Conquering Noise for Accurate RF and Microwave Signal Measurements

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Agilent Technologies

The Noise Presentation

- Review of Basics, Some Advanced & Newer Approaches
- Noise in Signal Measurements-Summary
- Basic Noise Reduction Approaches
- New Technologies
- Examples
- Resources, More Information

Noise is the Enemy
(Almost Always)

Communications, RADAR or other Imaging, Metrology, Science

- Creates Uncertainty in Time, Frequency, Power, Modulation
- Converts Deterministic Values to Statistical Distributions
- Imposes Cost Tradeoffs: Accuracy, Speed, Repeatability, Yield, €/£/¥/$, “False Alarms”
- Financial Impacts: Circuit Cost, Size, Complexity, Development Time, Mfg.

Noise is the Enemy (cont)

- Phase Noise
  - Increases noise floor close-in
  - Creates same problems as broadband noise
  - Imposes similar tradeoffs, costs
- Solutions for Analysis are Similar
  - Optimize measurement technique
  - Choose a higher performance analyzer
  - Use special techniques, processing

Use "Moore's Law" where it does not normally apply

Exceptions: Desirable Noise

- Noise Figure Measurements
- Accurately Generate to Test for Margins, Real World Performance
  - Generate known signal/noise, phase noise
- Broadband/Narrowband Noise as Stimulus Signal, with Different Statistics
- Add to Simulations to Avoid Non-Representative Behavior
- Noise Floor Appearance as a Clue or Hint

Noise Can Frequently be Ignored

But it is Important to be Alert

- Good Signal/Noise Ratio
- Measurement BW Wider than Signal
- Alert for Clues
  - Measurement variance large compared to desired accuracy
  - Measurements change with analyzer settings
  - Decreasing SNR
  - Comparing signals with different statistics

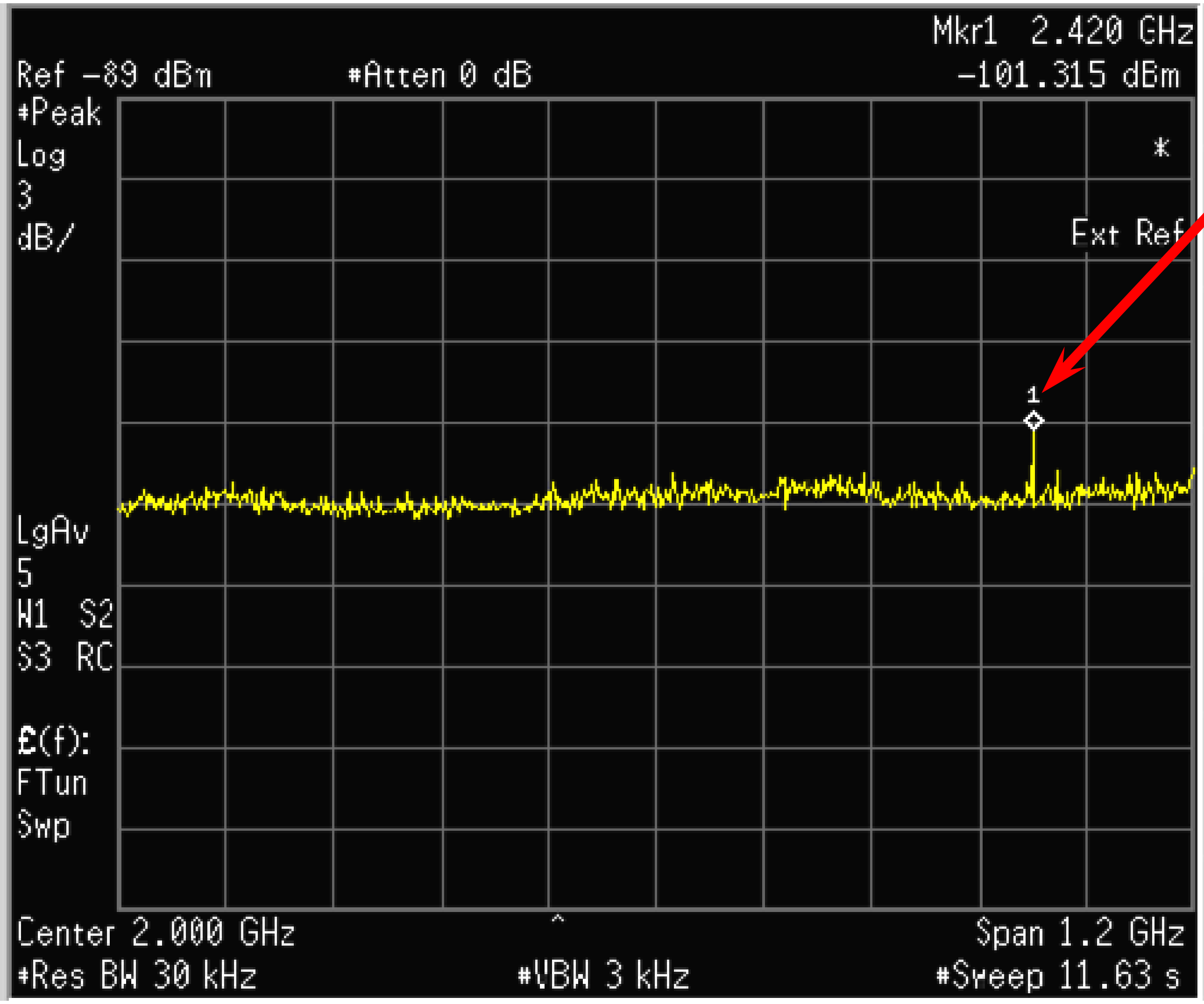
Optimize Noise vs. Other Measurement Priorities

- Attenuation = 0 dB Optimal for Sensitivity
- Attenuation = 10+ dB for Optimal Accuracy
- Attenuation = 4-6 dB a Compromise
- Problems with Impedance Match
- Problems with Distortion, Compression
- Chance of Analyzer Input Damage

Trade Away Extra Noise Performance for other Benefits

- Better Overload Performance
- Lower Distortion Measurements
- Faster Measurements

Bad Measurements are Easy to Make



Spur appears 3 dB above noise level

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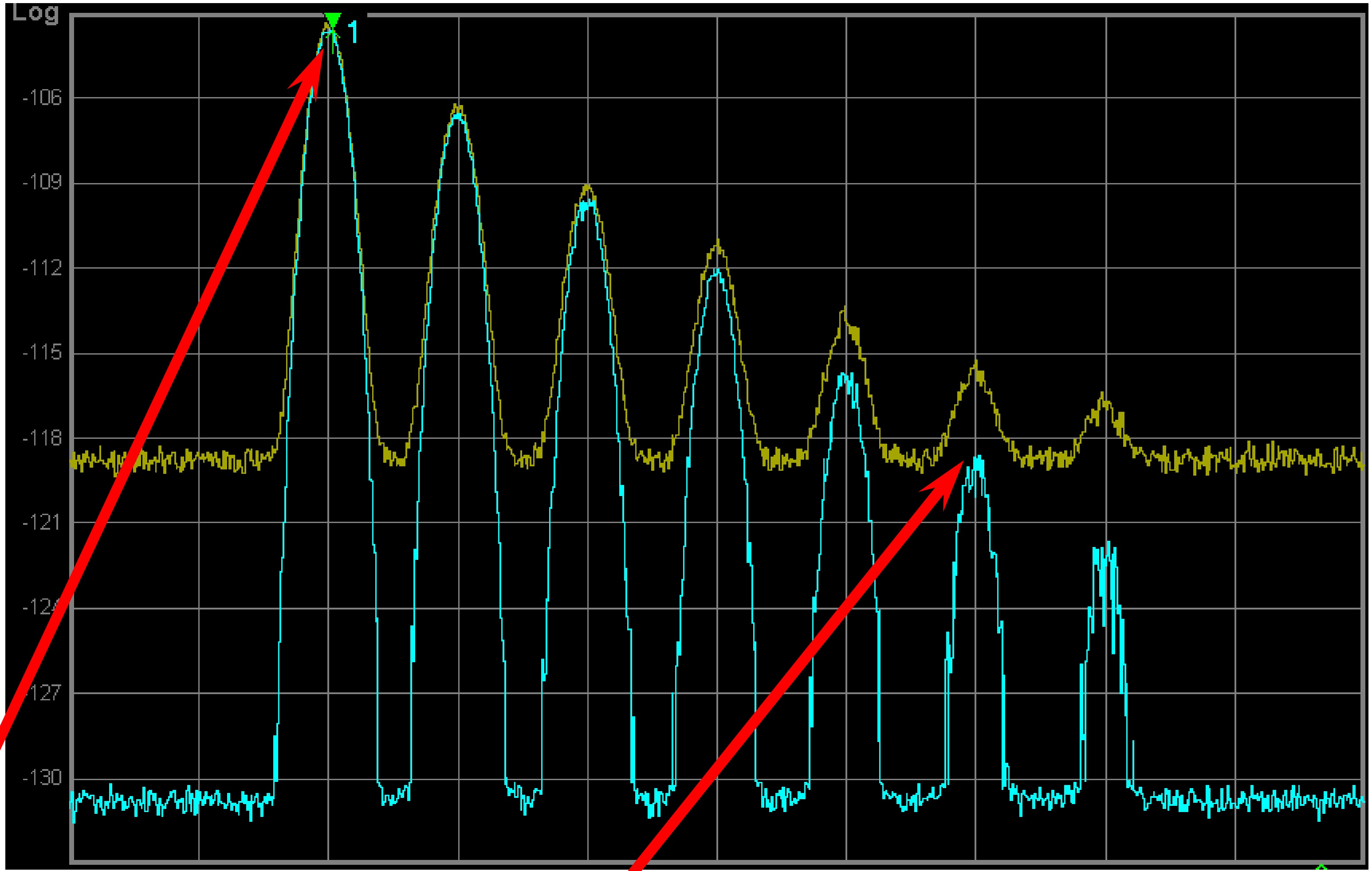
Error in Noise Level Measurements, Measured Near Analyzer Noise floor

Actual Noise Ratio	Measurement Error
0 dB	3.01 dB
1 dB	2.54 dB
3 dB	1.76 dB
5 dB	1.19 dB
10 dB	0.41 dB
15 dB	0.14 dB
20 dB	0.04 dB

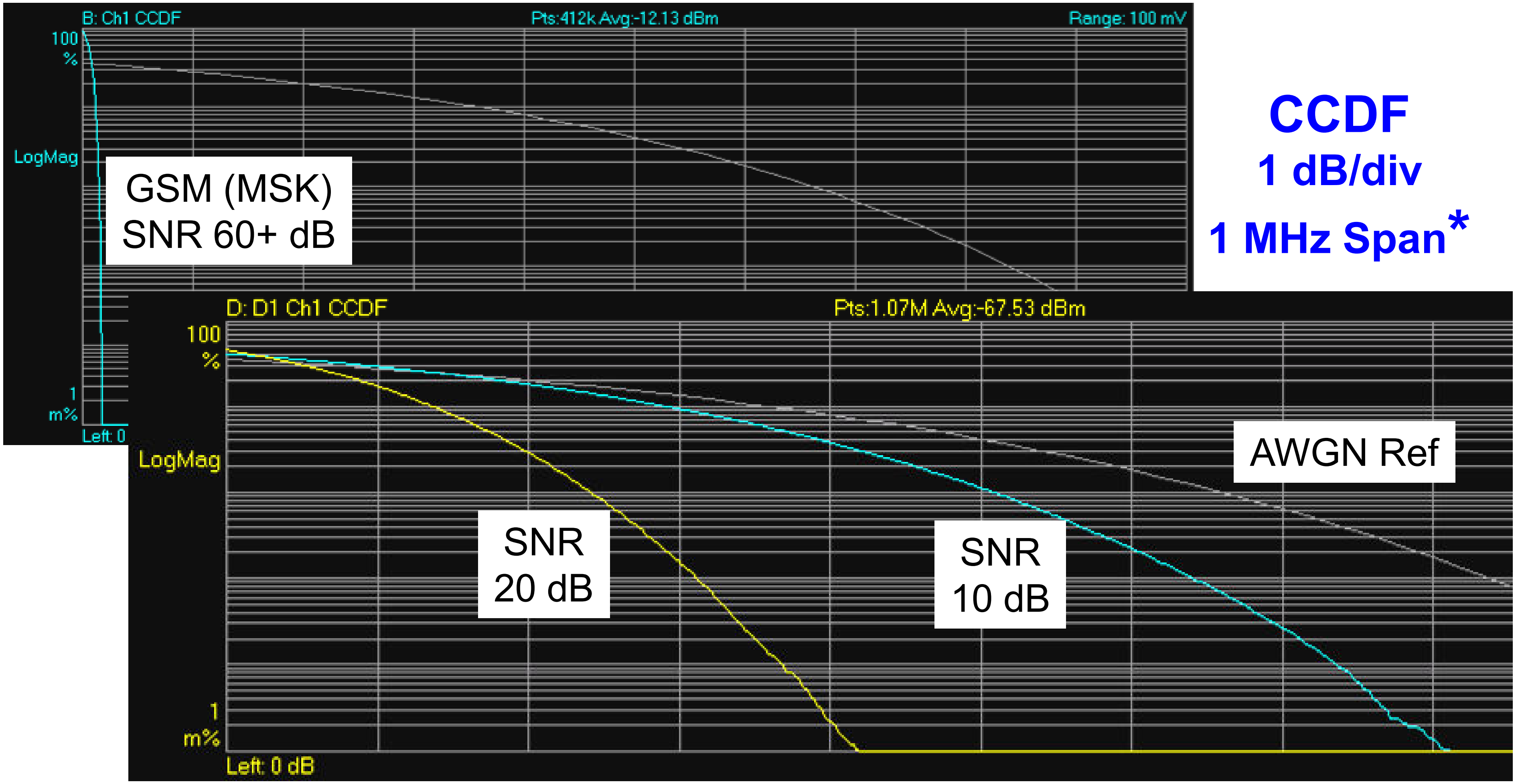
Note that error is always positive

Multiple Tones Example



"No" error for best S/N, 3 dB for signal at analyzer DANL

Noise Converts ~Deterministic Value to Statistical Distribution



CCDF

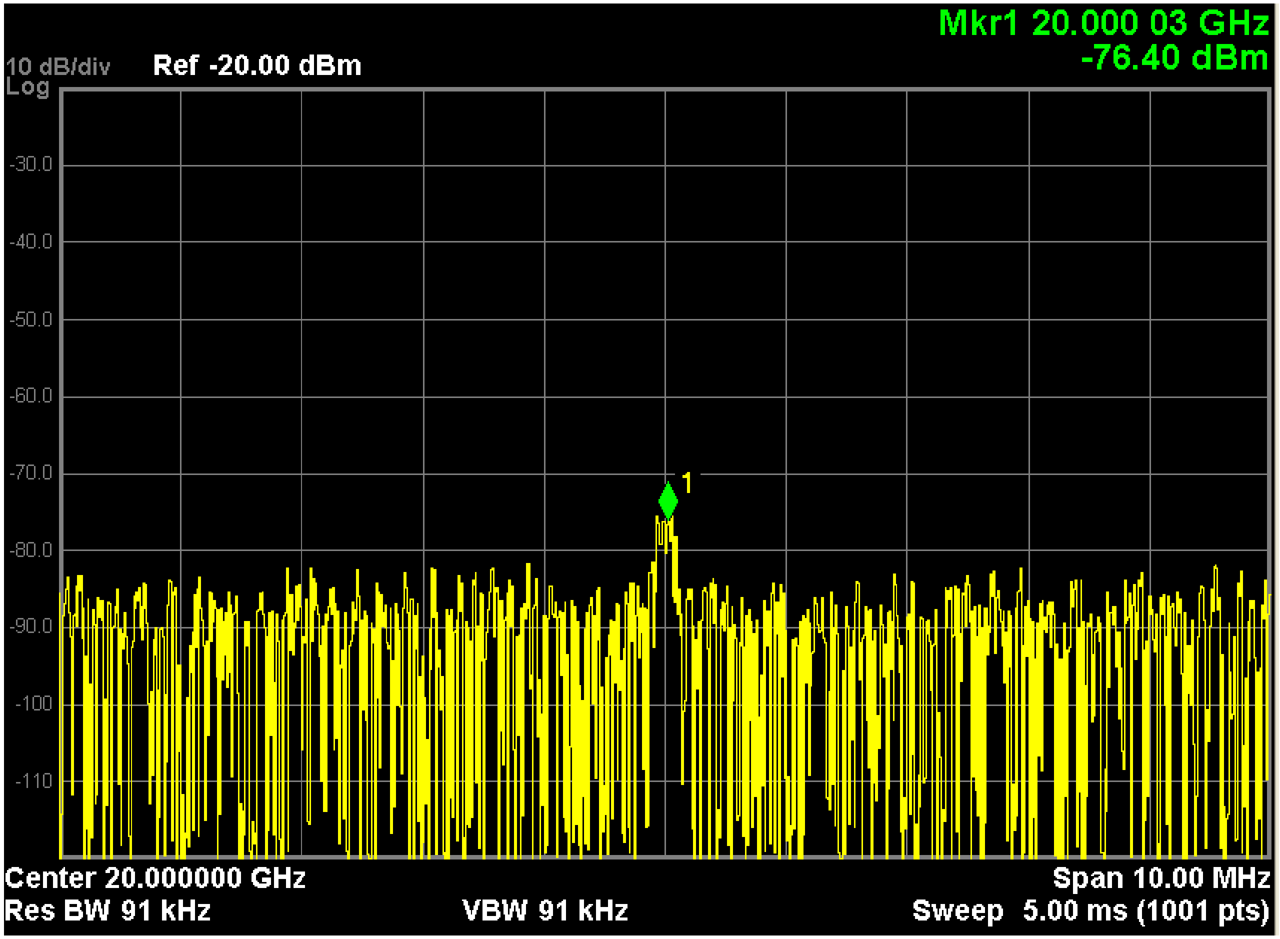
1 dB/div

1 MHz Span*

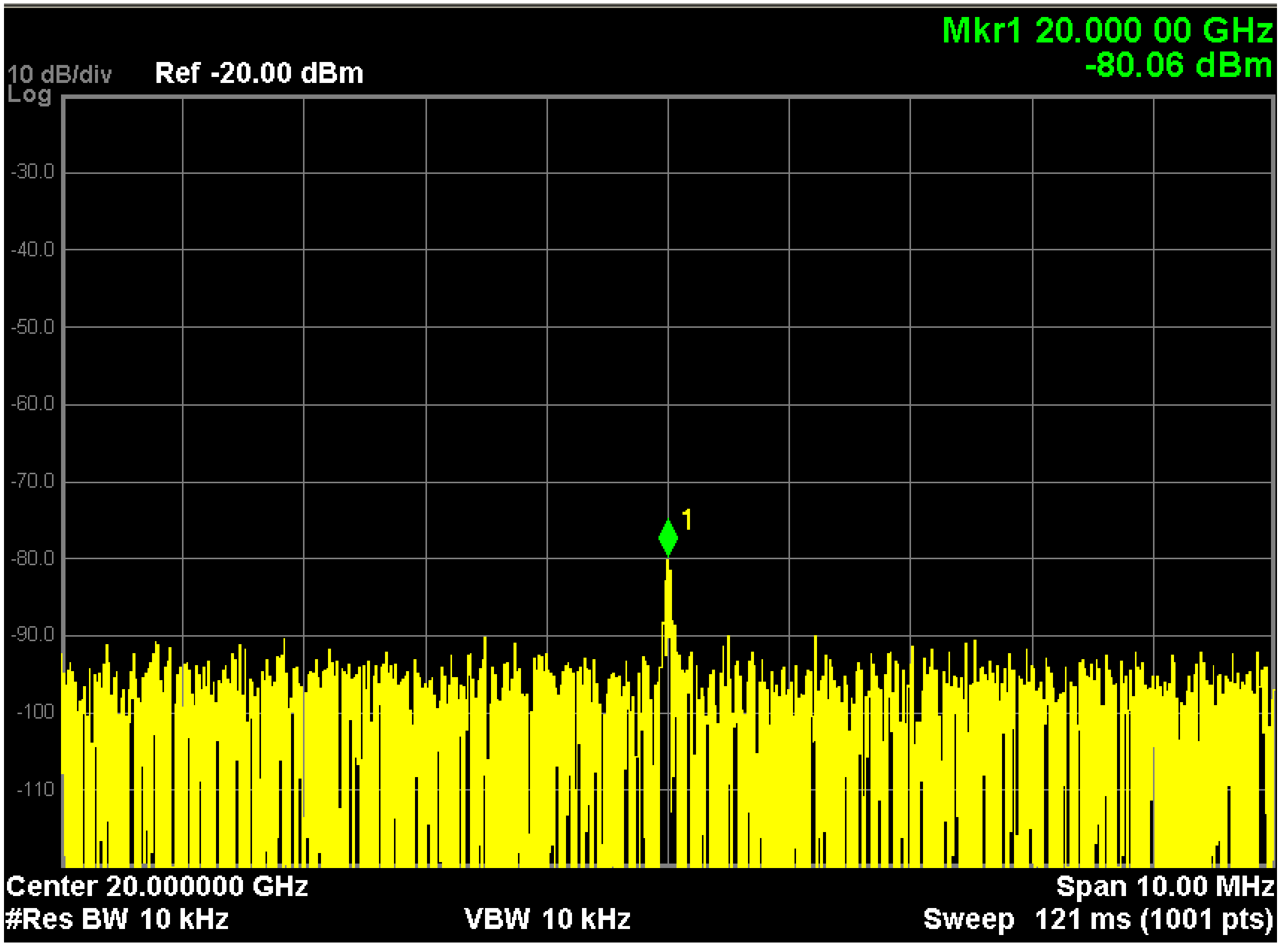
* CCDF varies significantly with span at low SNRs

Clues to Two Meas Problems

Signal Close to Noise, Wider than RBW

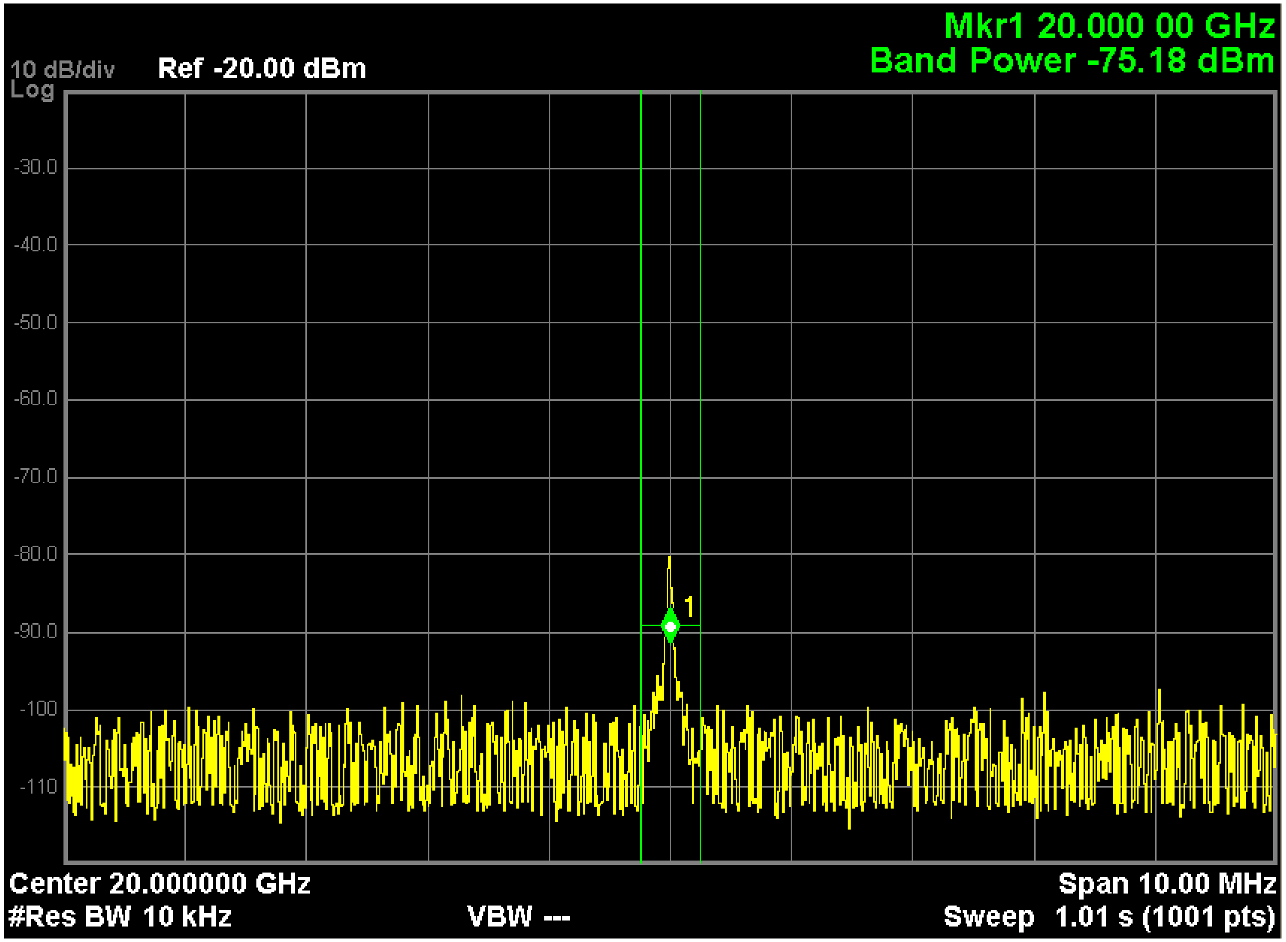


Narrower RBW Improves S/N



- Residual FM, signal is wider than RBW filter
- Amplitude measured low in error

Band Power Marker, Averaging



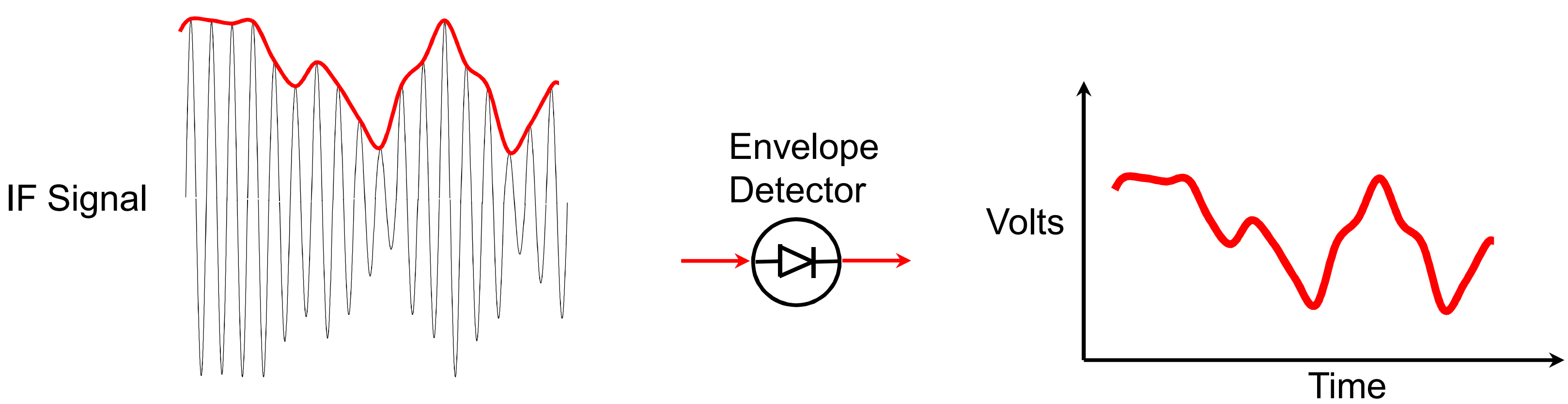
- Band power marker compensates for signal spread
- Longer sweep, average detector reduce variance

Detector Types, Averaging Scales

Understanding Enough

- Processing, Data Reduction Always Done
- Signal Characteristics Affect Results
- Basic Settings (RBW, Span, Sweep Time) Affect Results, Even With Same Detector
- Know Enough To:
  – Use your knowledge of your signal
  – Understand results, know what you are getting
  – Make good measurements
  – Identify signal problems, measurement errors

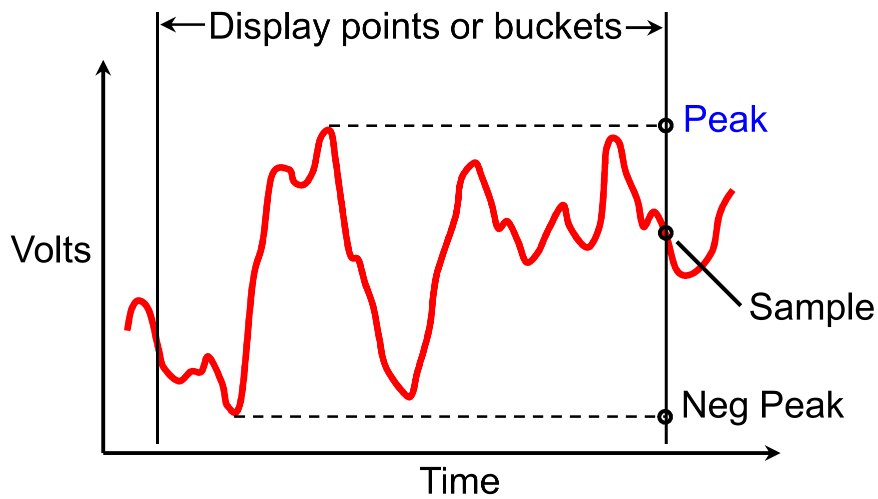
The IF Envelope Detector



- Input is the IF Signal (RBW), Output is Baseband
- Output Voltage is Proportional to Input Envelope
- Response is Different for CW Signals and Noise

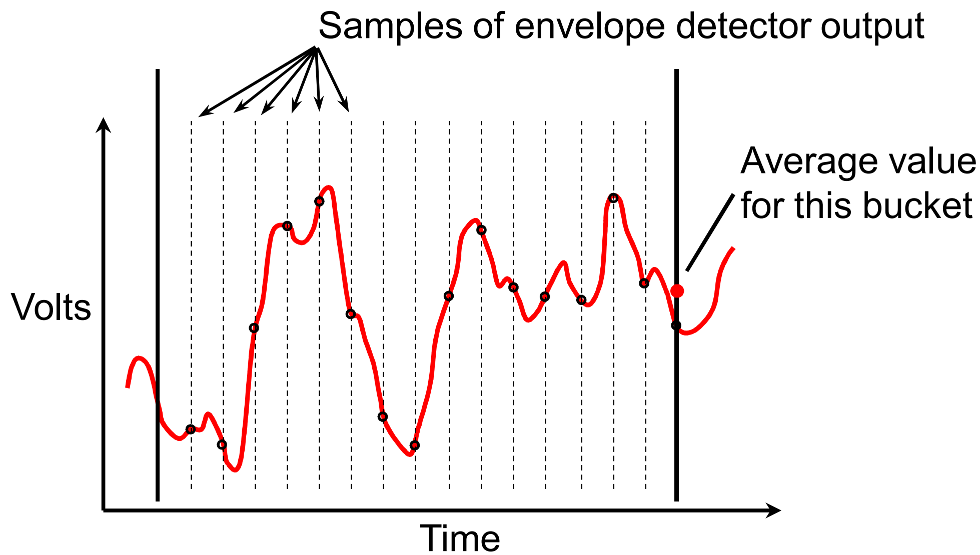
Display Detectors

Peak, Negative Peak, Sample



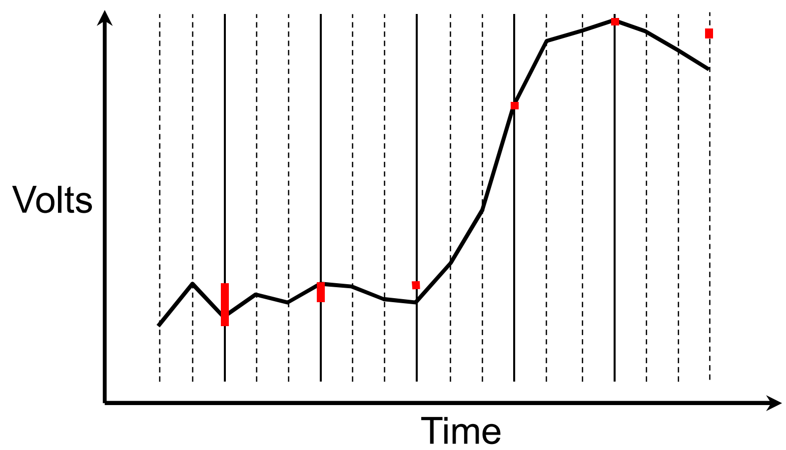
- Input is the IF Envelope Detector Output (log or linear scaled)
- Peak and Neg Peak Detectors Bias the Output Value, Perform Some Data Reduction

Averaging Detectors



- Each Output Represents 2 or More IF Envelope Values
- Reduces Variance Faster Than Single-Value Detectors; Reduce Variance Further by Increasing Sweep Time
- Good Choice for Channel Power or ACP Measurements

Signal-and-Noise Detectors



- Better Represent Combination of Signals and Noise
- Show Distribution of Noise and Noise-Like Signals
- Show Discrete Signals as a Single Value
- More Intuitive, but not Required for Accurate Measurements

Biased & Unbiased Detectors

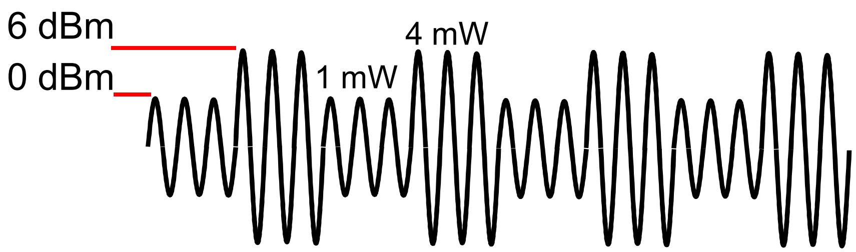
- Sample Detector-Unbiased
  - Data discarded, not good at reducing variance
- Average Detector-Unbiased
  - Efficient for reducing variance
- Peak, Negative Peak Detectors-Biased
  - Bias is desirable, special-purpose use
- "Normal" Detector
  - Bias depending on signals, implementation
  - Designed for combined signals and noise

Effects of Slower Sweep Speed

- Normal Detector: Wider band of results
- Average Detector: Narrower band of results
  - Variance decreases with square root of number of independent samples in average
- Sample Detector: Results band unchanged
- Peak Detector: Band is narrower, higher
- Neg Peak Detector: Band is narrower, lower

Averaging Error Example

Averaging Power

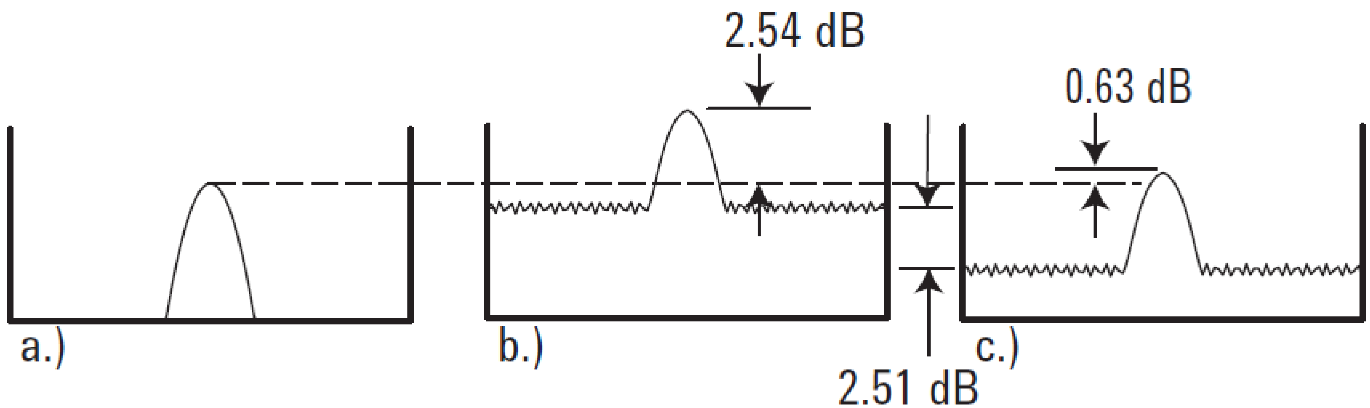


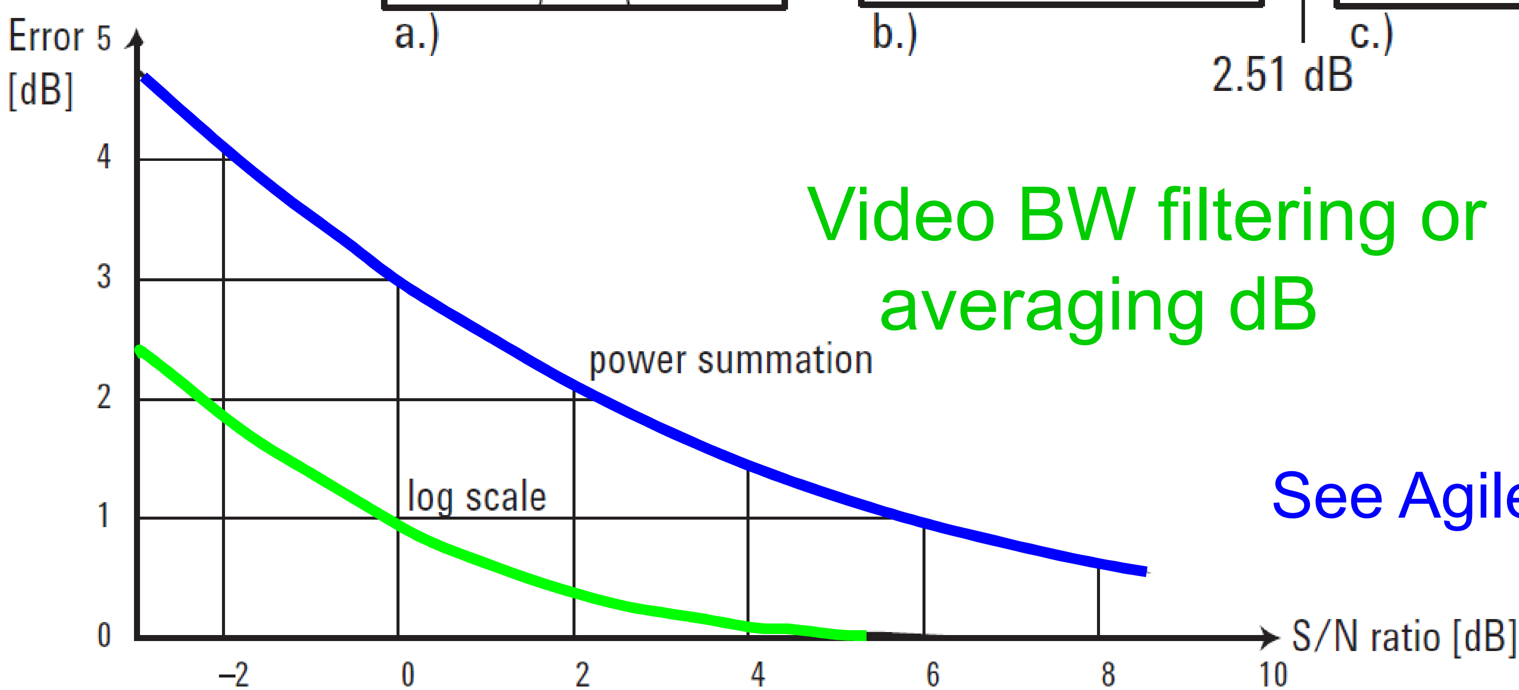
Average of the log of the power = 3 dBm
(0 dBm + 6 dBm)/2
Log of the signal's average power = 3.98 dBr
(1 mW + 4 mW)/2 = 2.5 mW

- Average of the Log is Not Equal to a Log of the Average
- Narrow VBW or Trace Averaging Performs an Average of the Log, an Error in Measuring Time-Varying Signals
- Instead, Average the Power or Report the RMS Value of the Voltage of the Signal

Log Scale Bias for CW Meas.

Log scale better for single CW signal near noise

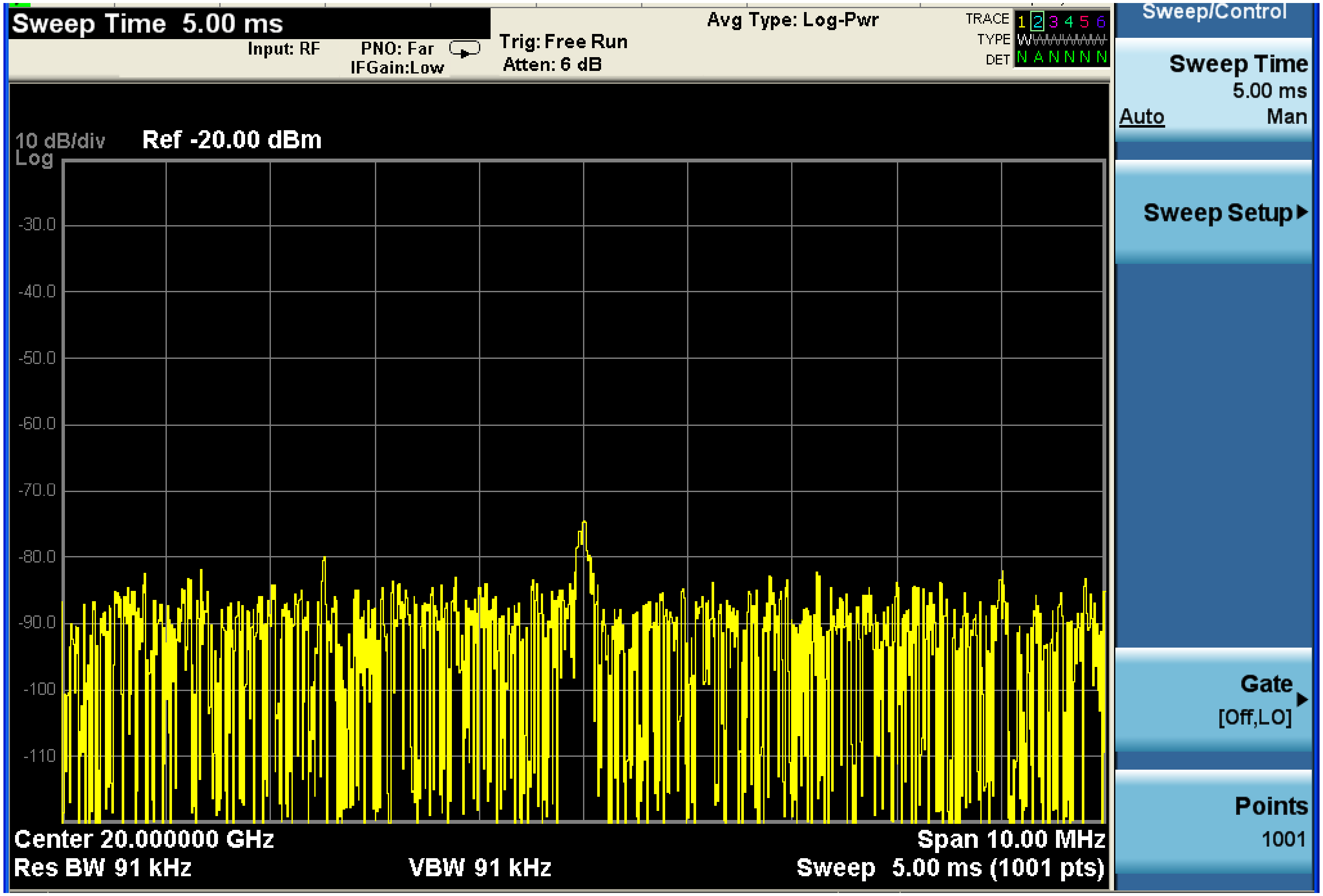




Video BW filtering or averaging dB

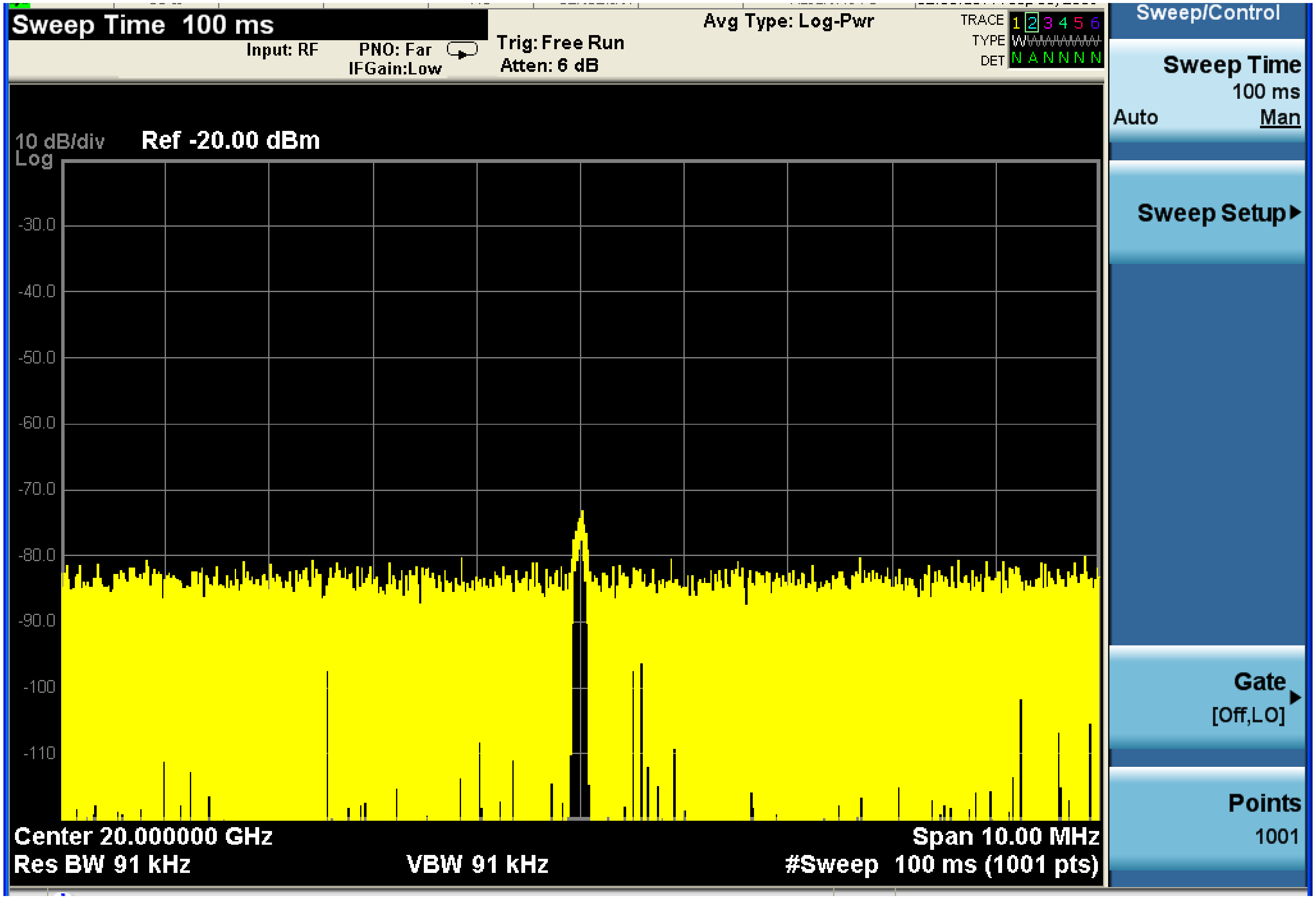
See Agilent AN1303

Detectors/Averaging Example



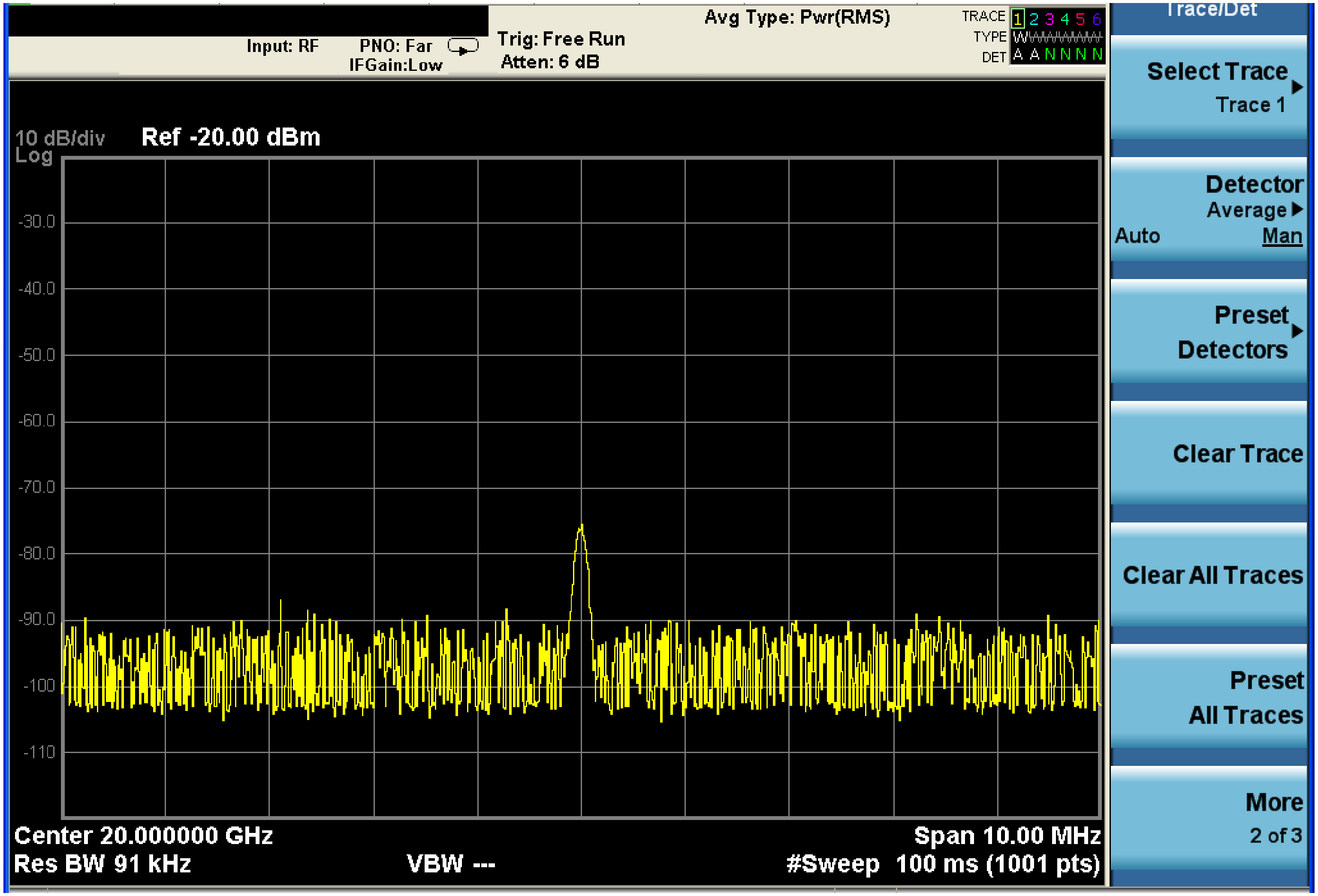
- Default: normal detector, log-power averaging

Detectors/Averaging Example



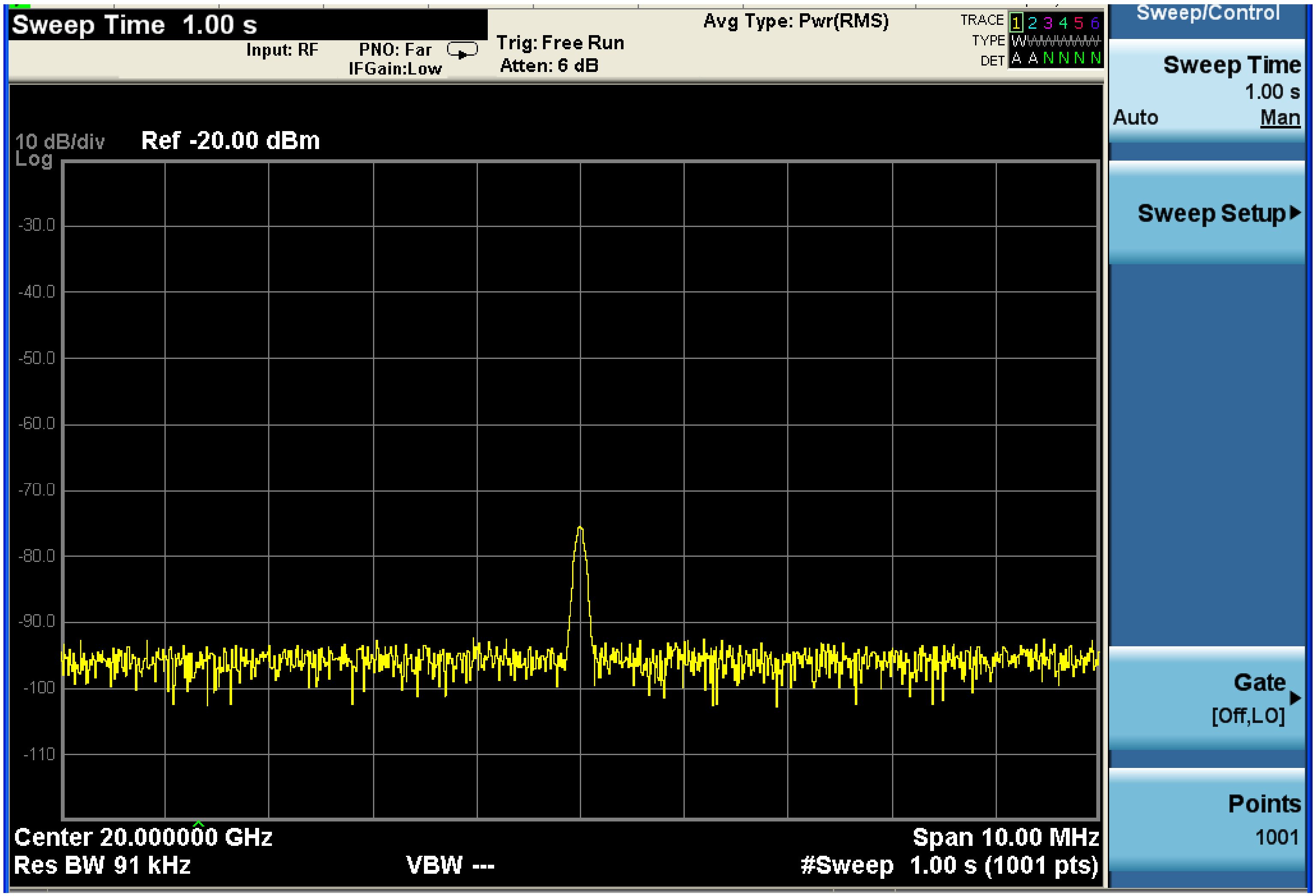
- Normal detector, log-power avg. longer sweep

Detectors/Averaging Example



- Average detector, RMS power

Detectors/Averaging Example



- Average detector, RMS power, longer sweep

Reducing Measurement Noise

- Filtering
  - RBW (not VBW or averaging)
  - Preselection
  - External
- Time or Synchronous Averaging
- Subtraction
- Best Practices

Costs of Sensitivity

- Time
  - Sweep time (narrower RBW, VBW)
  - Averaging
- Money
  - Better instruments
  - Better cables, connectors
  - Preamplifiers
  - External filtering

Traditional Approaches

- Narrower RBW
  - Reduces noise floor (ENBW)
  - May reduce measurement variance
- Video Filtering, Trace Averaging
  - Does not reduce noise floor
  - Reduces measurement variance
  - Average of log of meas, may distort results
  - Effect varies with signal statistics
- Detector Choices
  - Select for accuracy, fast reduction of variance

Traditional Approaches (cont)

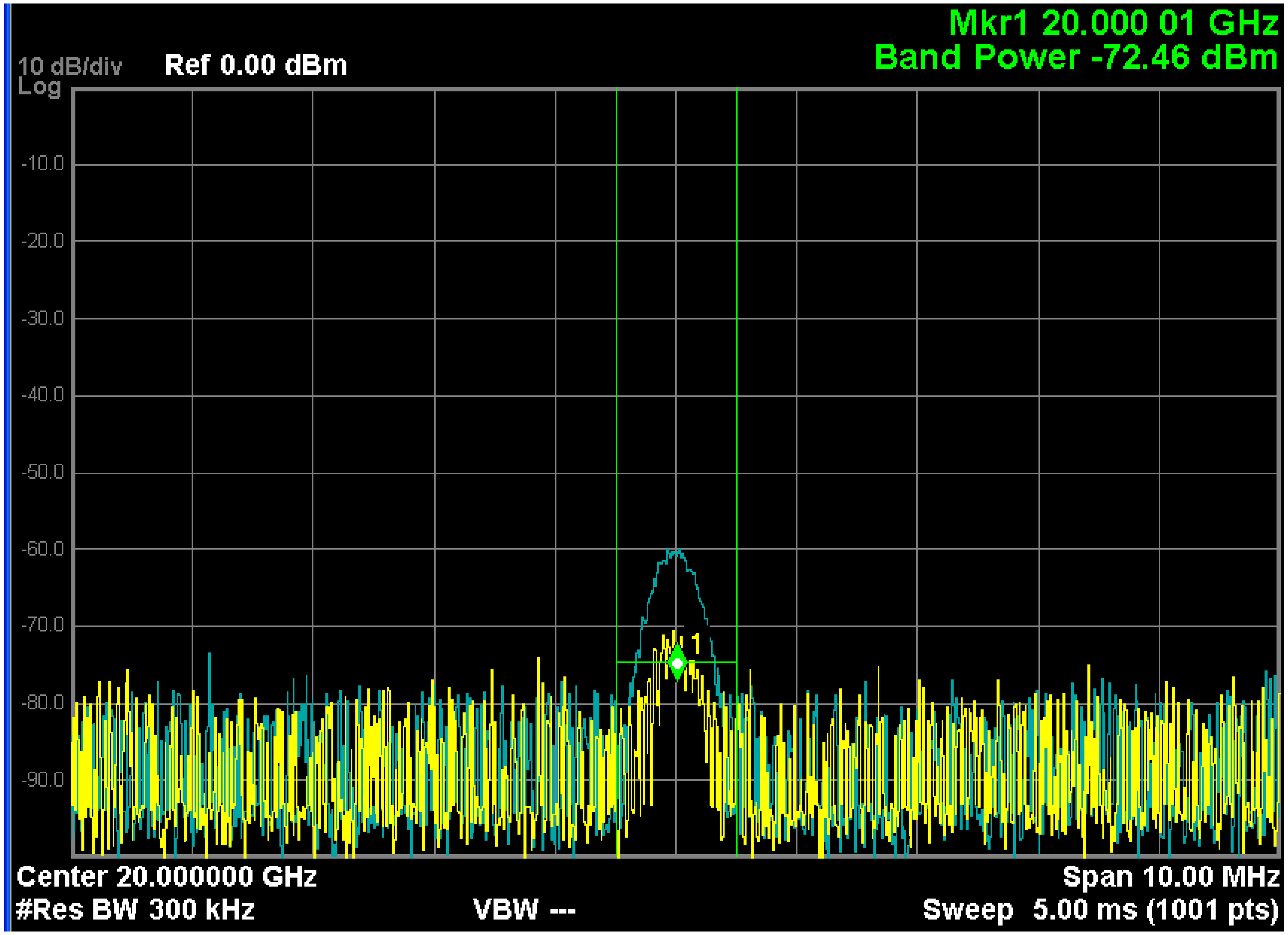
- Improve Measurement Noise Figure
  - Better connection to DUT
  - Preamplification - internal
  - Preamplification-external
  - Preselector (internal YIG-tuned filter)
  - External filtering
- Intelligent Operator Filtering
  - "If it looks good it is good" (?)
- Define Results, Objectives Better
  - Account correctly for noise effects

Cables, Connectors, Adapters

Importance Increases with Frequency

- Shortest, Best Connection to Circuit
  - Shorter cable, move analyzer or DUT
  - Choose best cable
  - Minimize adapters
  - Cable/connector hygiene
  - Periodically check cable assemblies
    - Visual inspection is not enough
- 1 dB Gained/Lost = 1 dB Noise Figure

Example: Different Cables



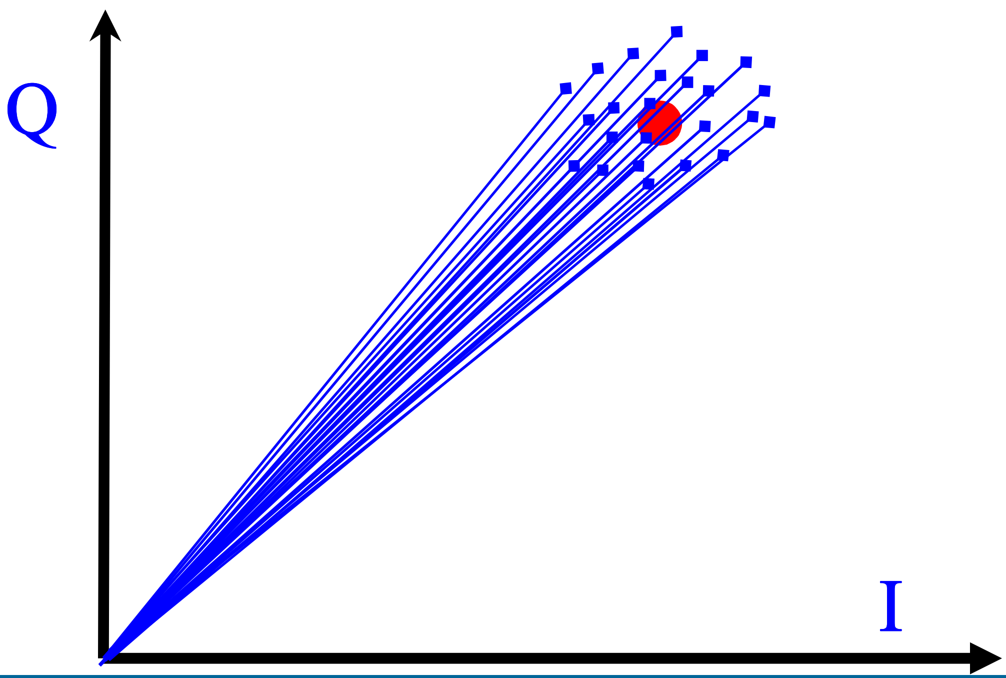
- 0.9 m and 1.6 m cables
- Clue in signal/noise ratios

Preamplifiers

- NF of Preamp must be Less than NF of Analyzer
- Benefits
  - Improved sensitivity
  - May be built-in, internally switchable
  - Gain may be included in analyzer calibration
- Drawbacks
  - Best when input is small signals only
  - May limit TOI, increase distortion
  - May have limited bandwidth
  - Calibration less convenient if external

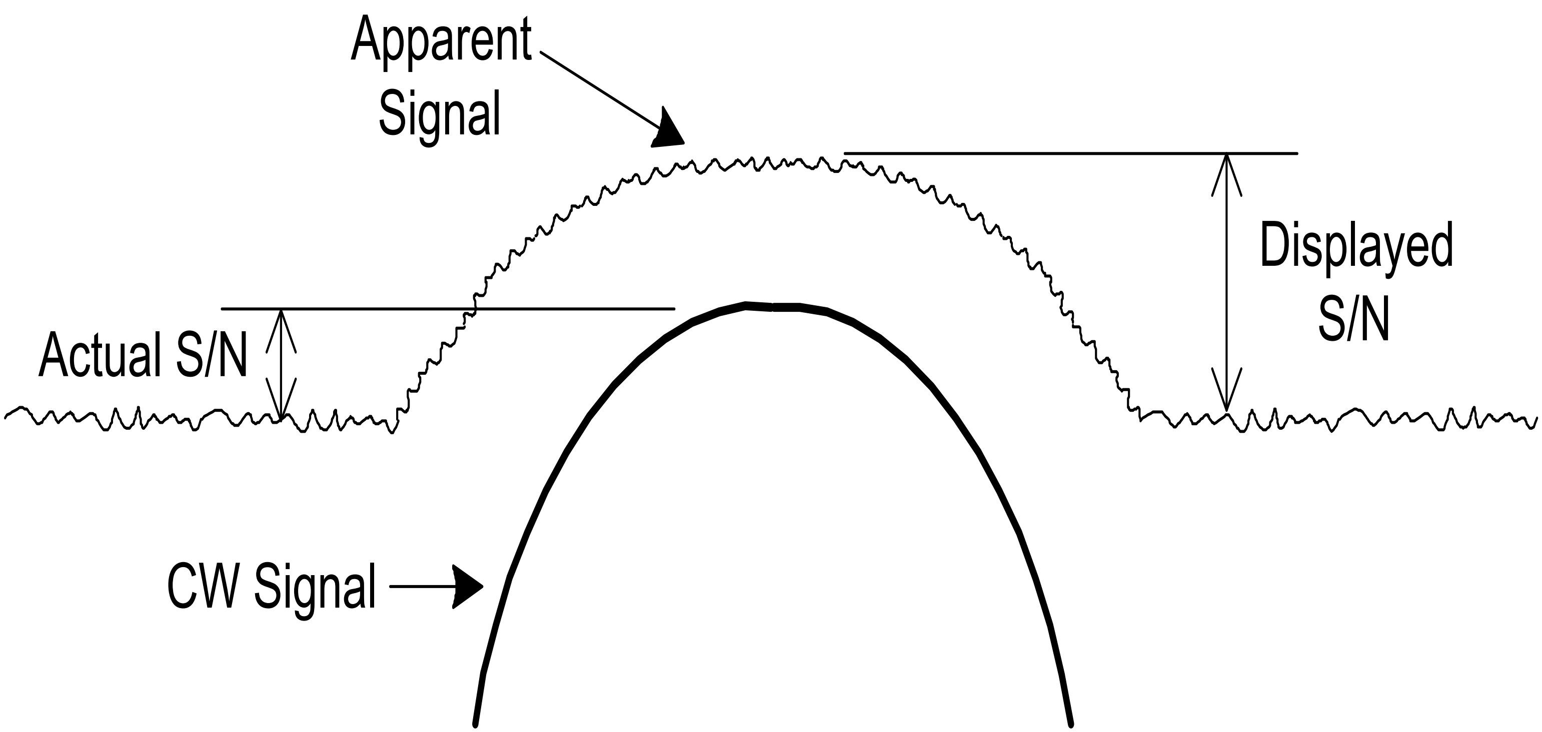
Less-Common Approaches

- Measure and Subtract the Noise Power
- Vector Average to Remove Noise
  - Coherent (time-triggered) averaging
  - Requires repeated signal, triggering



Vector average of repeated, synchronized measurements converges to the noiseless value

CW Signal Measured Near Analyzer Noise Floor



Amplitude & Frequency Axes Expanded

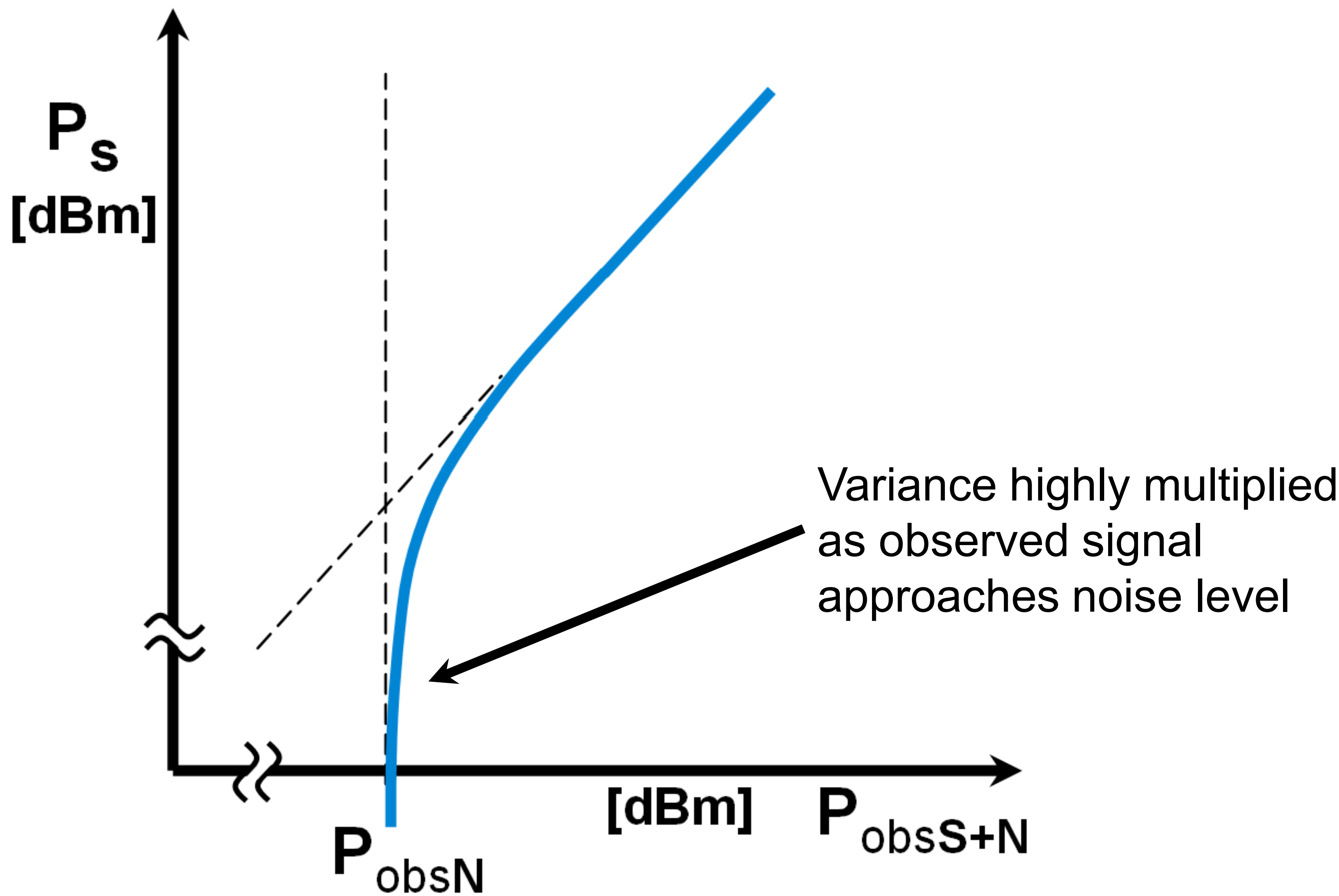
Noise Floor Subtraction

$$P_{obsS+N} = P_{obsN} + P_S$$

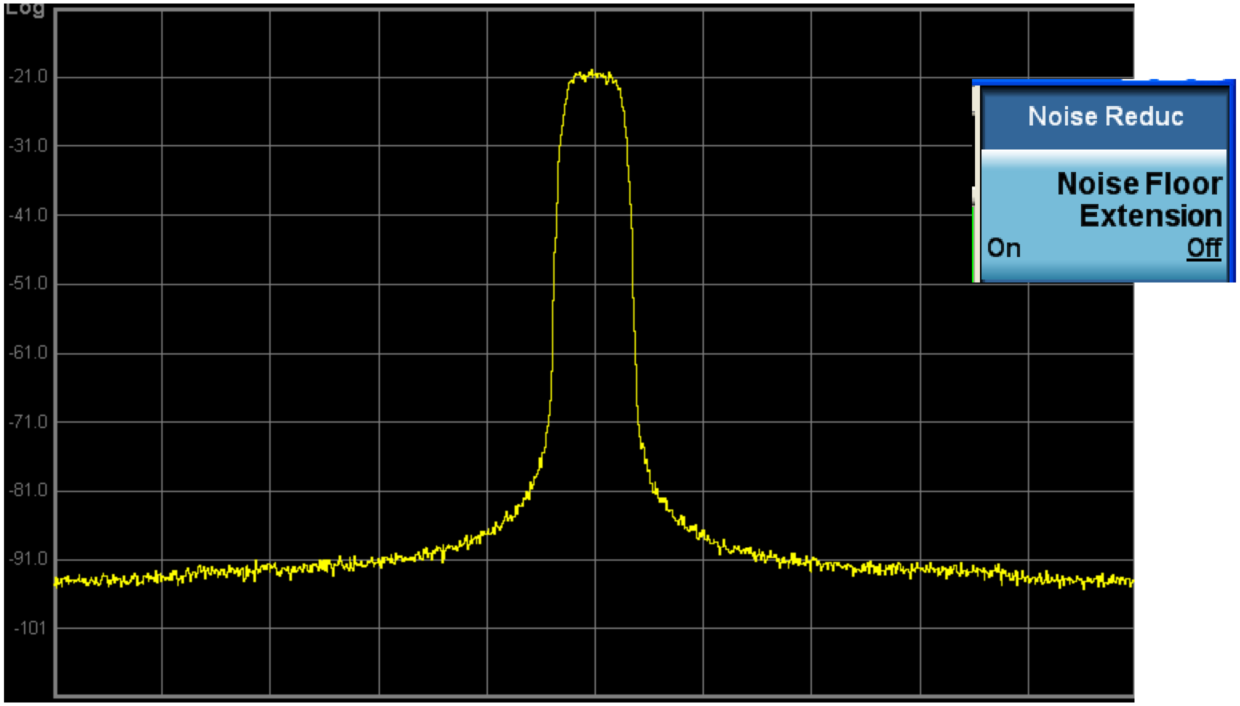
$$P_S = P_{obsS+N} - P_{obsN}$$

- Analyzer noise adds incoherently to any signal to be measured
- Power calculations are performed on a linear power scale (watts, not dBm) and results typically are shown in dBm

Plotting P_S on a dB Scale



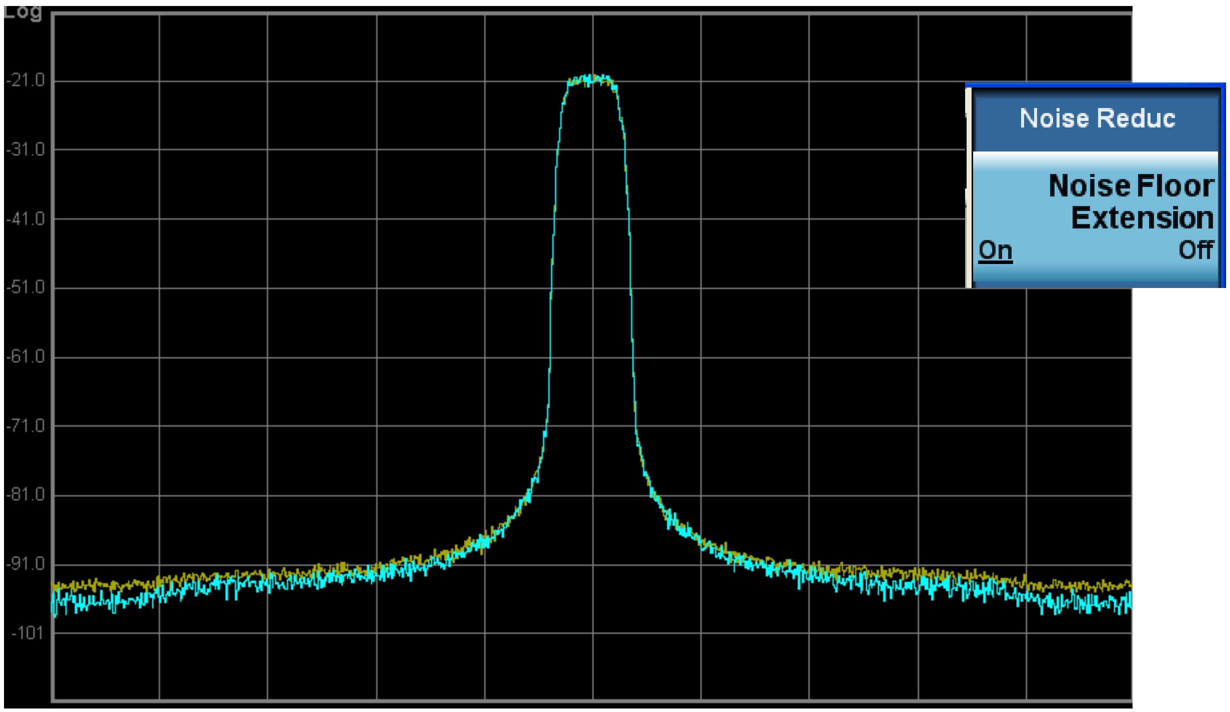
Noise-Like Signal and Noise



- 1 MSymbol/sec QPSK, 1.9 GHz
- Signal accurately measured, but noise biased higher by analyzer noise power (no NFE)
- Average detector, slower sweep to measure signal & noise, reduce variance

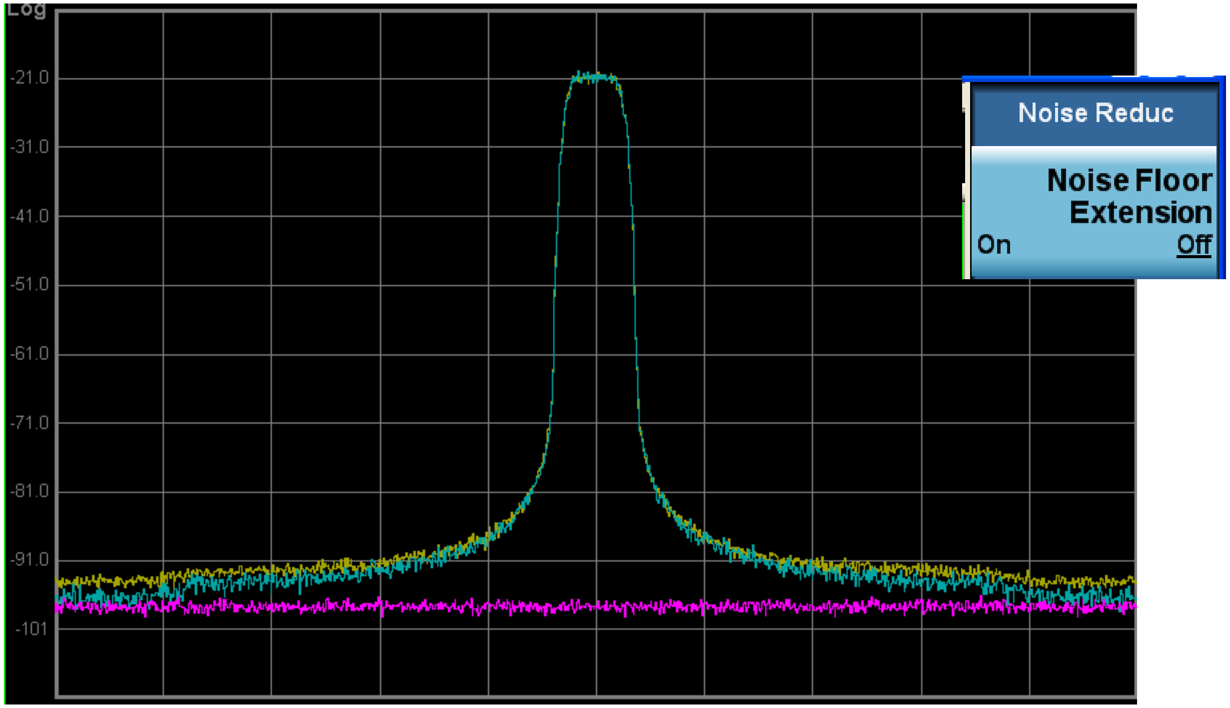
Result from Noise Subtraction

Implemented in the Agilent PXA Signal Analyzer



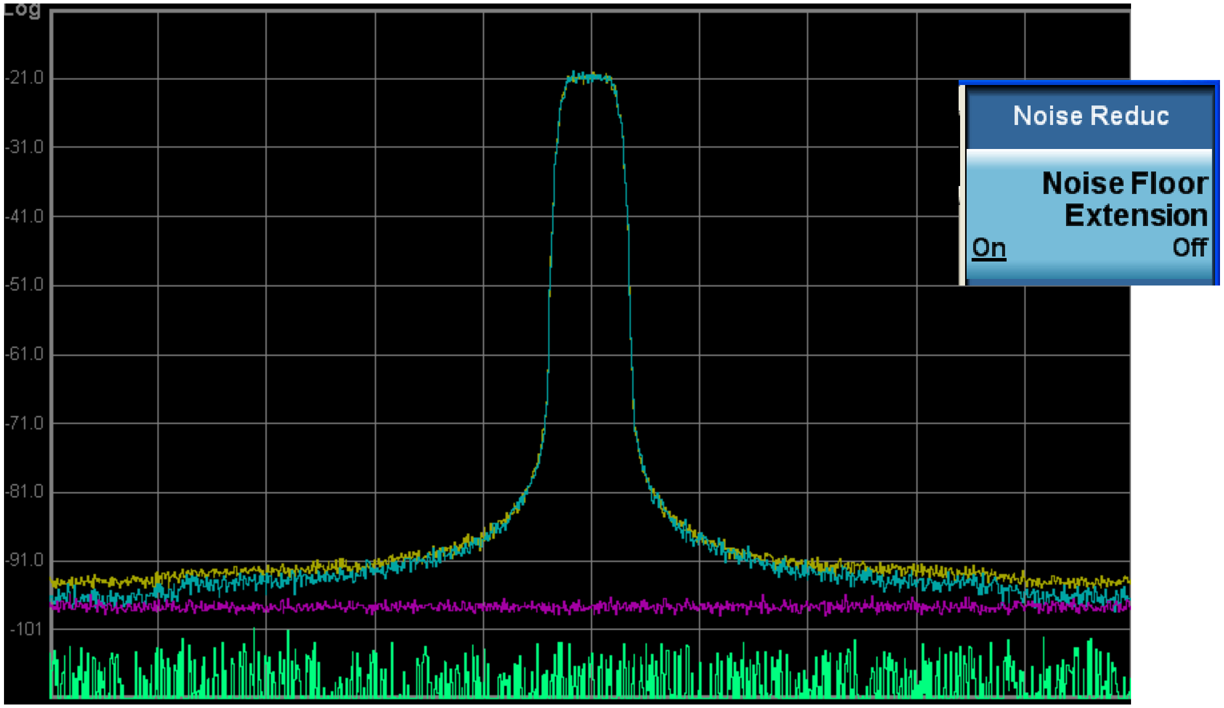
- Blue trace shows more accurate measurement due to removal of analyzer noise power
- Note increased variance of result

Analyzer Noise Floor without NFE



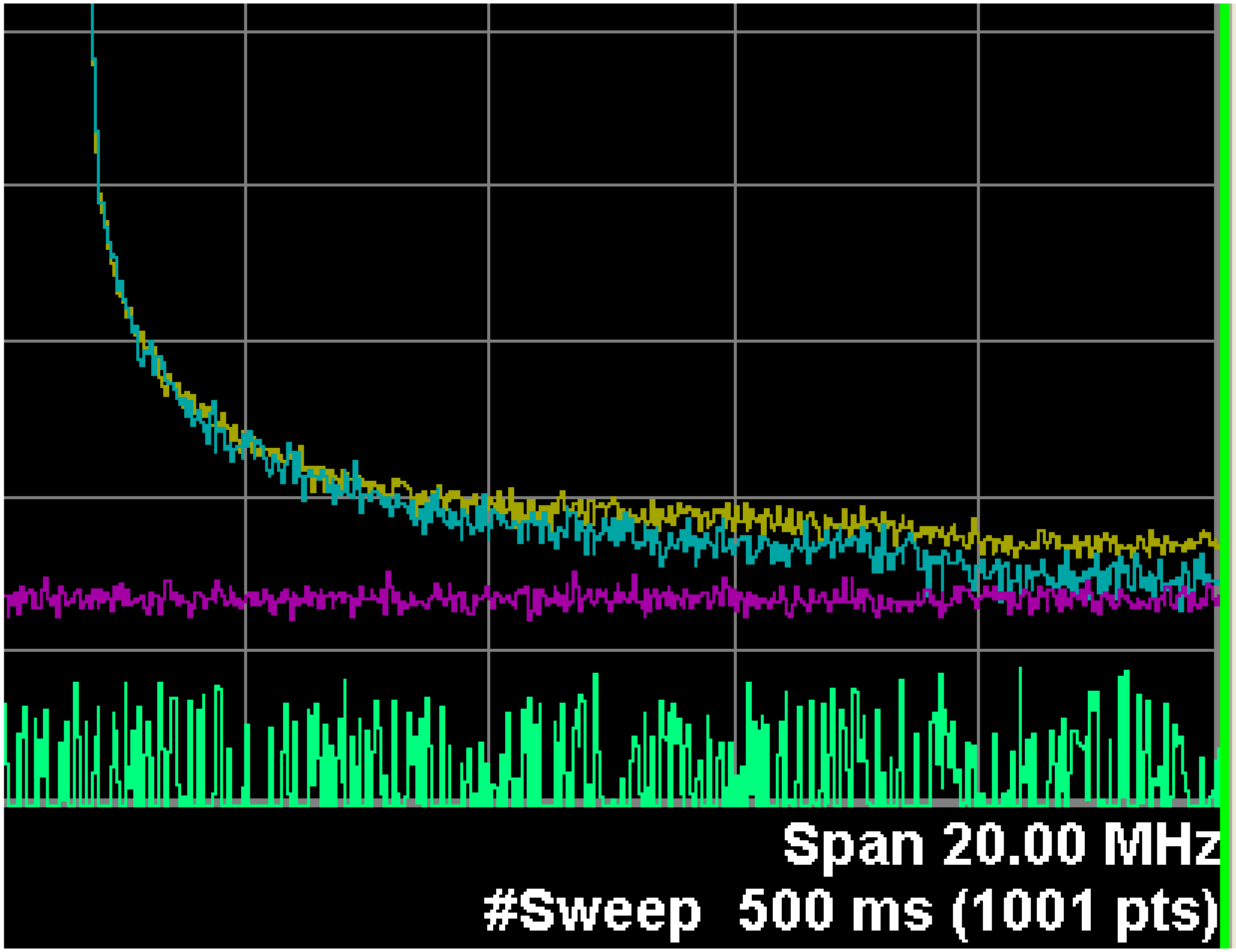
- Source switched off, pink trace shows analyzer noise level, no NFE
- Other measurement conditions unchanged
- PXA DANL (pink) adds to source power (blue) for first meas. result (yellow)
- Note that noise level variance (pink trace) is smaller without NFE

Analyzer Noise Floor with NFE



- Source still off, green trace shows analyzer noise level with NFE
- Other measurement conditions unchanged
- Note high variance result from subtraction of small, noisy numbers
- Analyzer DANL now far enough below source for minimal (0.2 - 0.4 dB) error

A Closer Look



- Pink trace adds to blue trace; result is yellow trace (NFE not used)
- Green trace is included in blue trace but resulting error very small

Noise Power Subtraction vs. Noise Cancellation or Removal

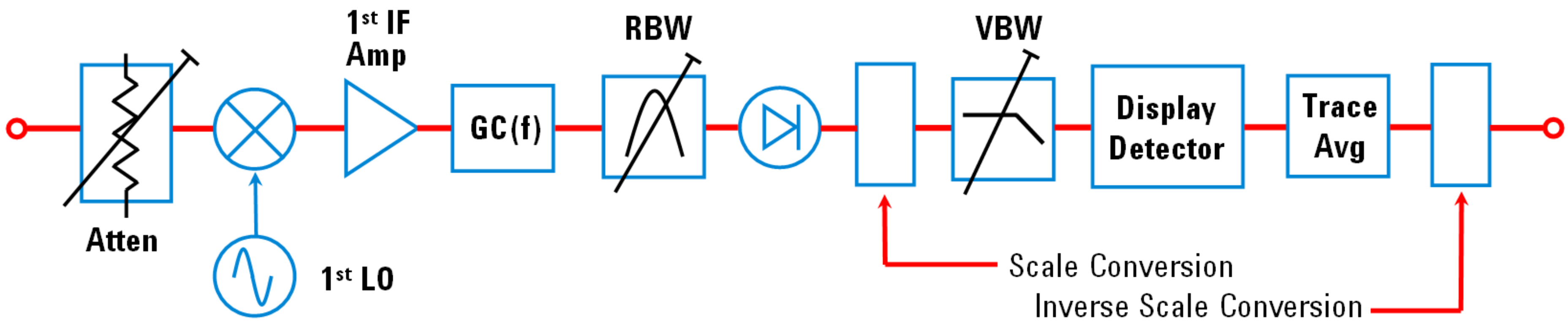
- Power Subtraction Useful for Spectrum & Power (channel power, ACPR) Meas.
- Noise Power from Phase Noise can be Removed
- Improving Demodulation (EVM, RCE, MER, all vector errors) Requires Lowering Inherent Noise or Vector Subtraction

Conditions and Requirements for Effective Noise Subtraction

- Signal and Analyzer Noise Uncorrelated
- RMS Detection (calculations simpler, more accurate)
- Extensive Averaging (to reduce signal variance)
- Averaging on Power Scale (even if results displayed on a log scale)
- Need
  - Method to remove input signal & measure noise

    -or-
  - Prior knowledge of analyzer noise floor under all measurement conditions

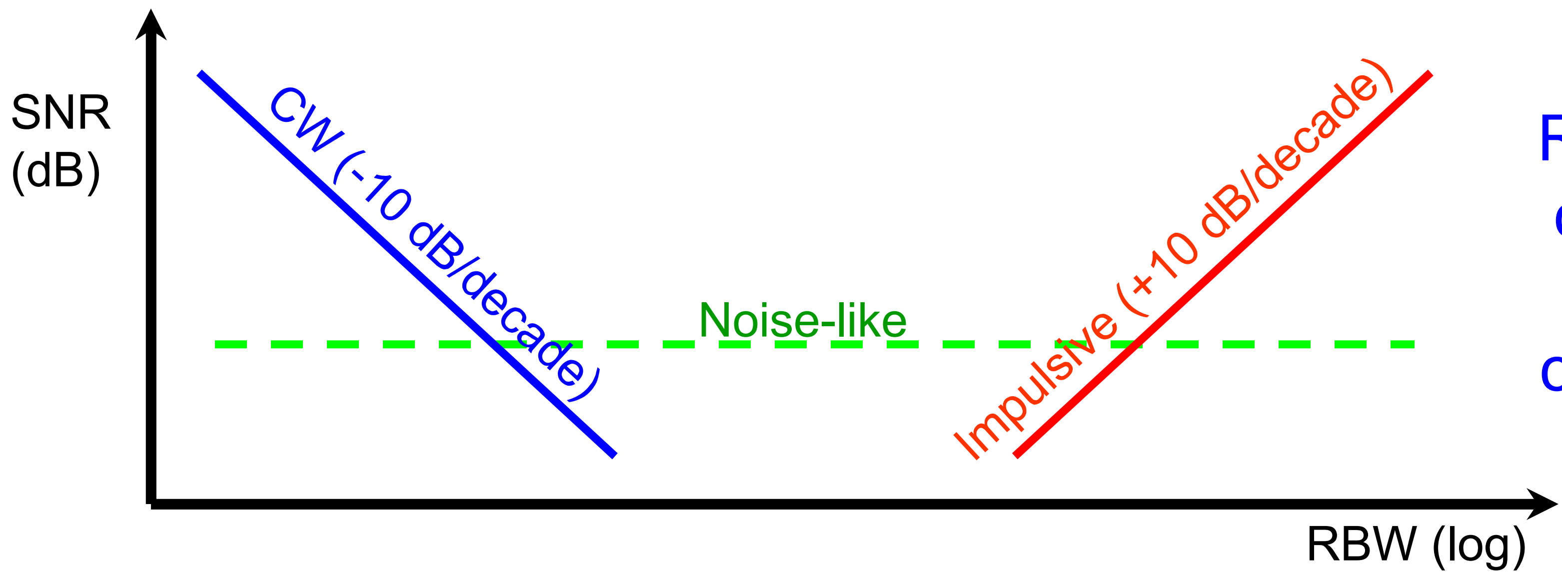
Signal Analyzer Low-Band



- Noise Contribution of Analyzer Elements must be Measured and/or Accurately Modeled for all Operating Settings

Signal Type vs. Effectiveness

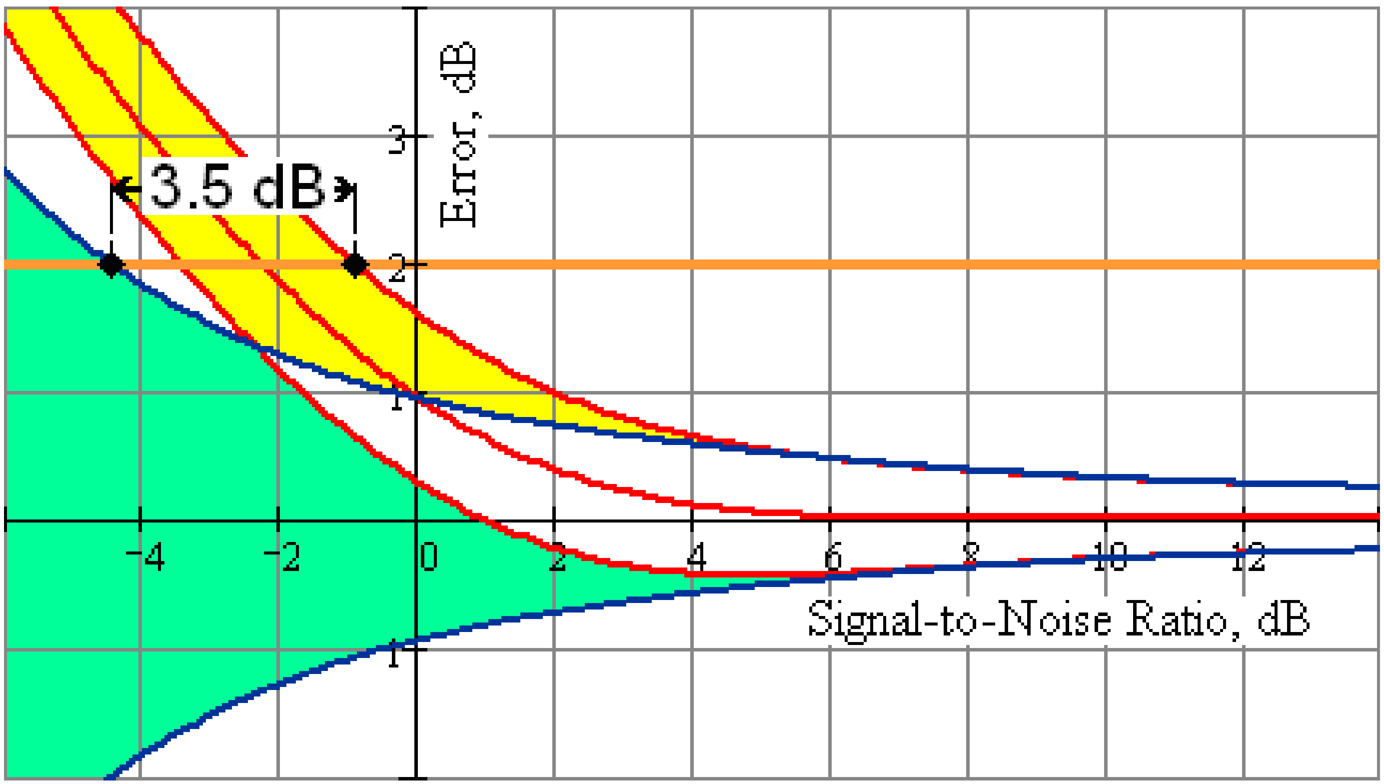
Signal/Noise Variation with RBW



Real signals can be one type or combination

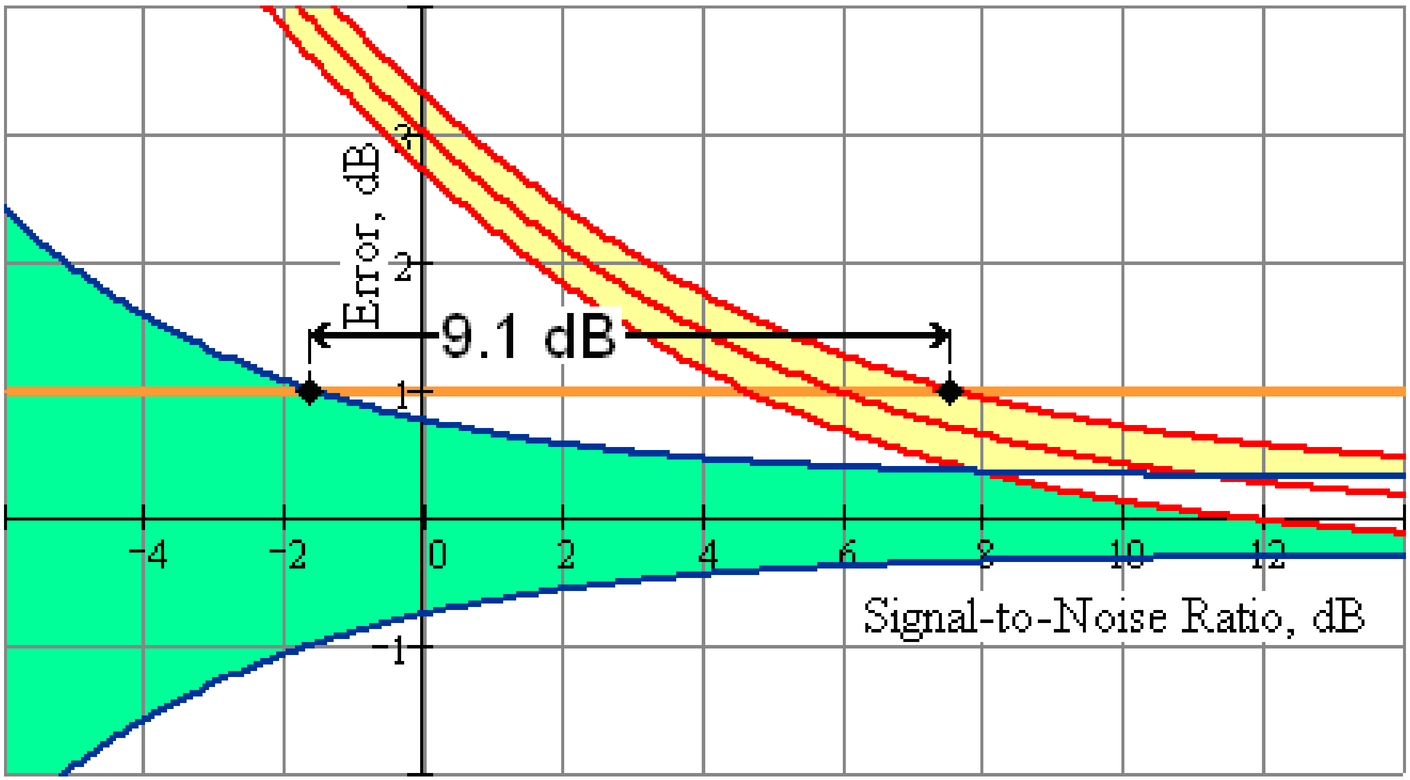
- Amplitude envelope vs. time
- Best RBW is one matched to signal
- Best ability to separate analyzer noise from signal

Noise Floor Enhancement CW Example



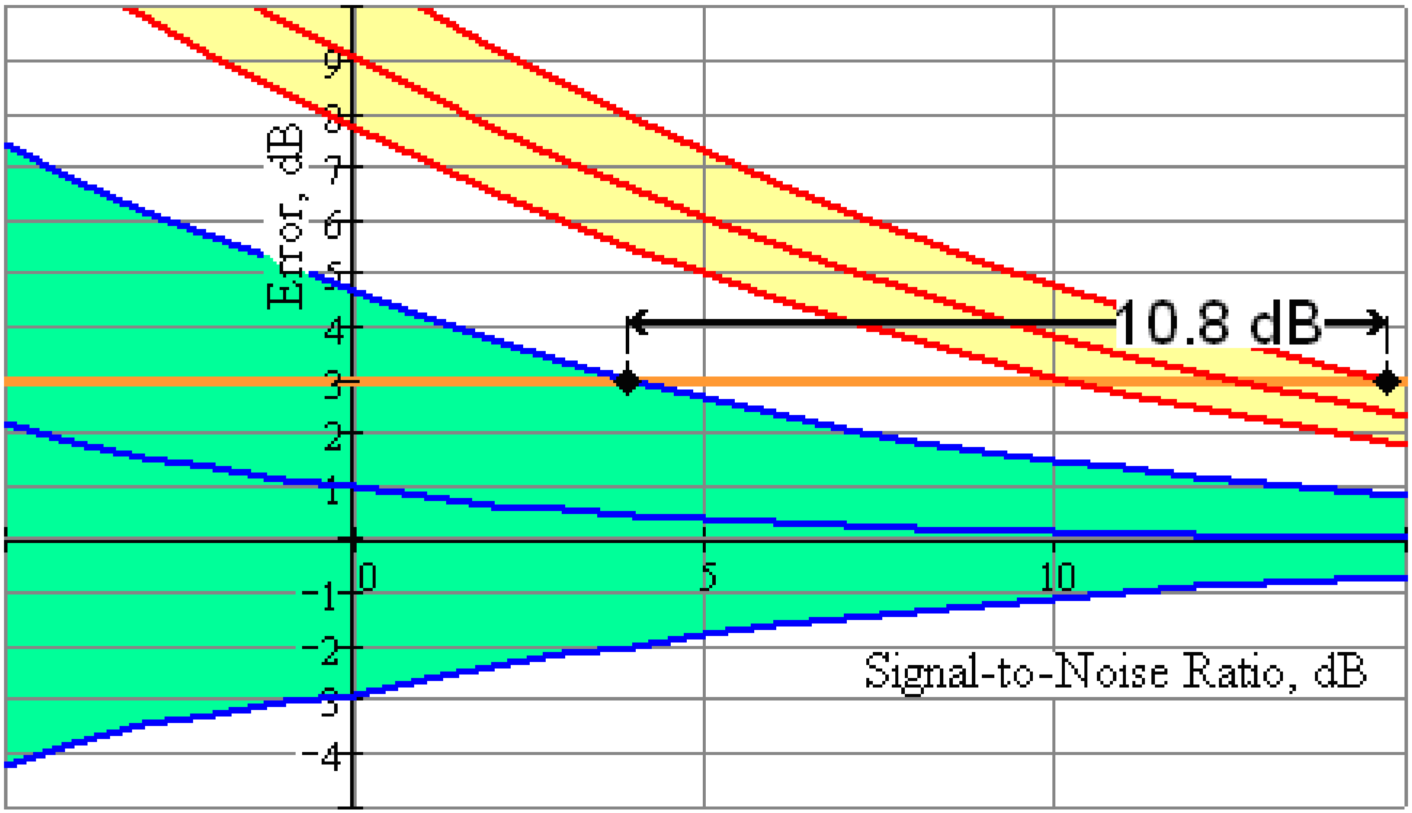
- 95% confidence interval, ±2 dB tolerance
- 3.5 dB improvement for CW signal

Noise Floor Enhancement Noise-Like Signal Example



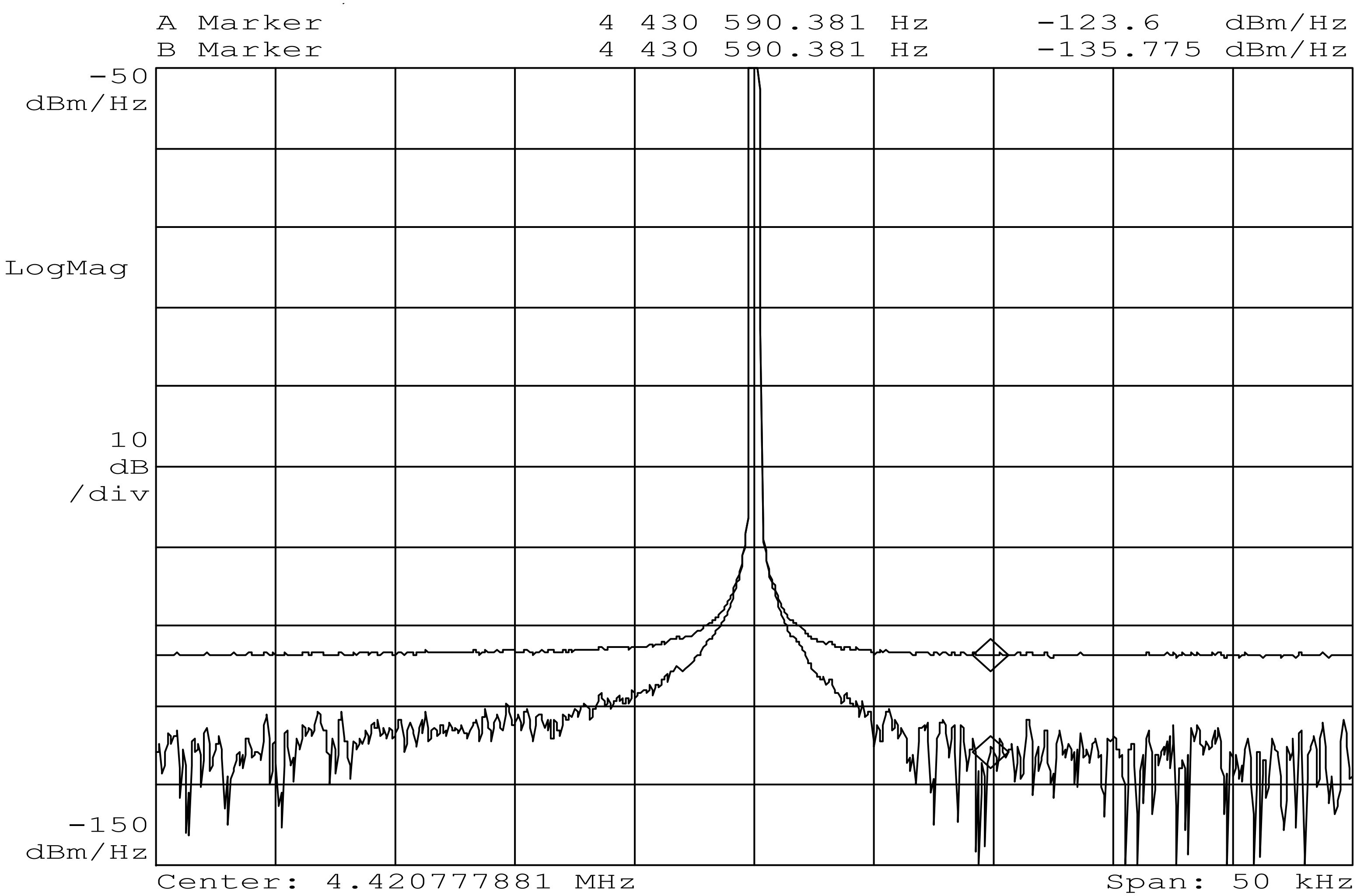
- 95% confidence interval, ±1 dB tolerance
- 9.1 dB improvement for noise-like signal

Noise Floor Enhancement Pulsed RF Example



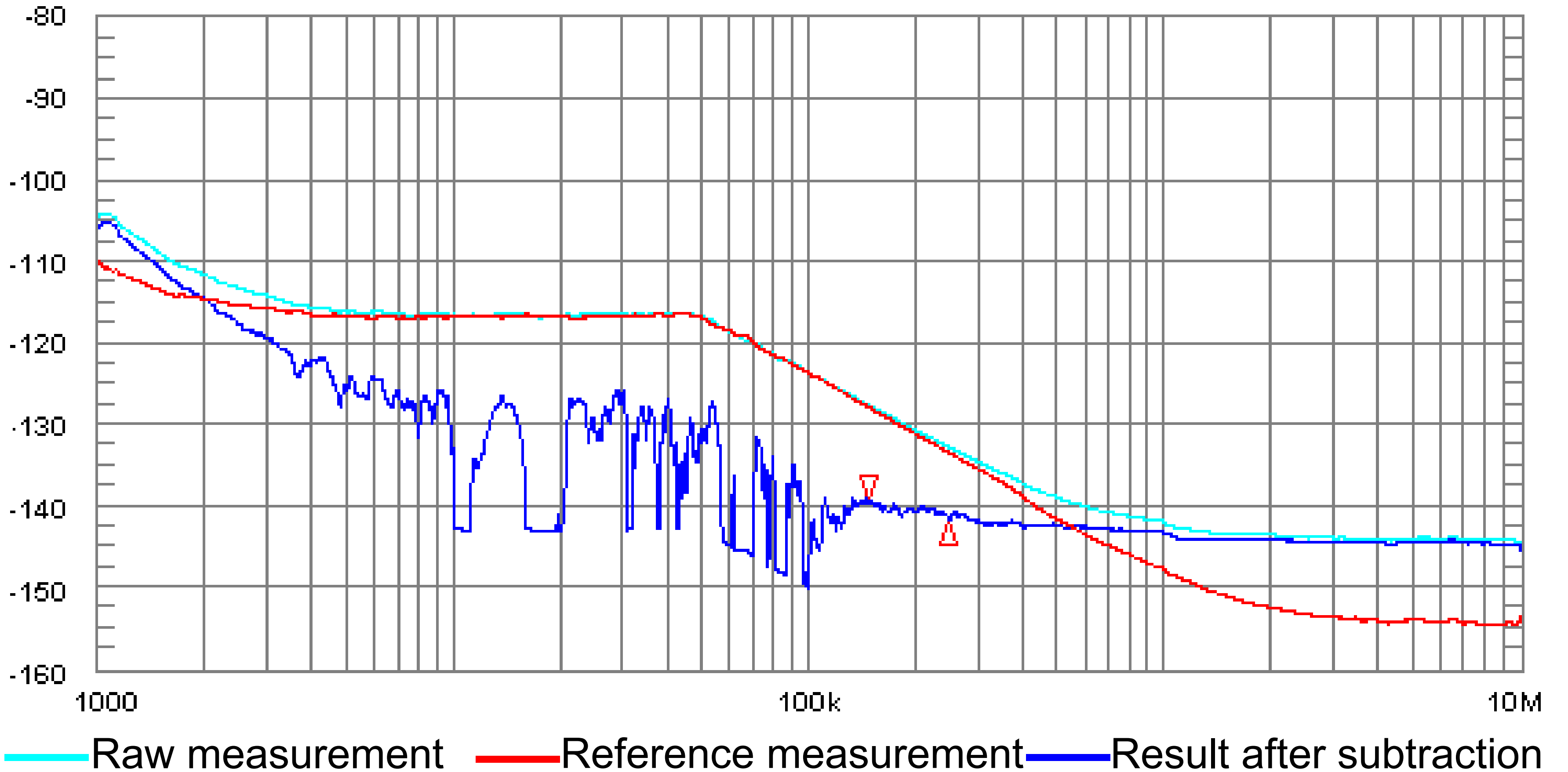
- 95% confidence interval, ±3 dB tolerance
- 10.8 dB improvement for pulsed-RF signal

Subtracting Broadband Noise in a Phase Noise Measurement



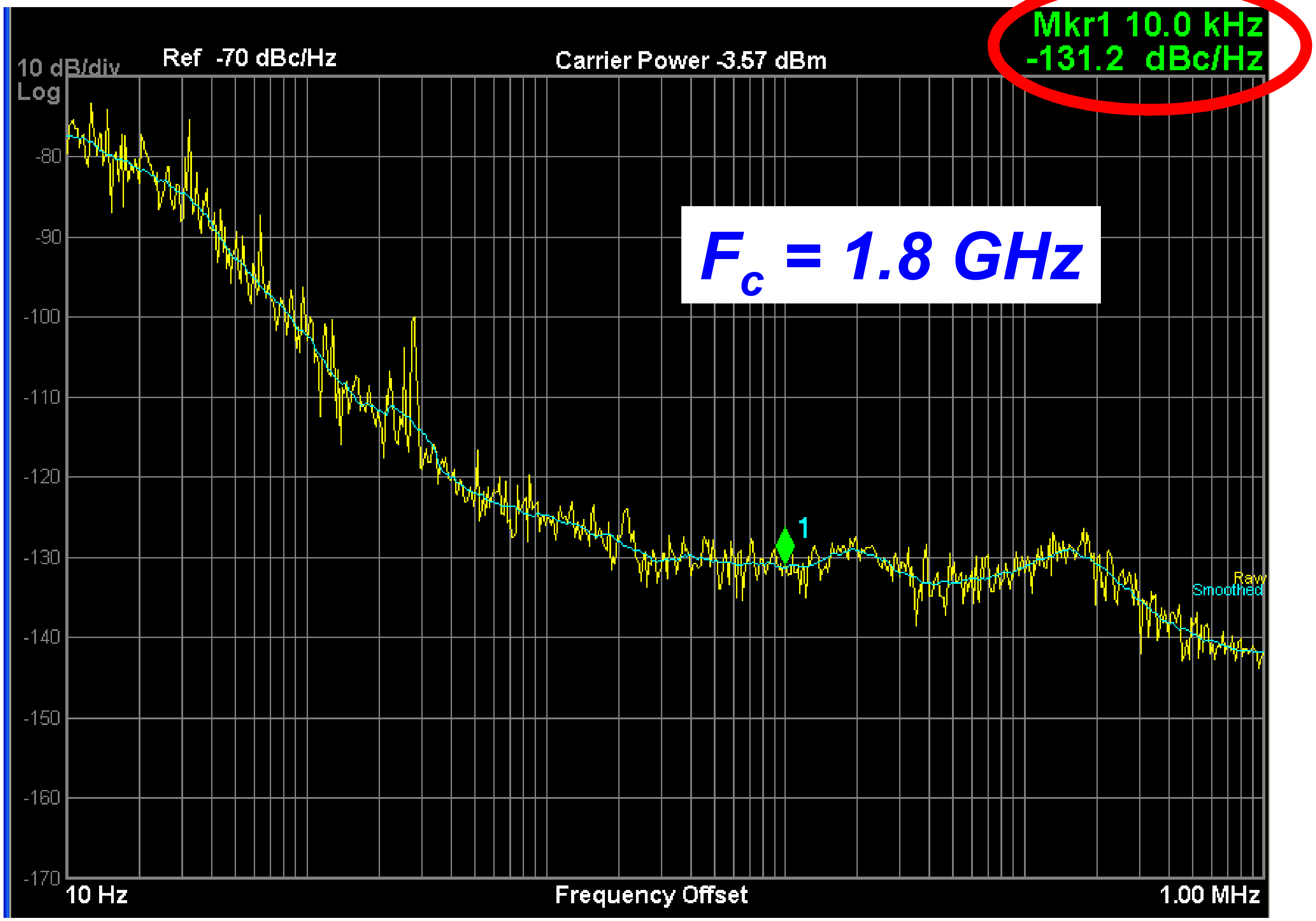
Subtracting Analyzer Phase Noise

Using Very Clean Source as Phase Noise Power Reference



Noise Subtraction Calculations Increase Variance of the Result

Better Reference Oscillator and/or Higher Performance Analyzer



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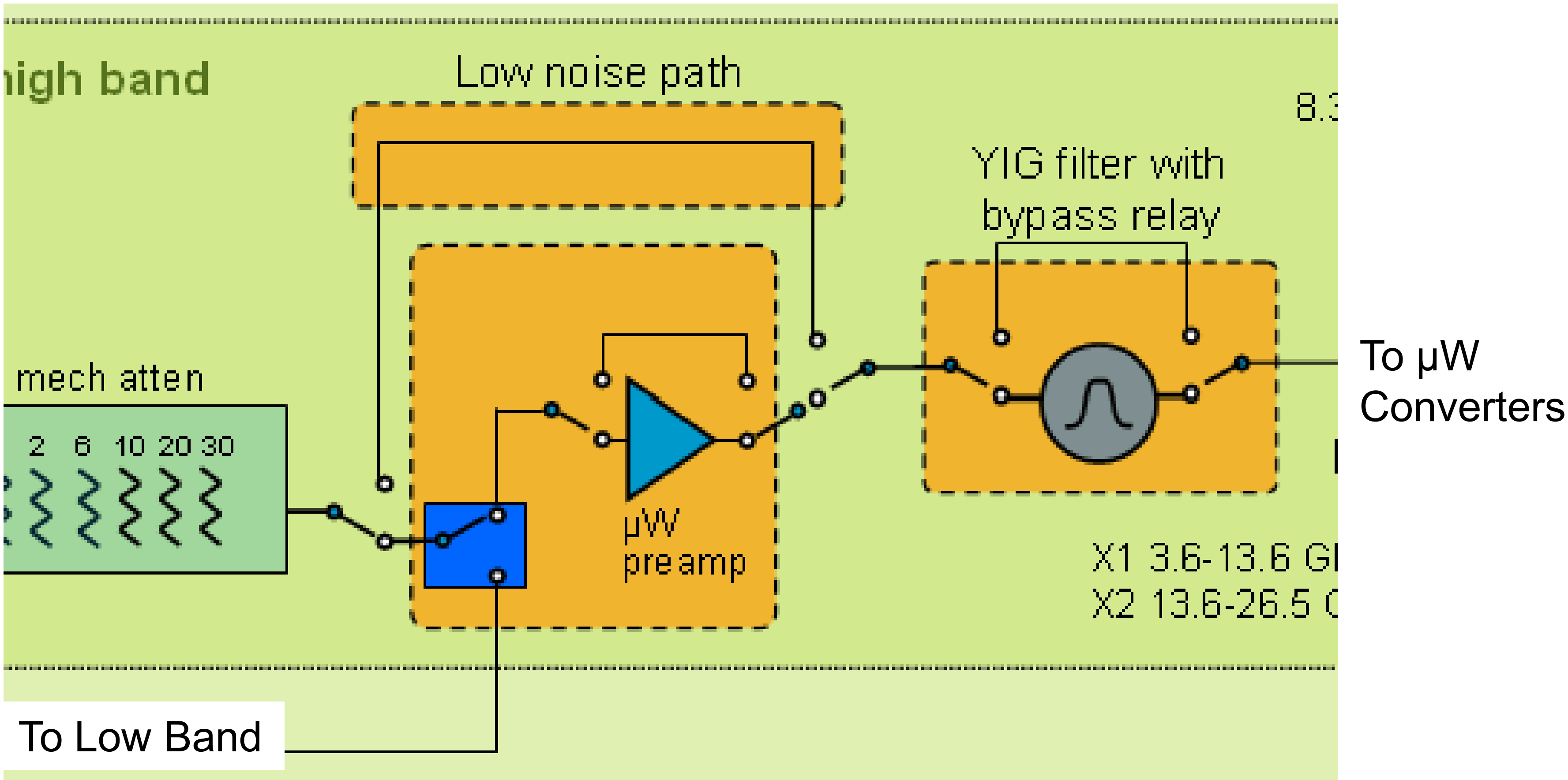
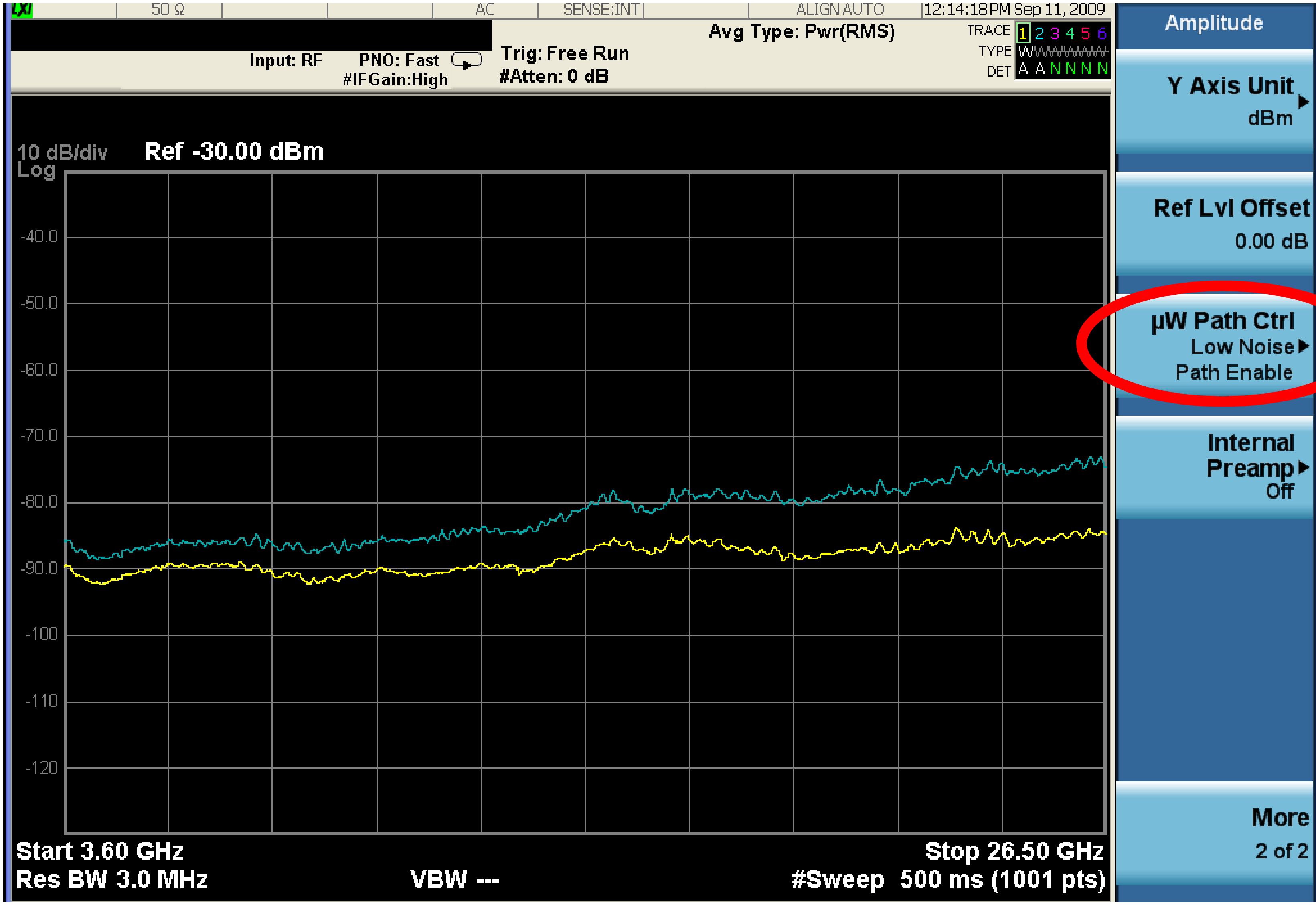
Microwave or High Band Architecture Tradeoffs

- Microwave or High Band Section
  - Path switching for low band
  - Path switching for microwave preamplifier
  - Other switching or path losses
- Alternate "Low Noise Path"
  - Optimized for high band
  - No microwave preamplifier

Low Noise Path



Alternate “Low Noise Path”



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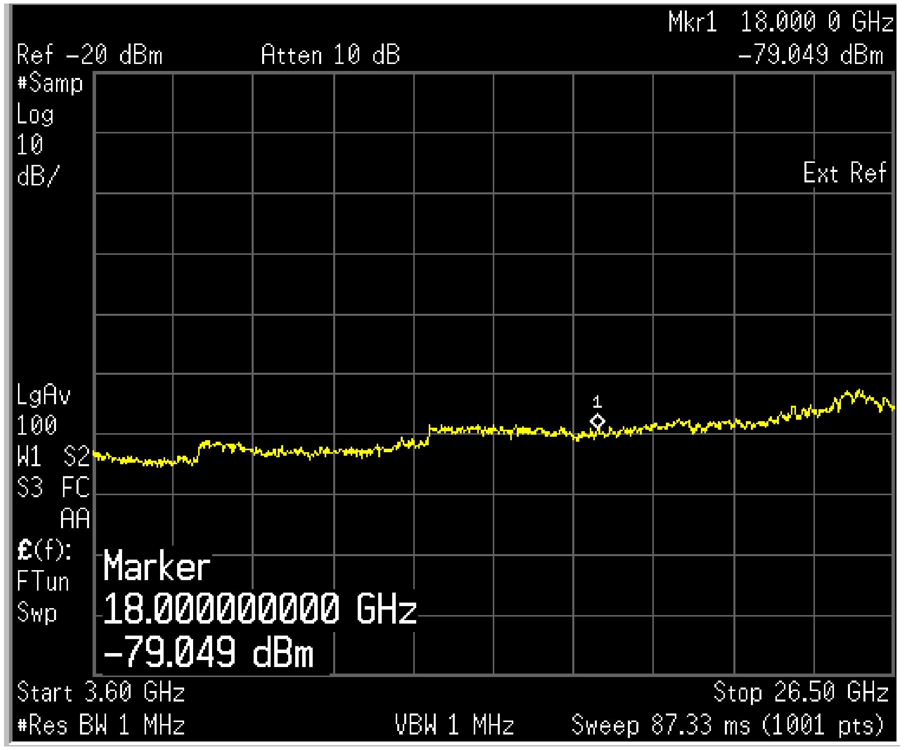
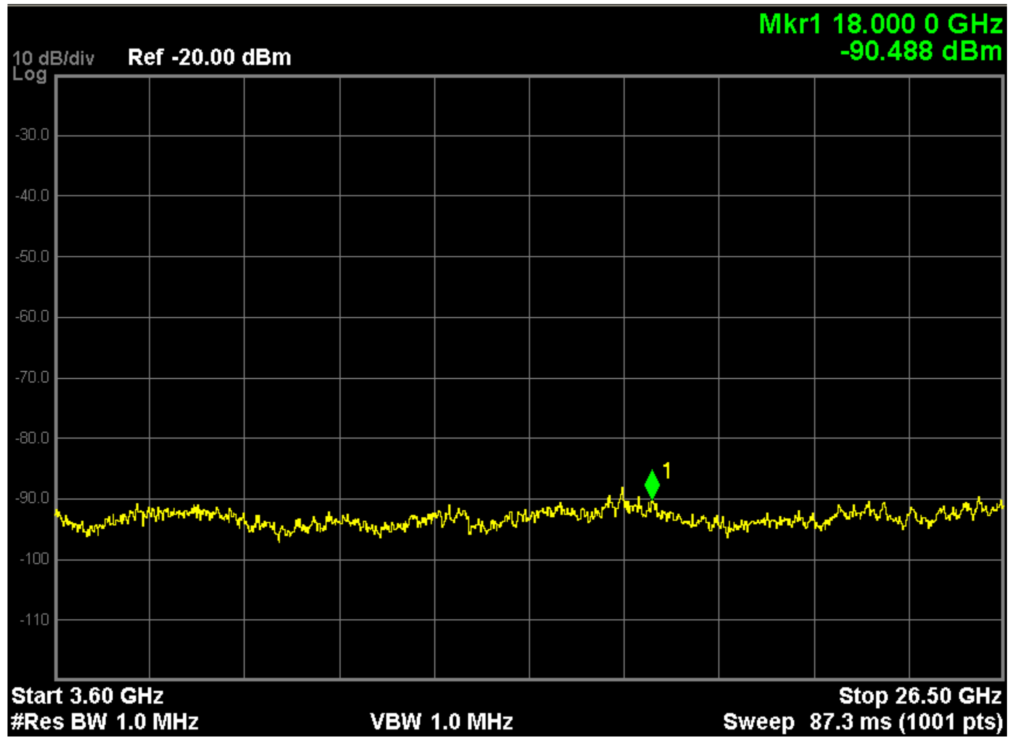
Combining Noise Floor Extension and Low Noise Path





- 3.6 - 26.5 GHz, preamplifier off
- Low noise path incompatible with preamp

Resources

- “Noise Floor Extension: Improving the Dynamic Range of Spectrum Analysis” Joe Gorin (to be published soon)
- “Improving the Dynamic Range of Spectrum Measurements by Compensating for the Effects of Phase Noise and Thermal Noise” Wing Mar & Ben Zarlingo, EuMW 2001
- “Spectrum Analyzer Detectors & Averaging for Wireless Measurements” Joe Gorin & Ben Zarlingo http://www.agilent.com/cm/wireless/pdf/detector_averaging.pdf
- “Spectrum Analyzer Measurements and Noise” Joe Gorin, Agilent Technologies Application Note 1303, literature number 5966-4008E
- “Spectrum & Network Measurements” Robert Witte, Noble Publishing 2001 ISBN 978-1884932168
- “Optimizing RF and Microwave Spectrum Analyzer Dynamic Range” Agilent application note AN-1315 literature number 5968-4545E
- “Electronic Test Instruments: Analog and Digital Measurements” Robert Witte, 2002 Prentice Hall ISBN 978-0130668301
- “The Art of Measurement: Theory and Practice” Ronald Potter, 1999 Prentice Hall ISBN 978-0130261748
- “Spectrum Analysis Basics” Agilent application note AN-150 literature number 5952-0292EN
- “Accurate Measurement of Signals Close to the Noise Floor of a Spectrum Analyzer” Andrew Mouthrup and Michael Muha, IEEE Transactions on Microwave Theory and Techniques, Vol. 39, No. 11, November 1991, pg. 1882 – 1885.