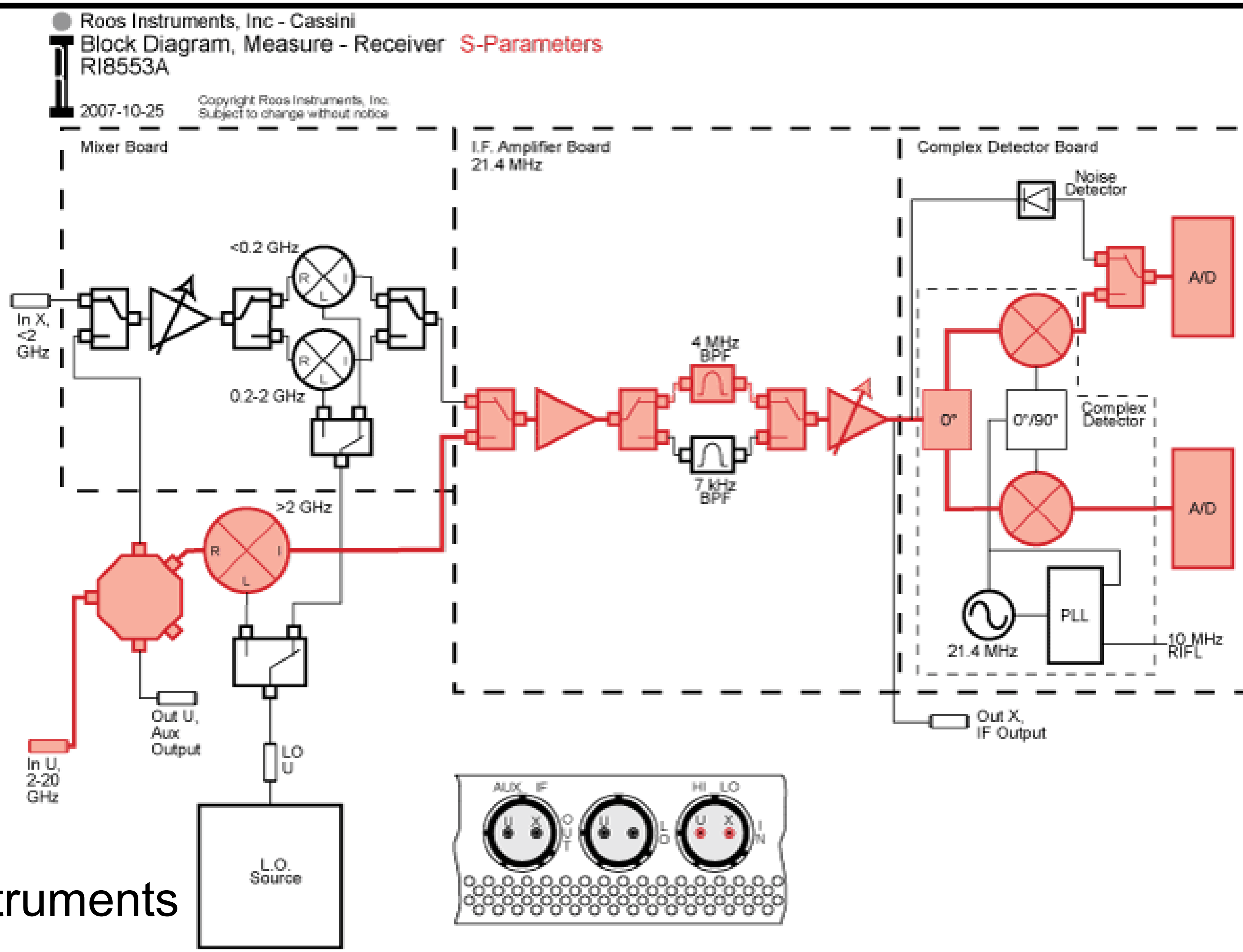
2 Port Calibration & Vector Error Correction

- Characterize Systematic Errors
- Remove Systematic Errors from Measurement
- Reflection Cal: Ms, D, Tr
- Through Connection : Tt, ML
- Isolation Measurement : C

4 Port Testset Config for S-Parameter Measurements



Receiver S-Parameters Measurements

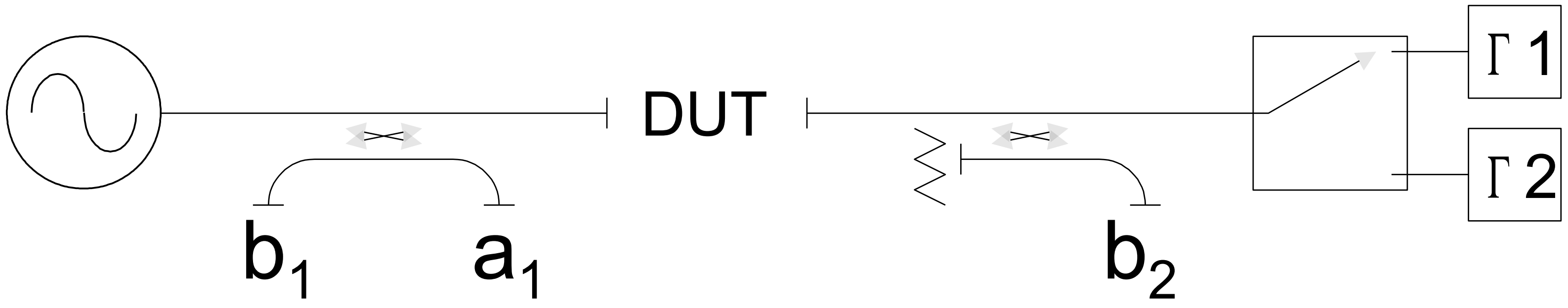


Forward or Unidirectional

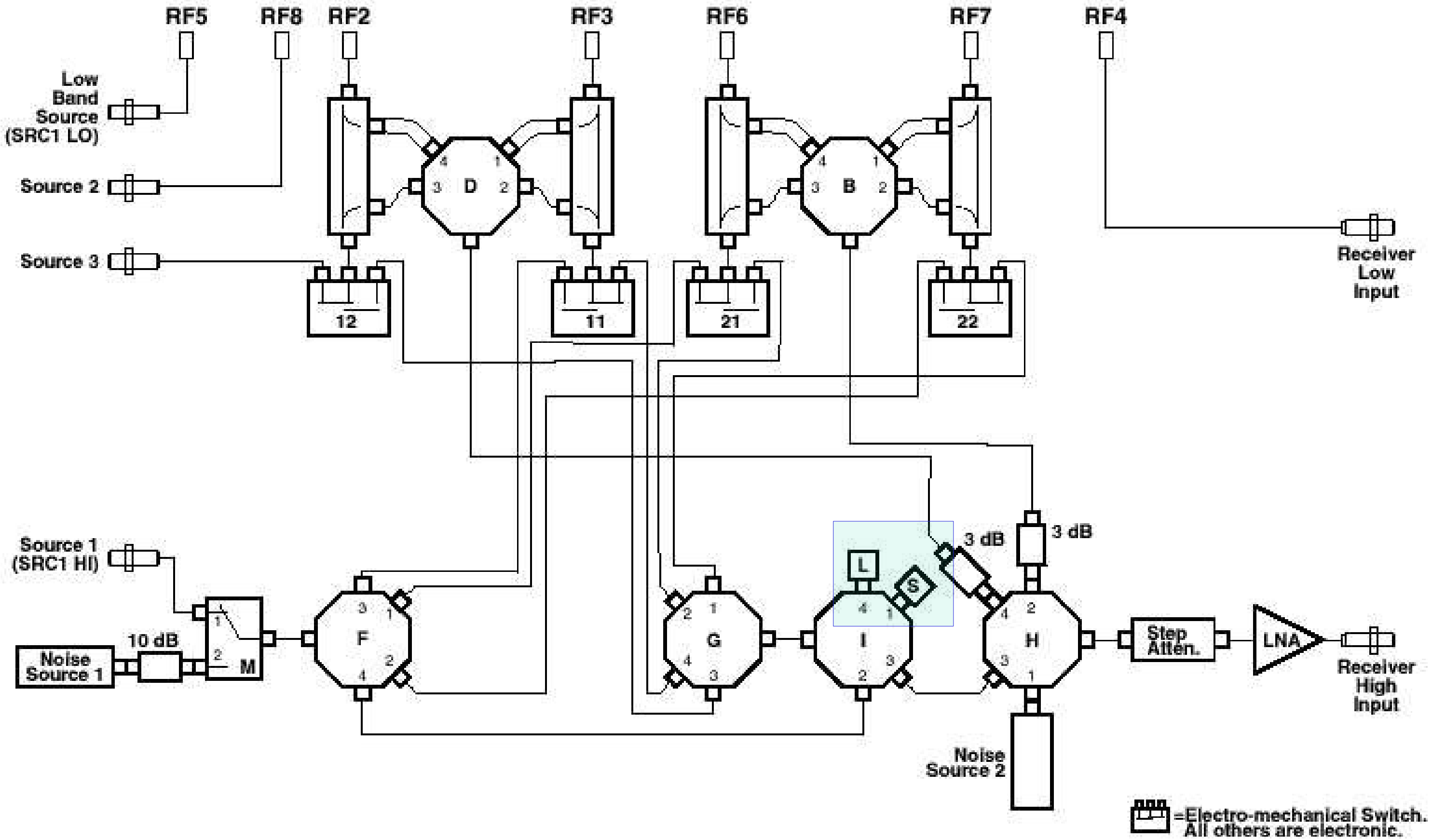
- Fastest method
- 6 Vector Measurements
- No Source Switching
- Allows "Hot" S_{22}
- Default RI Method

Forward Method

- Measure a_1, b_1 and b_2 terminated with known Γ_1 and again with known Γ_2.
- Equations infer a_2, and therefore s_{22}



Forward Method

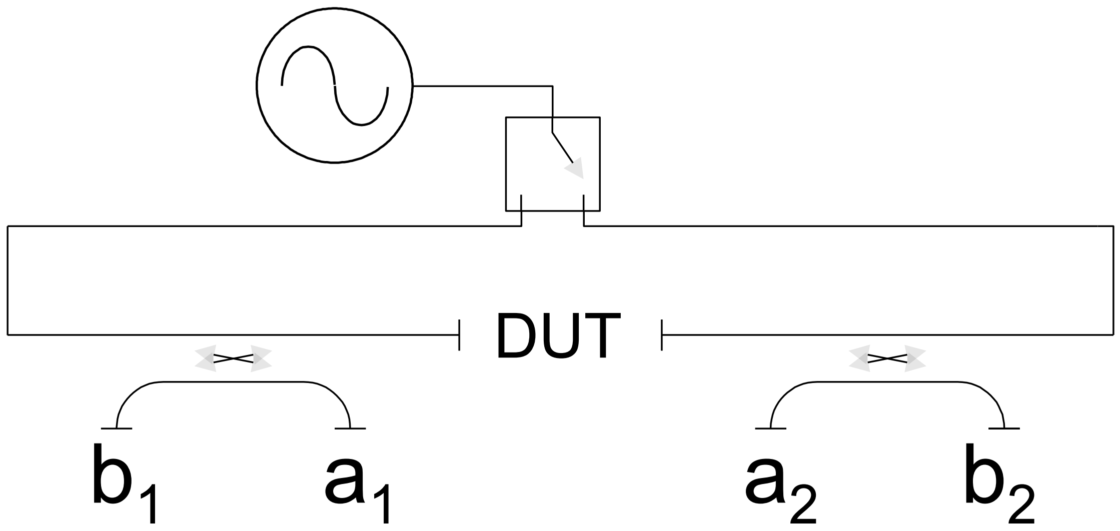


Conventional or Bi-directional

- VNA Method
- 8 Measurements Required
- Slower
- Most Accurate
- Switch Source to Output Side
- No Hot S_{22}

Conventional Method

- Measure a_1, b_1, a_2 and b_2 ; Stimulated forward and reverse



Unidirectional or Bi-directional

- Use Unidirectional for:
  - Speed
  - Hot S_{22}
- Use Bi-directional for:
  - $S_{22,}$ S_{12} accuracy

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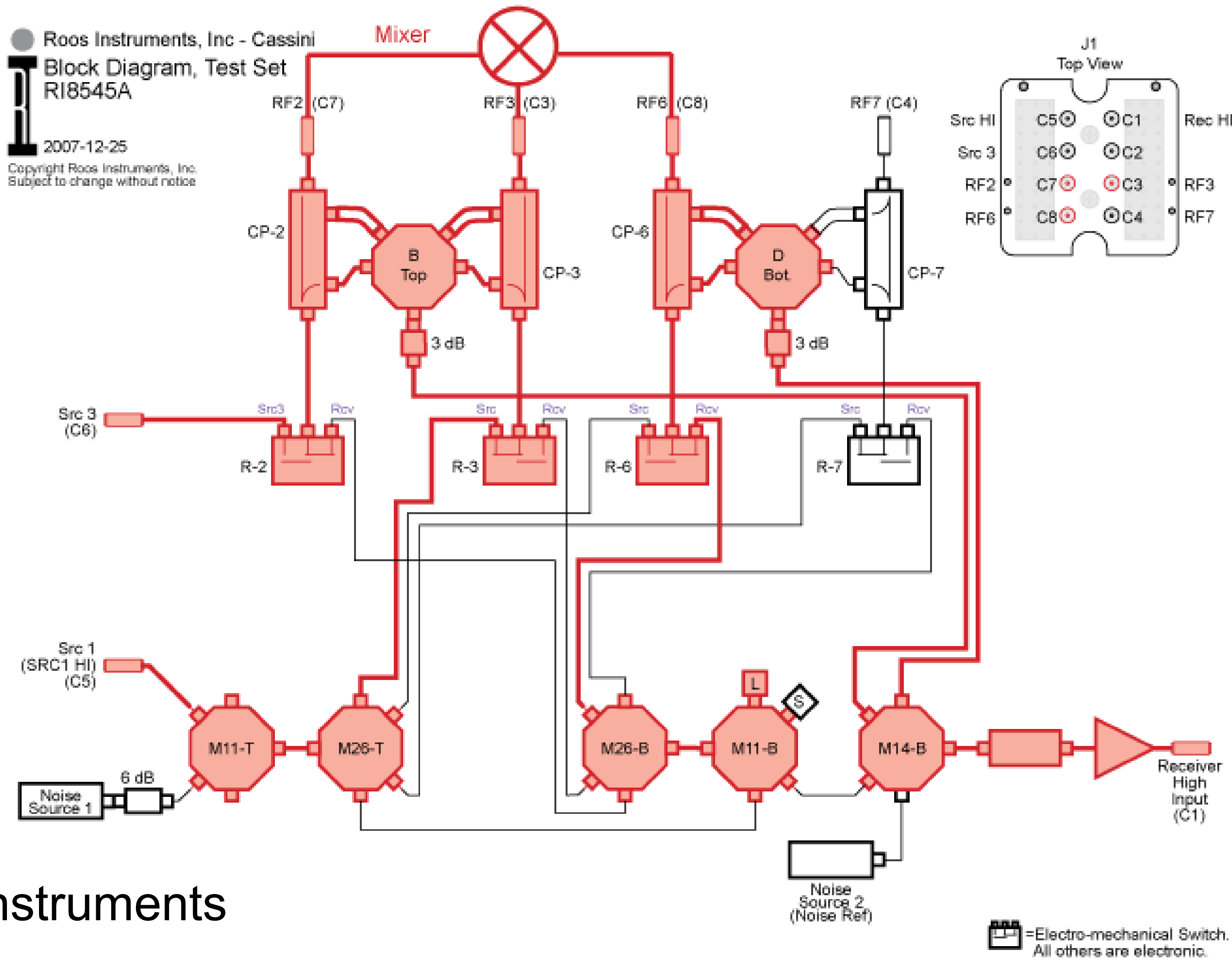
- Noise Figure Measurements

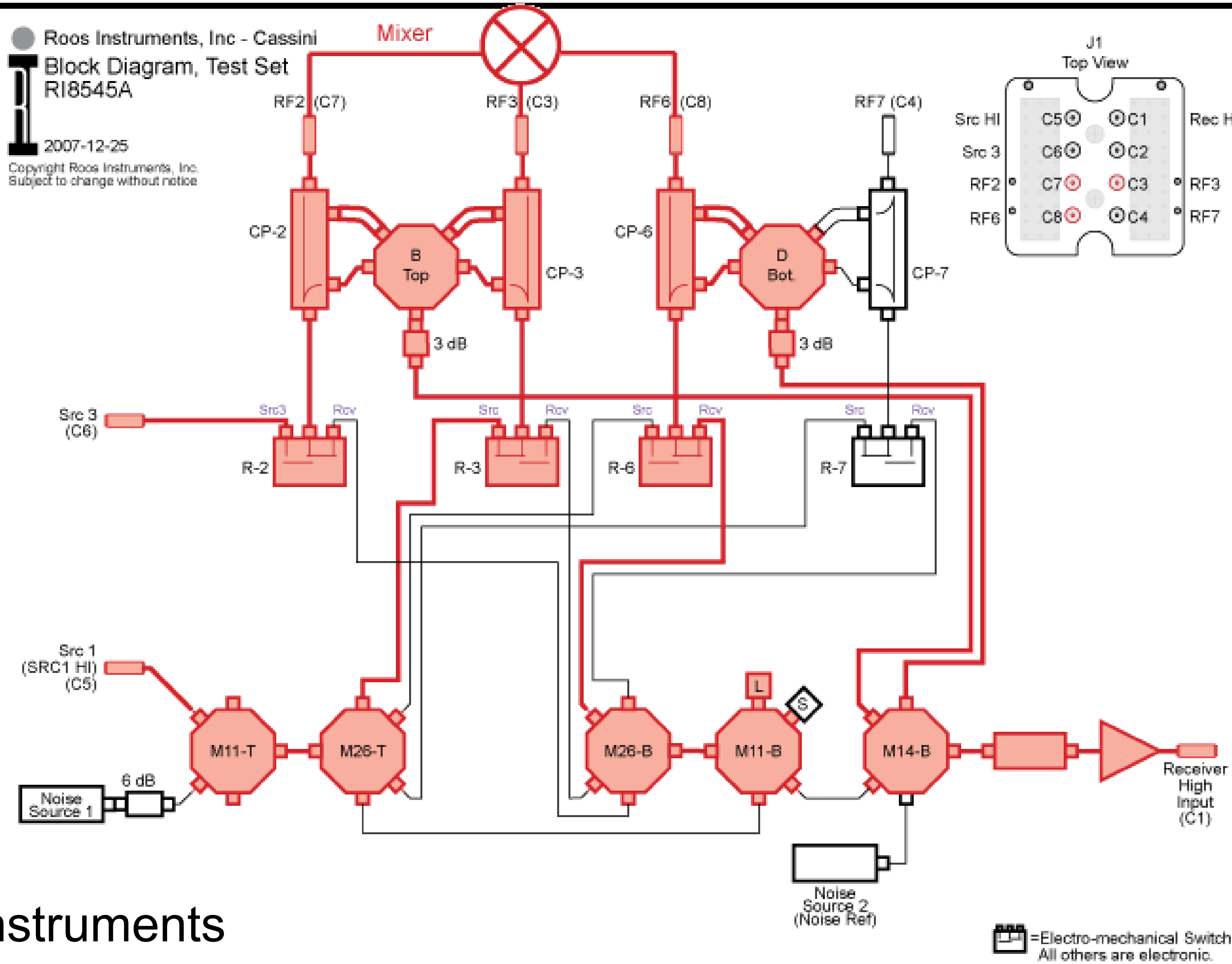
Frequency Translation Device Measurement

- Cassini Measurement Approach
  - Multi-Port S Parameter Detection Hardware 100MHz to 20 GHz
  - Requires one or more additional RF Source for DUT LO
- Stimulus:
  - RF Stimulus Source: RF Input 100 MHz to 20 GHz
  - DUT LO Source: LO Input 10 MHz to 20 GHz
  - Maintain Constant IF Freq
  - Sweep RF and DUT LO Frequency
  - Requires 3 RF Sources to be at Different Frequencies
- Measure: Pin(RF) and Pout(IF)
- Calculate: Conversion Gain/Loss=Pout(IF)/Pin(RF)
- Test Plan Optimizer Determines the Measurement Sequence

Frequency Translation Device Measurements



Frequency Translation Device Measurements



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RF Power

- Cassini Vector Corrected RF Power Measurements
- Bandwidth Selectable Absolute RF Power (dBm, watts, etc.)
- True RMS RF Power of Wide Band Digitally Modulated Signals
- S Parameter Detection Hardware
- Amplitude Only Measurement
- IF Measurement
- Wide Dynamic Range
- Automatically Corrects for Signal Path Losses

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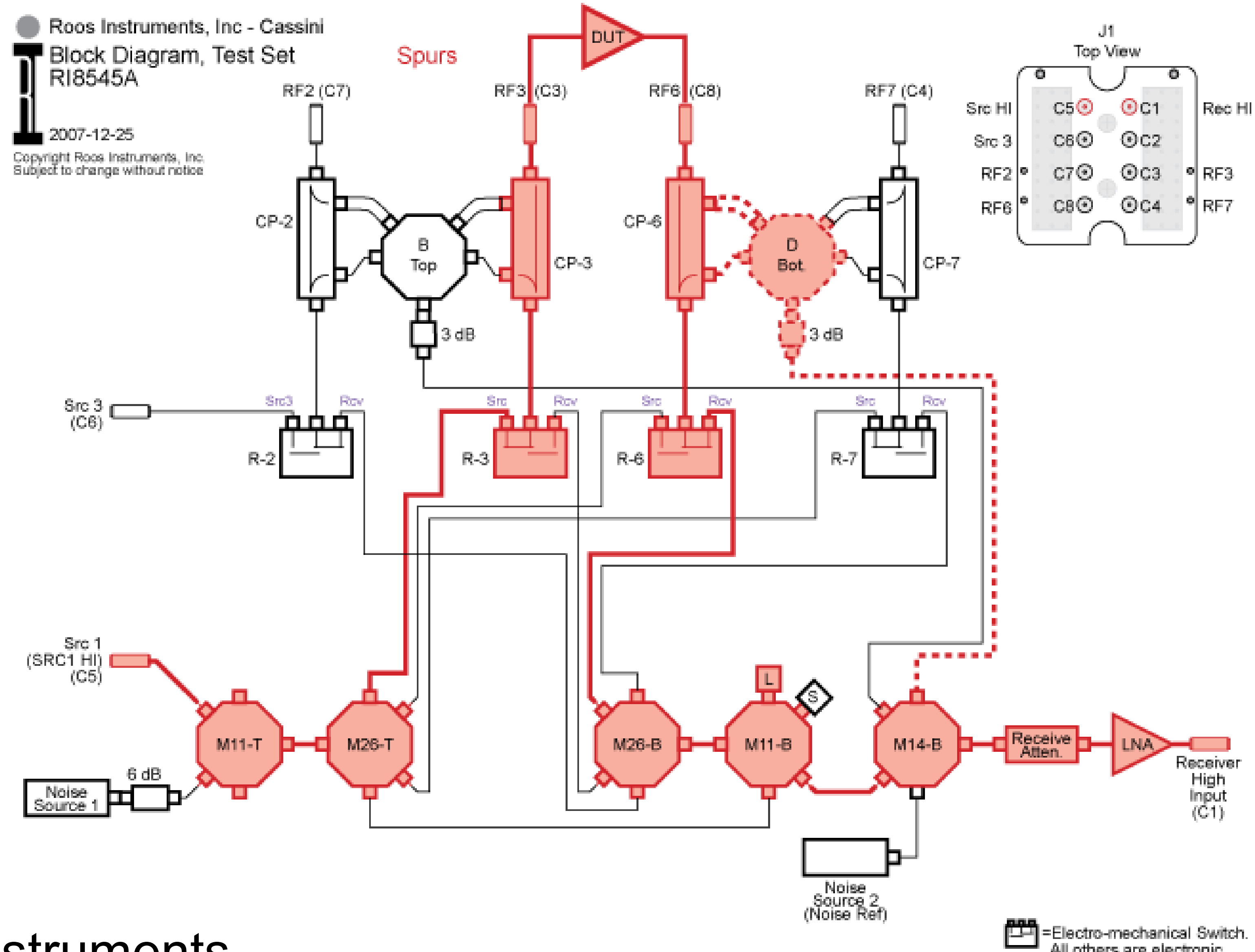
Spectral Purity (Harmonics or Spurs) Measurements

- Cassini Measurement Approach
  - S Parameter Detection Hardware 100MHz to 20GHz
  - Relative RF Level Measurements
- Stimulus
  - Single RF Tone at F1
  - User Specifies Harmonic No., N or Spur Frequency F2
- Measure: Pout(F1) and Pout(F1xN) or Pout (F2)
- Calculate: Pout(F1) - Pout(F1xN)) or Pout (F2)
- Where Pout(F) = DUT Output Signal Level in dBm at Frequency F

Testset Configuration for Spectral Purity



RF Measurements Outline

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- **Intermod Distortion Measurements**
- Digitally Modulated RF Signal Measurements
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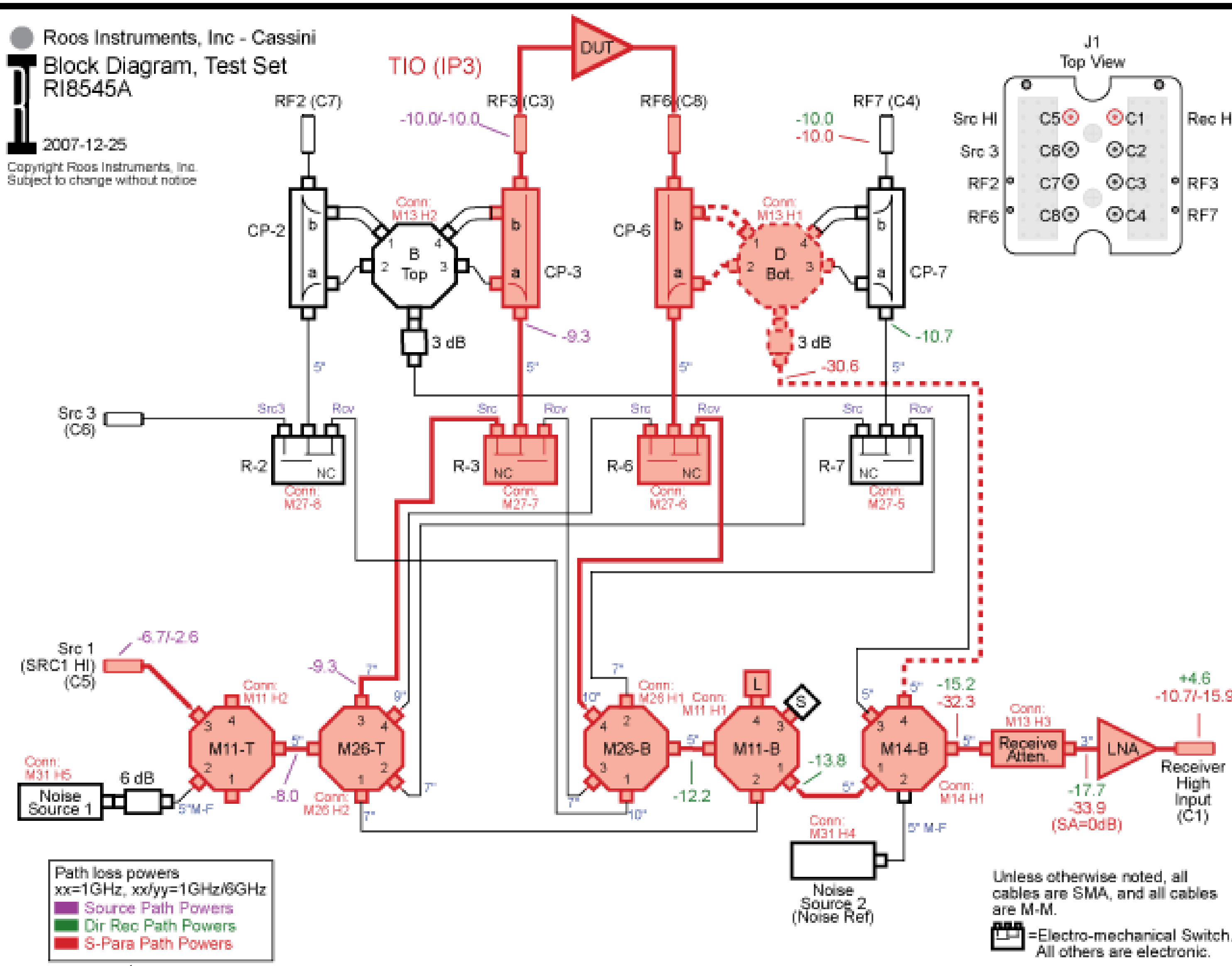
- Noise Figure Measurements

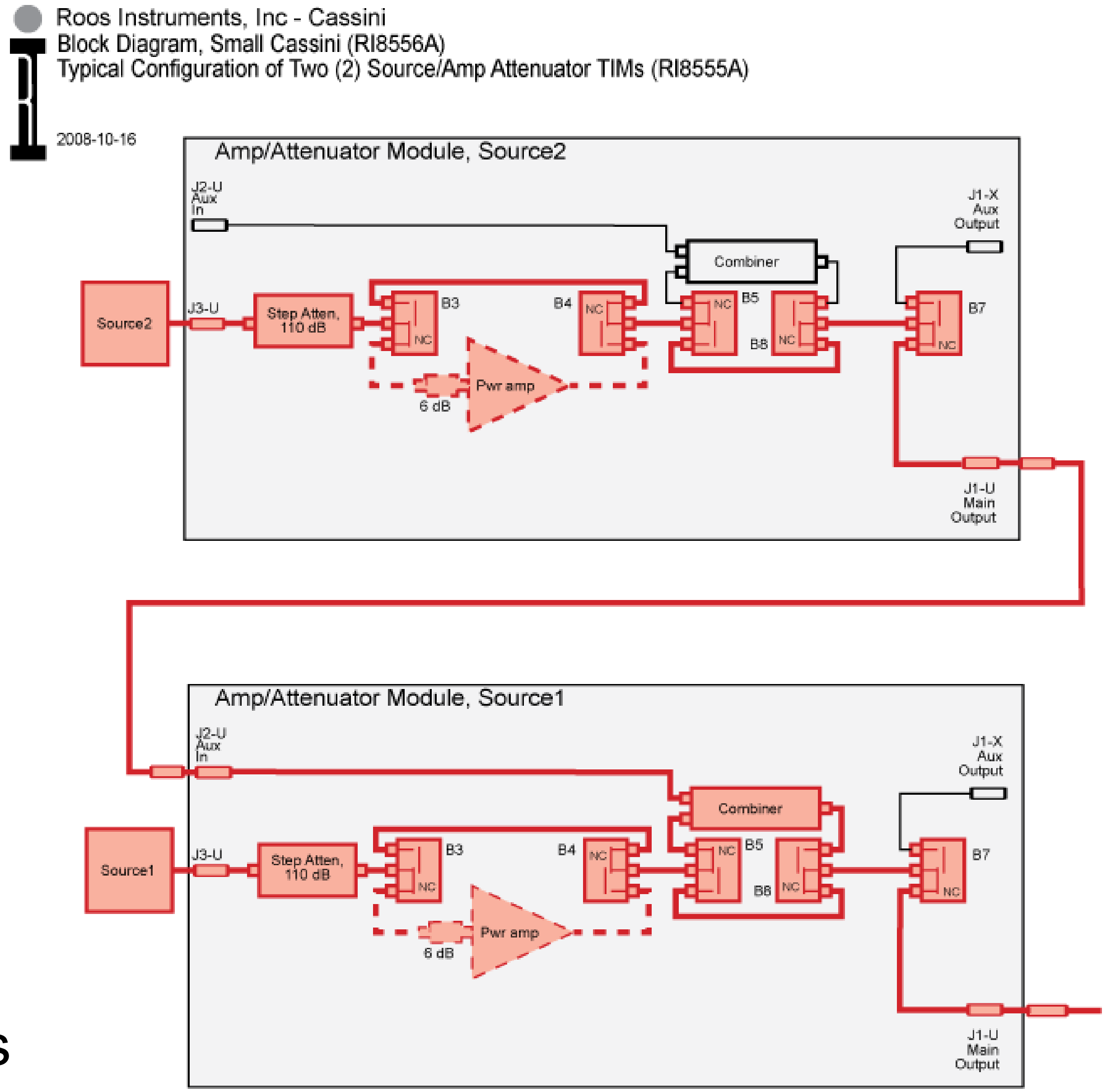
Intermodulation Distortion / TOI Measurements

- Cassini Measurement Approach
  - S Parameter Detection Hardware
  - RF Level Measurements
- Stimulus
  - Two Equal Amplitude RF Tones
  - Specify RF Level, Center Freq (F_1) and Spacing
  - 2nd RF Tone: $F_2 = F_1$-Spacing
- Measure: 3rd Order Distortion Product Term
  - $Pout(2xF_1 - F_2)$
- Calculate: IP3 / TOI in dBm:
  - $Pout(F_1) + [Pout(F_1) - Pout(2xF_1 - F_2)] / 2$

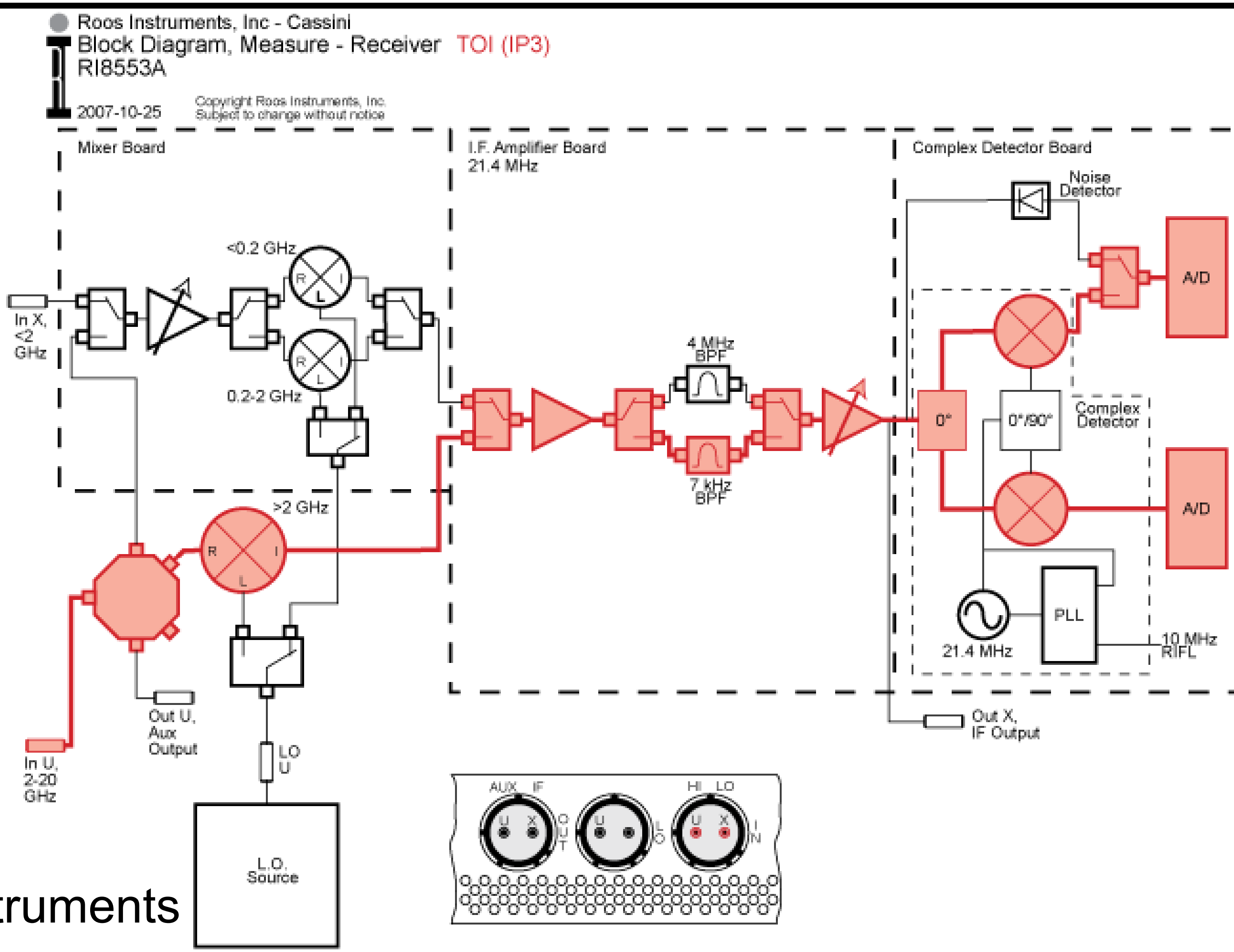
Testset Configuration for Intermodulation



RF Source Configuration for Intermodulation



Receiver Configuration for Intermodulation



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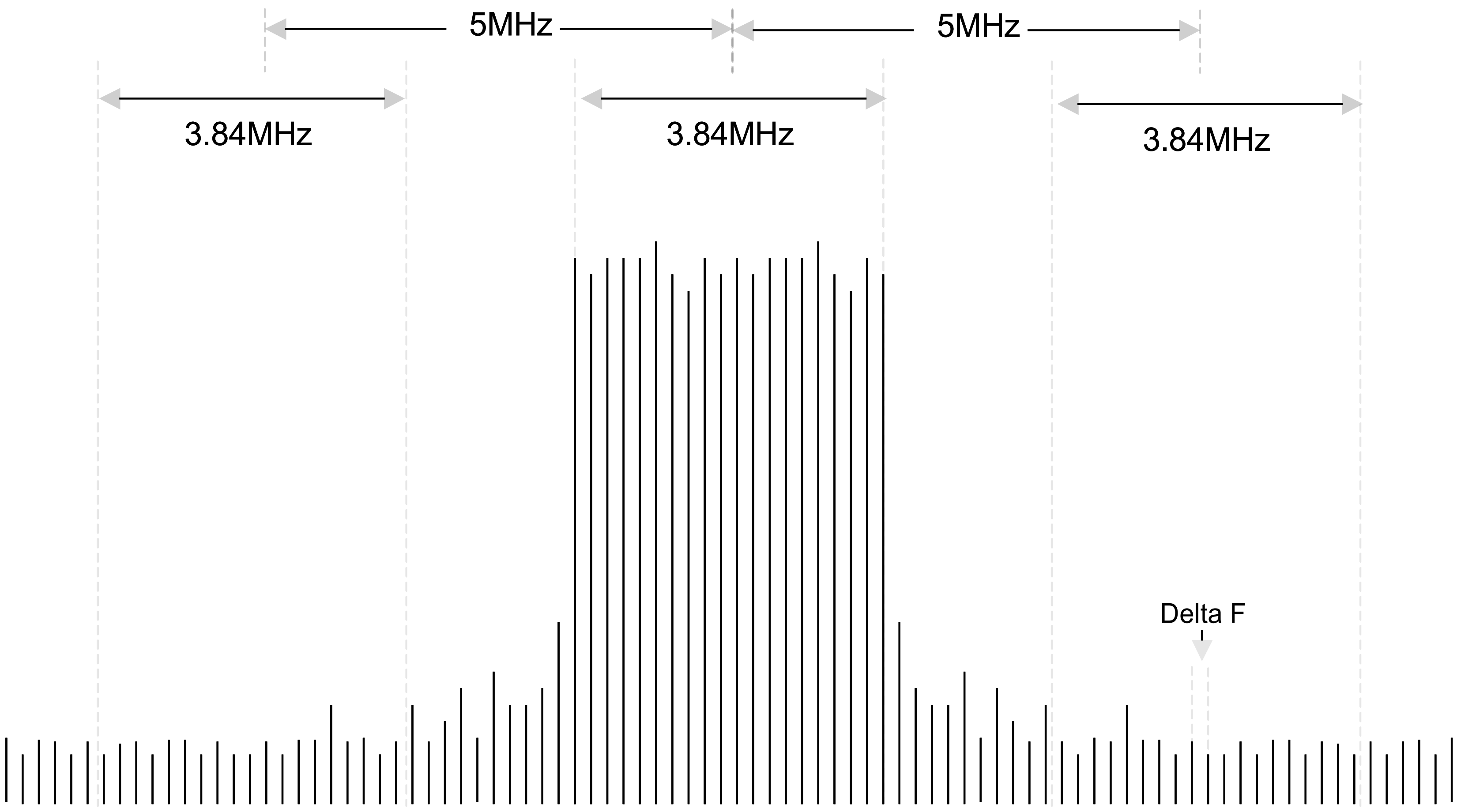
Wide Band Digitally Modulated Signal Measurements

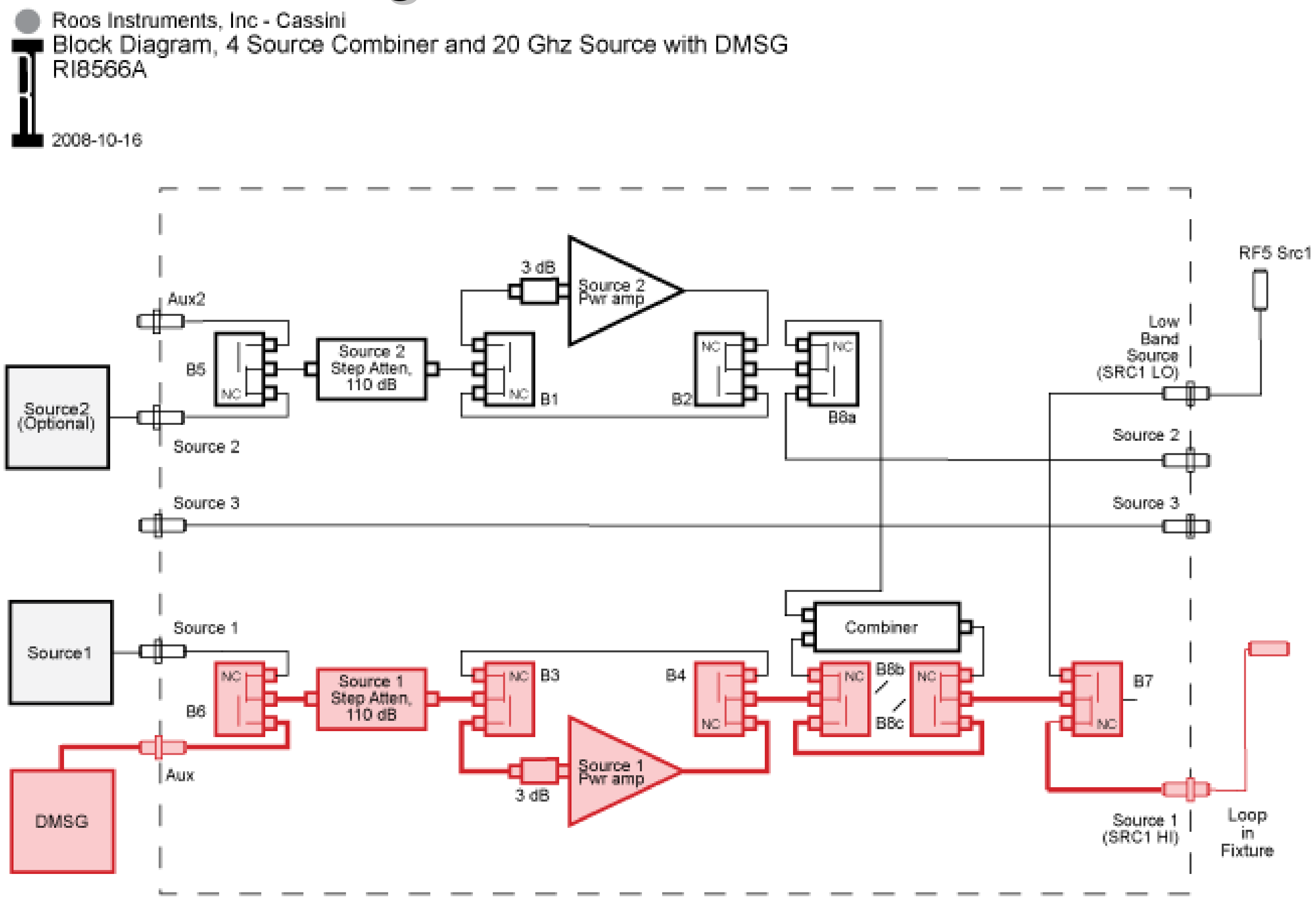
- Cassini Measurement Approach
  - S Parameter Detection Hardware
  - True RMS Noise Detector
- Stimulus
  - Digital Modulation Signal Generator
  - Auxiliary Source Fast Power Control

Typical CDMA Signal

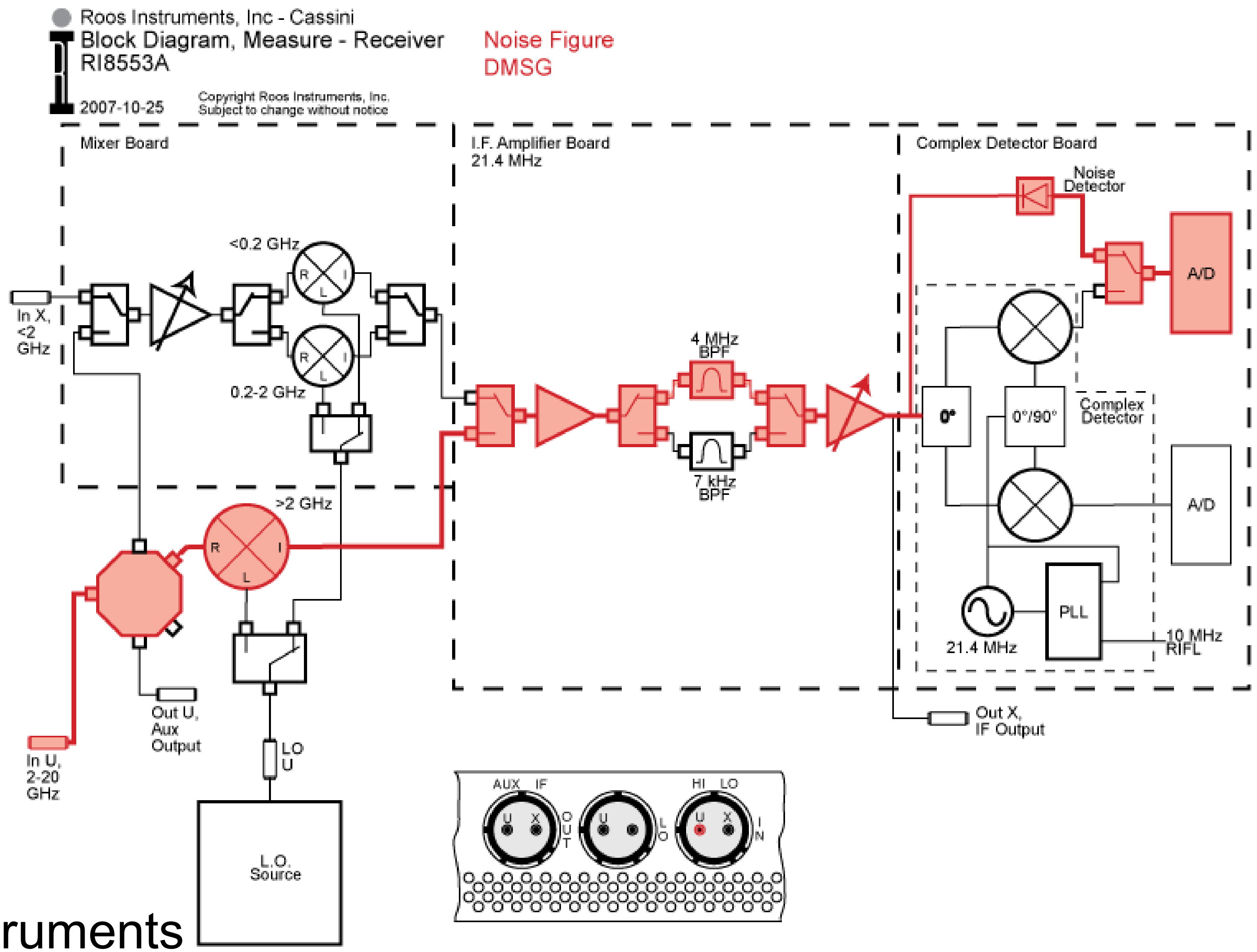


ACLR = power in channel 3.84 MHz/Power in adjacent channel 3.84 MHx BW . Typical 55dB

Source 1 & 2 Combiner Module for Modulated Signals



Wide Band Modulation Receiver Measurements



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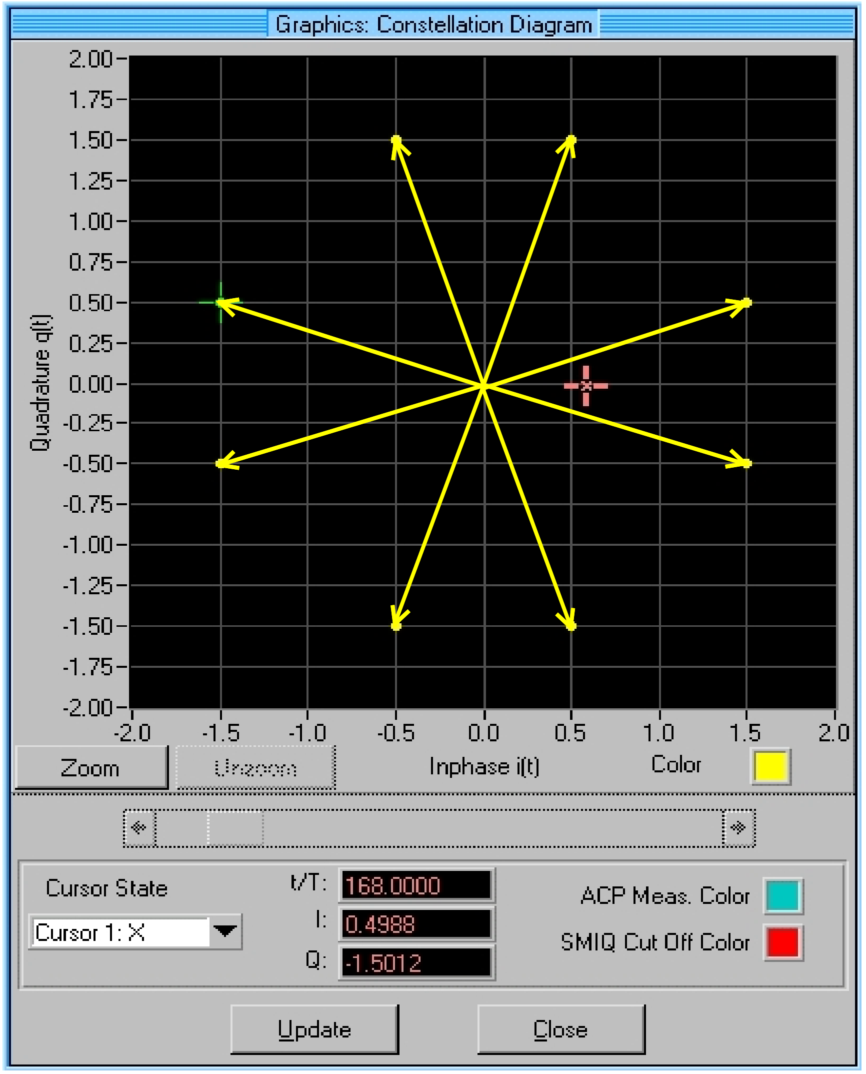
Digitally Modulated Signal Error Vector Measurements

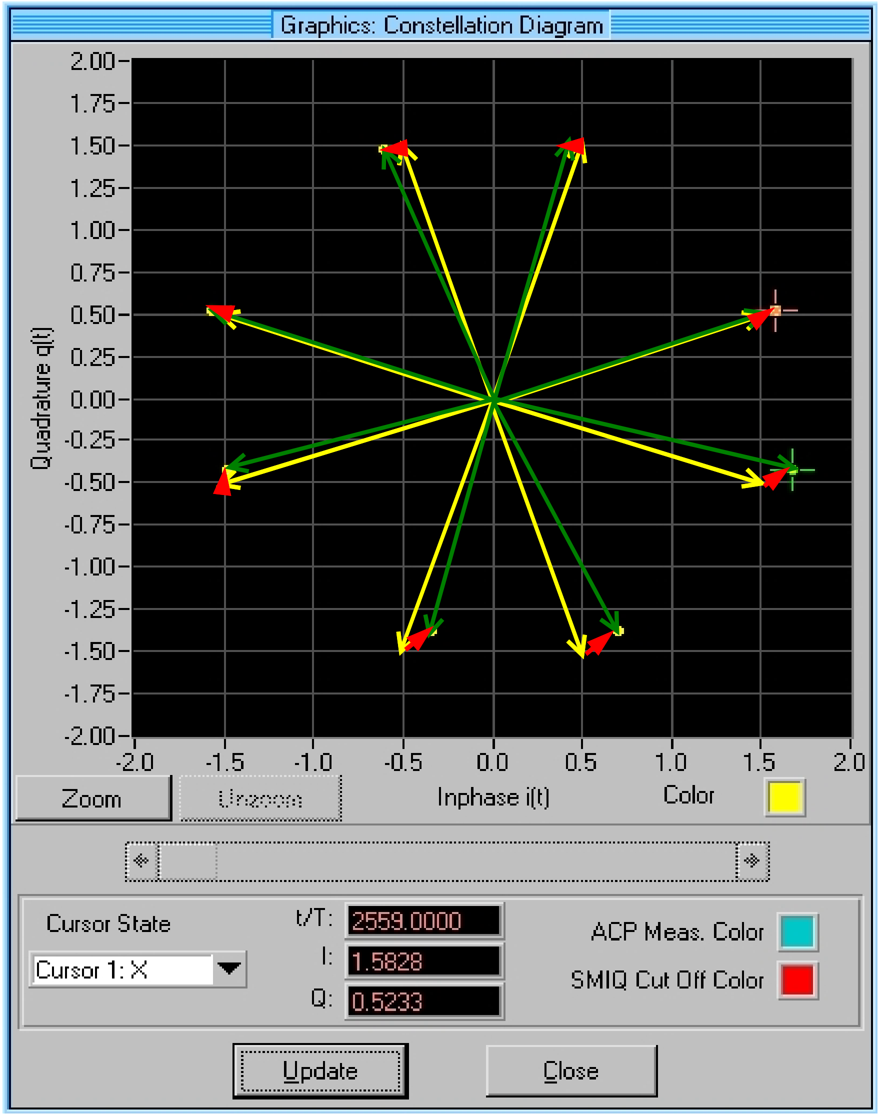
- Cassini Measurement Approach
  - Intrinsic Errors measured directly
  - I/Q DC Offsets and Mag & Phase errors for Mod/Demod
  - AM to AM and AM to PM for PA's
- Stimulus
  - CW Signal Generator
  - Arbitrary Waveform Generator
  - Digital Modulation Signal Generator

- "The Error Vector and Amplifier Distortion" - Published 1997 at the Wireless Communications Conference - Lucent / Bell Labs - Heutmaker
- "WCDMA Transmit IC : Application case study" - Wireless Workshop - Published at the 2002 International Test Conference (ITC) - Jointly by IBM and RI
- " Edge PA EVM" - to be Published at the 2004 International Test Conference (ITC) -

What is EVM?


Graphics: Constellation Diagram
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.50
-1.75
-2.00
Quadrature q(t)
-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0
Zoom
Inphase i(t)
Color
Cursor State
Cursor 1: X
t/T: 168.0000
I: 0.4988
Q: -1.5012
ACP Meas. Color
SMIQ Cut Off Color
Update
Close

This is EVM!



Graphics: Constellation Diagram
Quadrature q(t)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.50
-1.75
-2.00
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
Zoom
Inphase i(t)
Color
Cursor State
Cursor 1: X
t/T:
2559.0000
I:
1.5828
Q:
0.5233
ACP Meas. Color
SMIQ Cut Off Color
Update
Close

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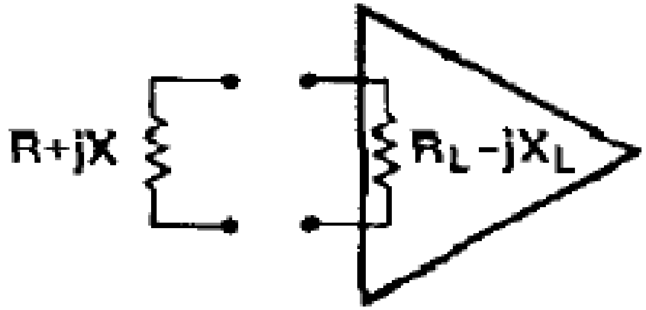
- **Noise Figure Measurements**

Noise Figure Measurements

- Definitions
- What is Noise Figure
- Y Factor Type Measurements
- Second Stage Error Correction
- Mismatch Effects
- System Noise Figure Effects

What is RF Noise?

AVAILABLE NOISE POWER
(THERMAL)



$P_{av} = kTB =$ Power Delivered to a Conjugate Load, i.e. $R_L = R$, $X_L = X$.

$k =$ Boltzmann's constant (1.38×10^{-23} Joule/K)

$T =$ Temperature (K)

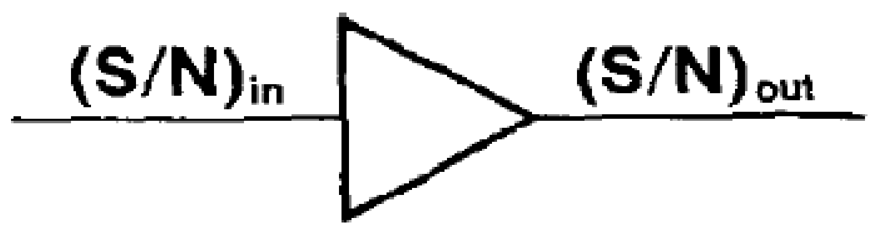
$B =$ Bandwidth (Hz)

Note: At Standard Temperature T_o (=290K):

$kT_o = 4 \times 10^{-21}$ W/Hz = –174 dBm/Hz

What is Nosie Figure?

WHAT IS NOISE FIGURE
(ORIGINAL DEFINITION)

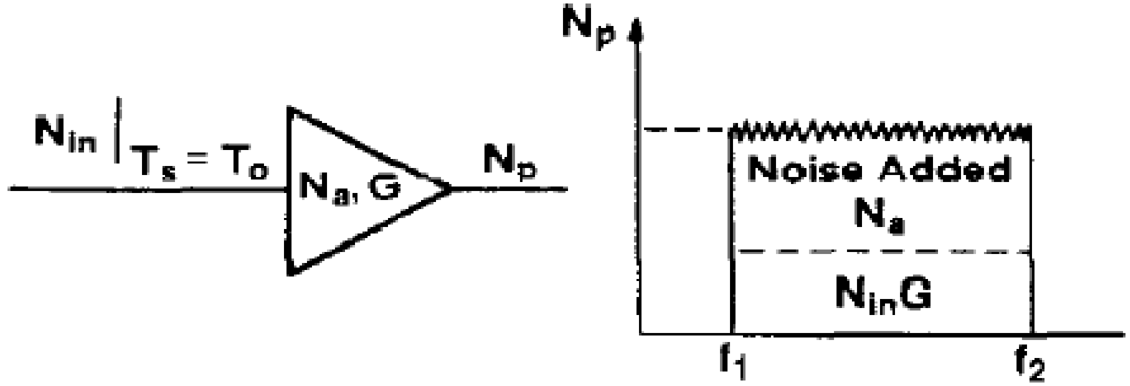


$$F \equiv \left. \frac{(S/N)_{in}}{(S/N)_{out}} \right|_{T_s = 290K}$$

$$F\,(dB) \equiv 10 \log \left. \frac{(S/N)_{in}}{(S/N)_{out}} \right|_{T_s = 290K}$$

S/N is too Difficult to Measure Directly - Additive Noise is Not

AN EQUIVALENT DEFINITION OF NOISE FIGURE (IRE)



Noise Figure: $F \equiv \left. \dfrac{N_a + N_{in}G}{N_{in}G} \right|_{T_s = T_o = 290K}$

Where

N_{in} = P_{av} From the Source When at 290K
i.e., $N_{in} - kT_oB$

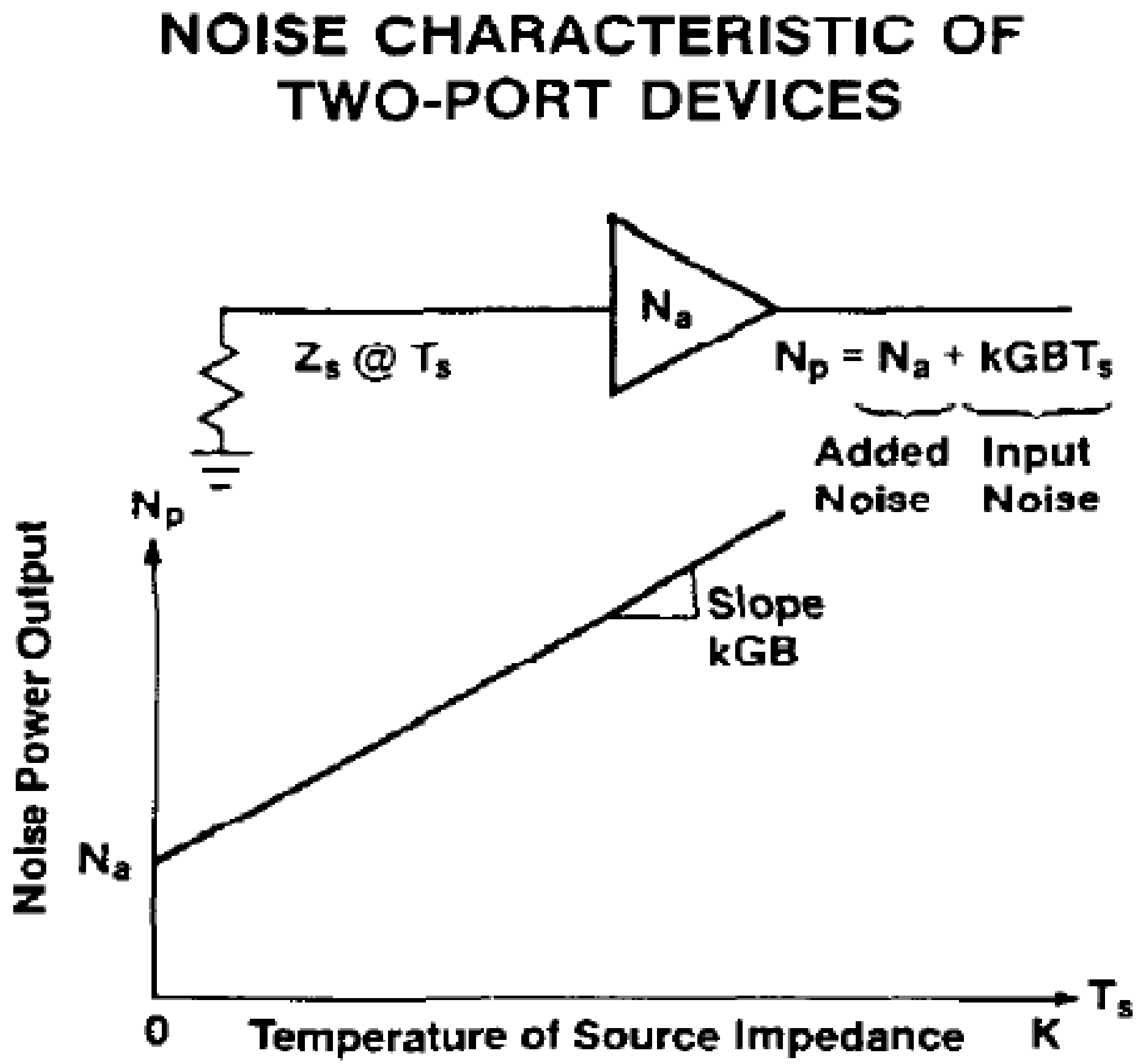
G = Available Gain

B = Bandwidth

T_o = Temperature of Source Resistance (290K)

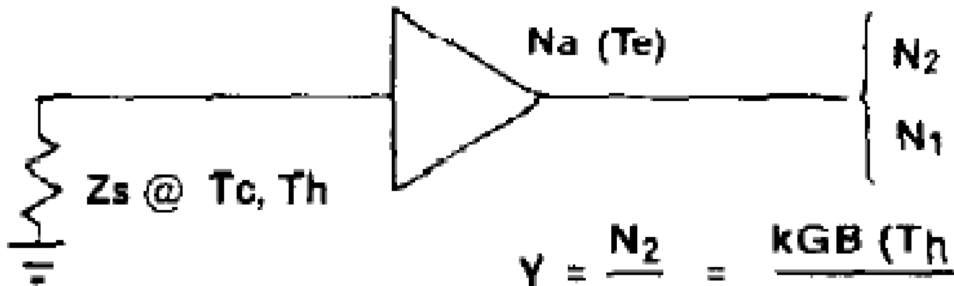
Note: $N_a = kT_oBG\,(F-1)$

2 Port device NF Testing Model



2 Port NF Measurement Process
Y- Factor Technique

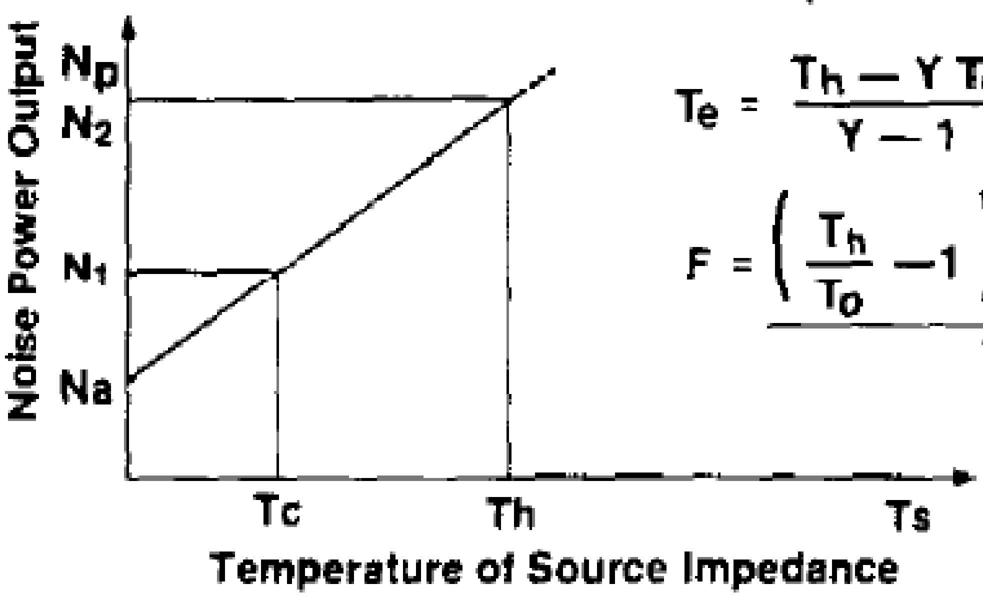
MEASUREMENT OF NOISE



$$Y = \frac{N_2}{N_1} = \frac{kGB\,(T_h + T_e)}{kGB\,(T_c + T_e)}$$

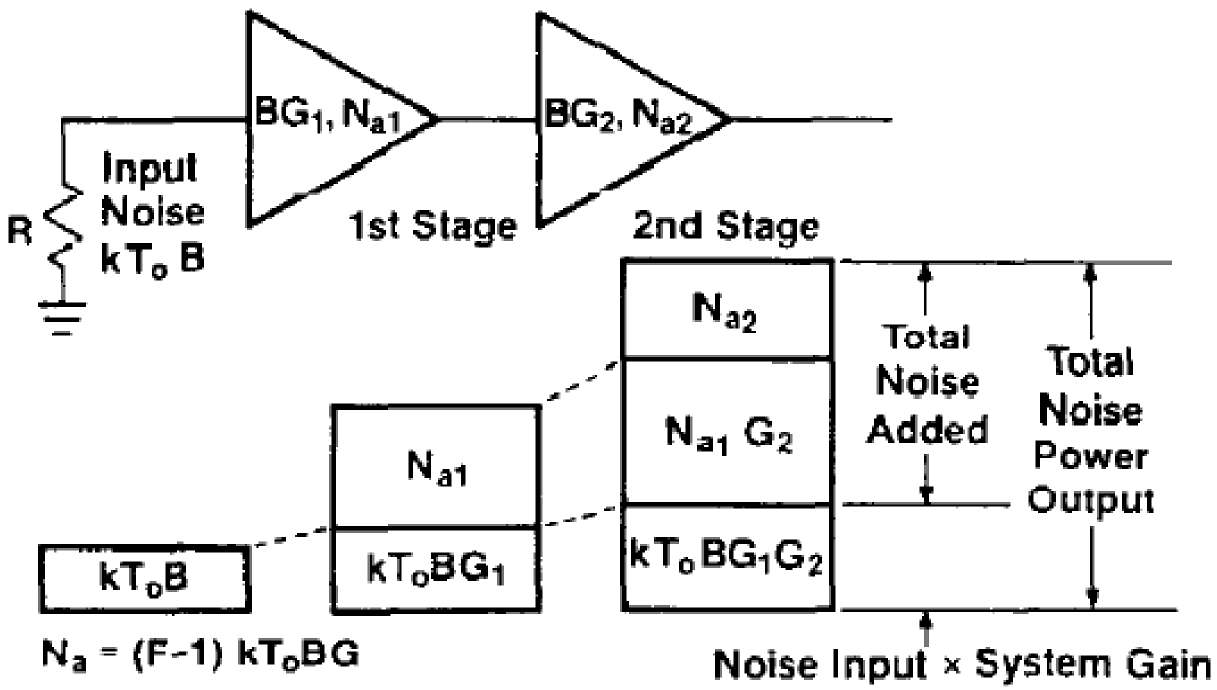
$$T_e = \frac{T_h - Y\,T_c}{Y - 1}, \quad F = \frac{T_e + T_o}{T_o}$$

$$F = \frac{\left(\frac{T_h}{T_o} - 1\right) - Y\left(\frac{T_c}{T_o} - 1\right)}{Y - 1}$$



2nd Stage Error Effects

EFFECT OF SECOND STAGE CONTRIBUTION



$N_a = (F-1)\, kT_oBG$

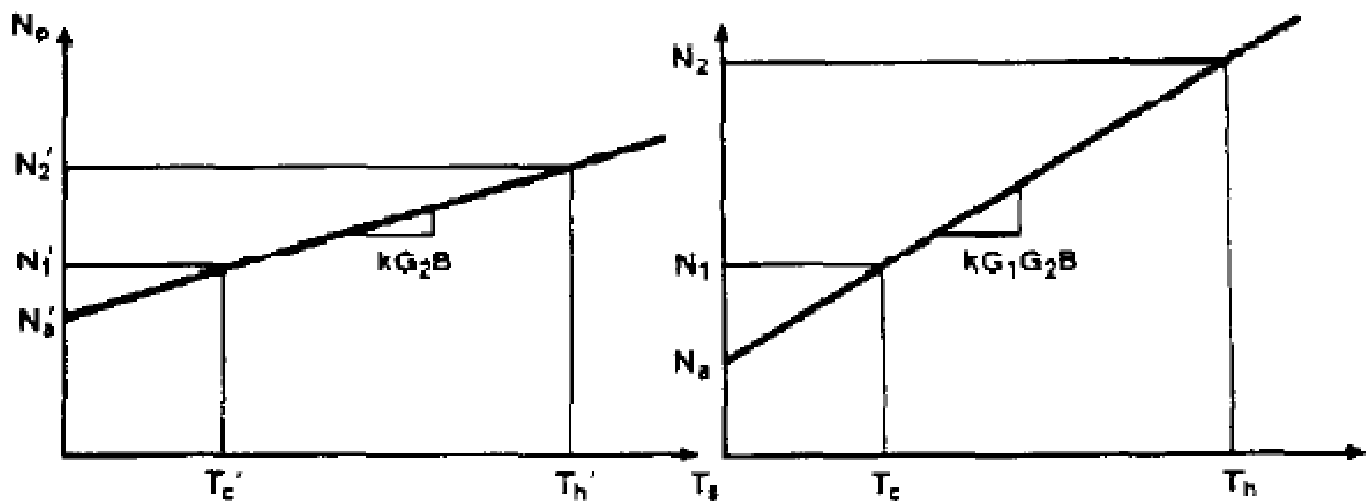
$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \cdots\cdots \frac{F_n - 1}{G_1 G_2 \ldots G_n - 1}$$

$$F_{12} = F_1 + \frac{F_2 - 1}{G_1}$$

Gain of Device needed to extract Noise Figure

GAIN MEASUREMENT

Calibration (Measurement System) | DUT Measurement (DUT & System)



slope = $kG_2B = \frac{N_2' - N_1'}{T_h' - T_c'}$

slope = $kG_1G_2B = \frac{N_2 - N_1}{T_h - T_c}$

$$G_1 = \frac{\frac{N_2 - N_1}{T_h - T_c}}{\frac{N_2' - N_1'}{T_h' - T_c'}}$$

Noise Source
External Calibration Standard

EXCESS NOISE RATIO

FREQUENCY	ENR (dB)
XXX	AAA
YYY	BBB
ZZZ	CCC

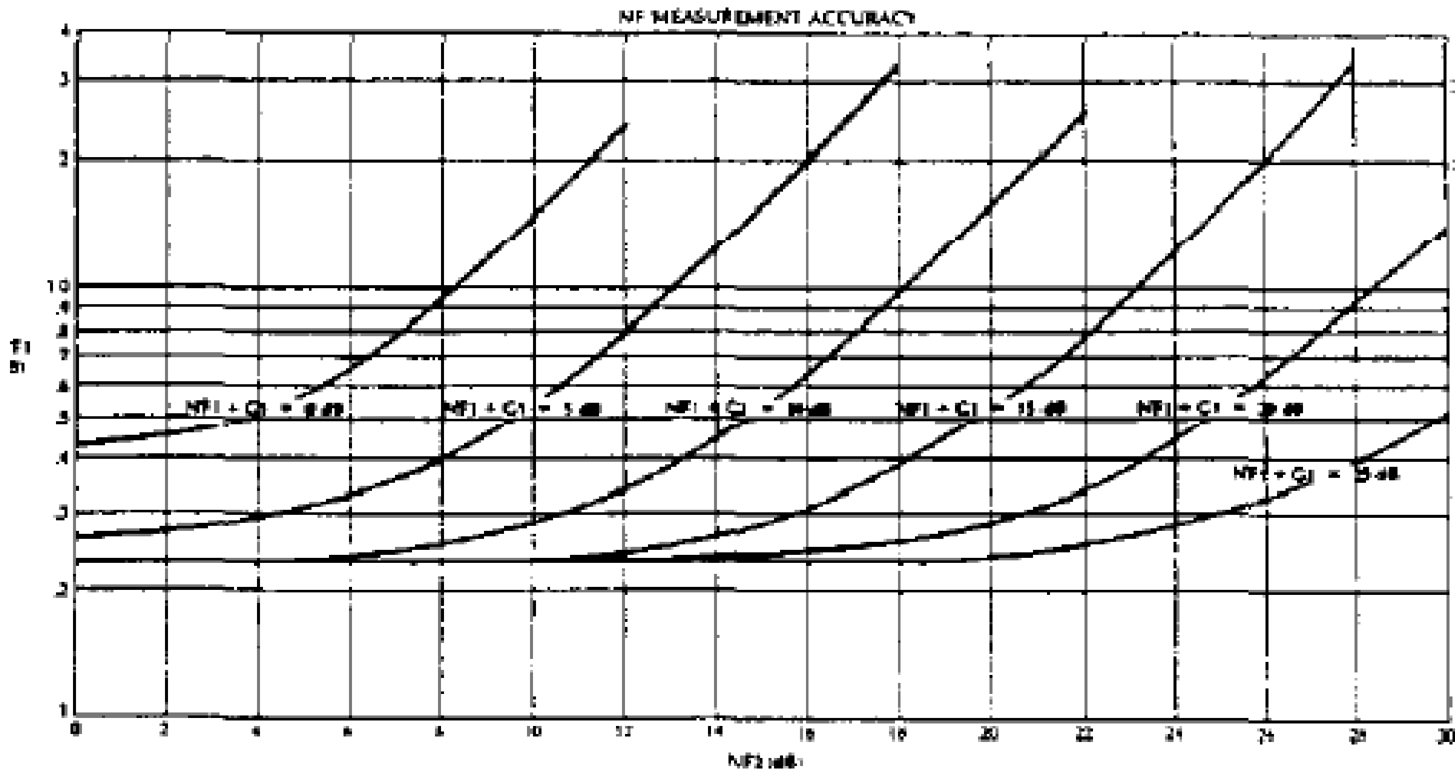
Excess Noise Ratio or ENR (dB)

$$ENR\ (dB) = 10 \log_{10} \left(\frac{T_h - 290}{290} \right)$$

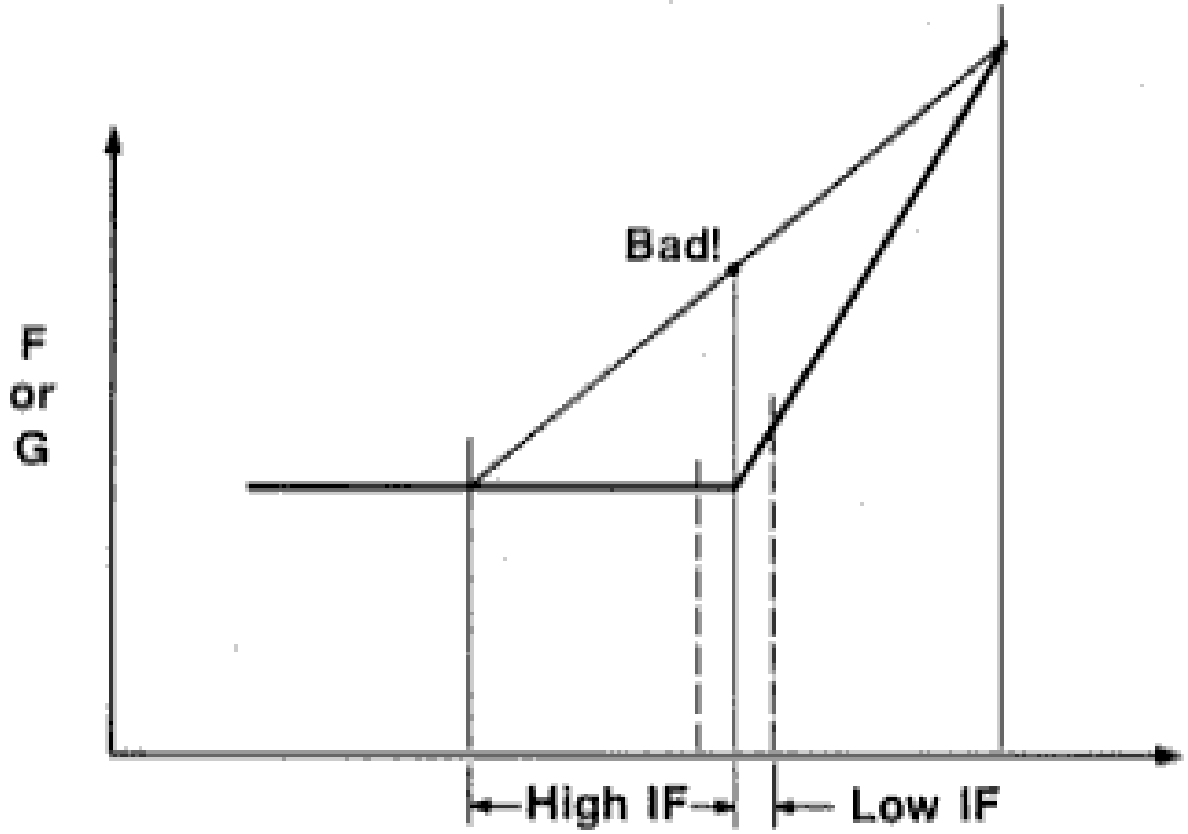
$$\text{or} \quad T_h = \left[10^{\frac{ENR\ (dB)}{10}} + 1 \right] \cdot 290$$

NF Uncertainty - Gain helps!

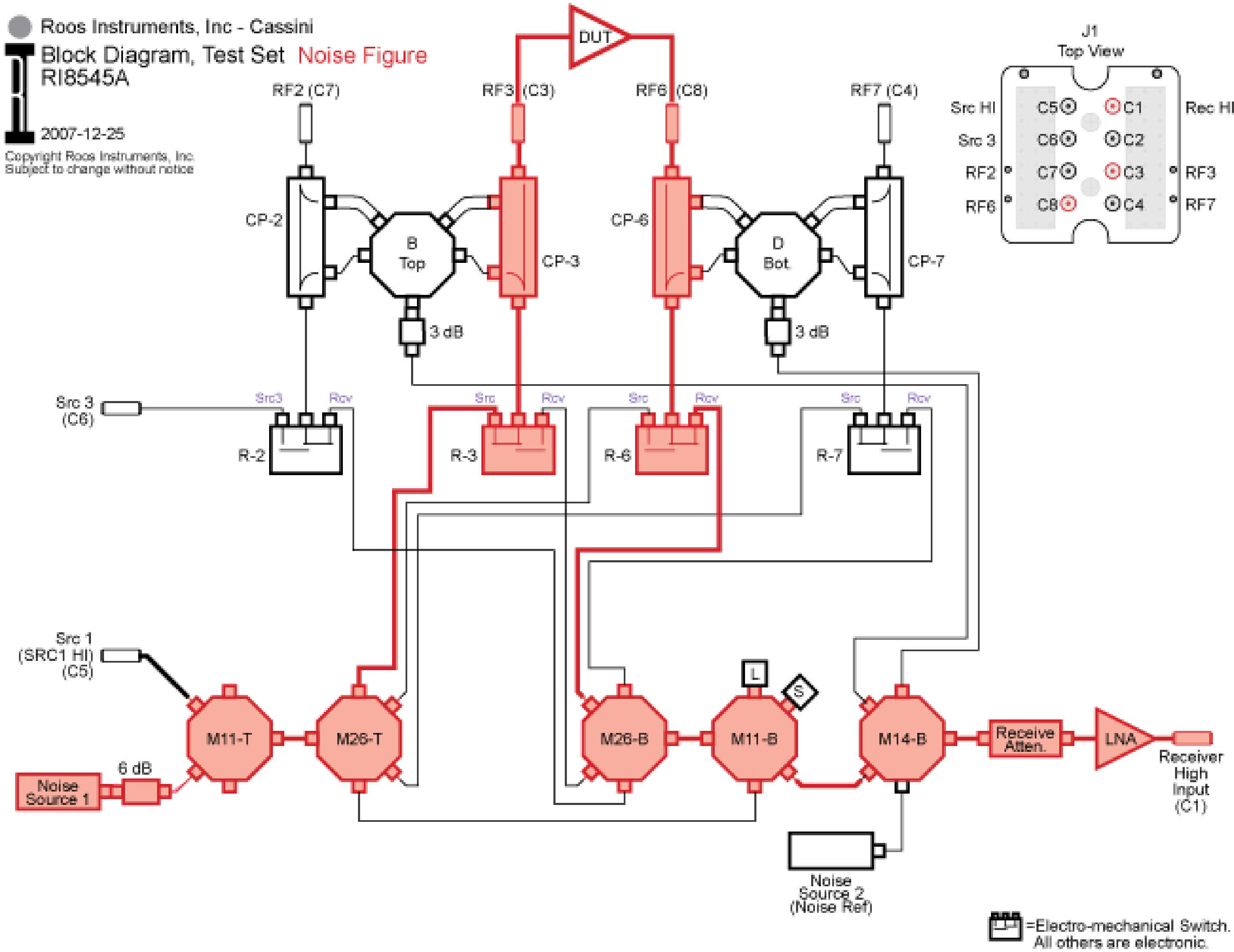
NOISE FIGURE
MEASUREMENT UNCERTAINTY VS
MEASUREMENT SYSTEM NOISE FIGURE



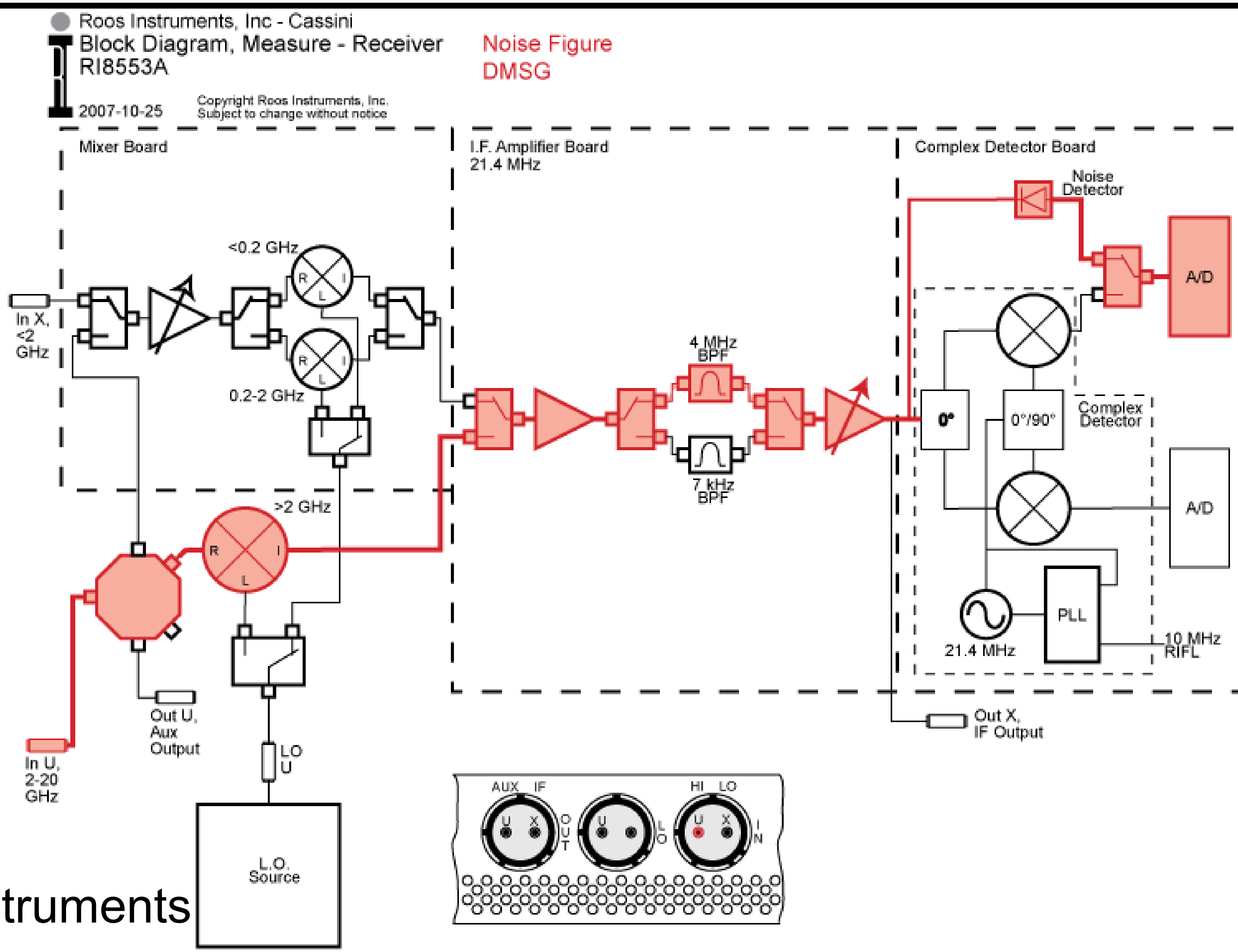
Single or Double Side Band Noise Figure?



4 Port Testset Config for Noise Figure Measurements



Receiver Noise Figure Measurements



Roos Instruments

RF Measurements Outline

- Basic Measurements
- Phase and Magnitude
- Scattering Parameters
- Conversion Gain/Loss Measurements
- RF Power Measurements
- Spectral Purity (Harmonics) Measurements
- Intermod Distortion Measurements
- Digitally Modulated RF Signal Measurements
- Error Vector Magnitude (EVM)
- Noise Figure Measurements

Preview Next Chapter Developing and Running RI Test Plans

- Test Plan Concepts
- Test Plan Development Overview
- Creating a New Test Plan
- Test Plan Structure
- Building a Test
- Saving Device Data
- Viewing Tester Configuration
- Compiling & Running
- Viewing Test Results
- Setting Limits
- Release for Production
- Lab C

Questions?

Any Questions from this Chapter?