# Discussion of Error Models for PM and AM Noise Measurements

## TUTORIAL – QUESTIONS AND ANSWERS

Note from the editor

The questions were asked at various points during the presentation. They were transcribed and are presented here at the end of each tutorial.

**RICHARD KEATING (USNO):** I have a problem with what you mean by "harmonic distortion." Do you mean just simply the amount of power in the upper harmonics? Do you mean that a harmonic is just something that is some integer multiple of the fundamental? Or, do you refer to it as a partial? Do you mean something like that which is used in audio terminology where they talk about the "total power in the upper harmonics as being a distortion?" In short, what do you mean by "harmonic distortion?" Am I being clear?

**FRED WALLS (NIST):** Yeah, you're being perfectly clear. And I wasn't very clear on purpose. And the reason for that is convenience I guess. You can say "harmonic distortion," or you can say "The second harmonic is minus 25 dBc, the third harmonic is minus dBc," etcetera; and I'm just trying to show you this is the relative $K_d$. The sensitivity of the mixer to read out those harmonics in the signal, given an LO of a particular size, as a power ratio, relative to the fundamental. I've normalized the sensitivity of the fundamental to be zero dB or one.

And so you can see that I can change the sensitivity to, say, the third harmonic by 20 dB, depending how I tune LO and RF. And it's easy to see here, it's very clear that there's an even/odd–kind of symmetry, namely the even orders are typically much less sensitive than the odds; but I can point this one out to you where, in fact, the fifth and sixth have about the same sensitivity. And the other thing that's clear is, as you go to higher and higher harmonics, that the difference between odd and even tends to kind of wash out. And by *tuning*, you can make quite a difference here, 20, 25 dB. And some mixers will be better than others, low–level mixers will be different than high–level mixers, etcetera. And it's a complicated structure, but it's something you need to be aware of.

Now you can use it to your advantage. Sometimes you want to measure the phase noise of signal up here, and that's the LO that you have. And if you tune it, you can see that you can do the ninth harmonic with a penalty of only 20 dB. Maybe that's enough to get it done, maybe it isn't. And, in some cases, you can actually run up to the 25th or the 45th, or whatever; what you pay is in the noise floor.

# STATE-OF-THE-ART MEASUREMENT TECHNIQUES FOR PM AND AM NOISE

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## State-of-the-art measurement techniques for PM and AM noise

- Ultra wideband measurements (Fourier frequencies 0.1Hz to 1 GHz)
- Integral PM and AM noise standards
- Ultra low-noise PM and AM measurement systems (S(f) ≤ -190 dBc/Hz)

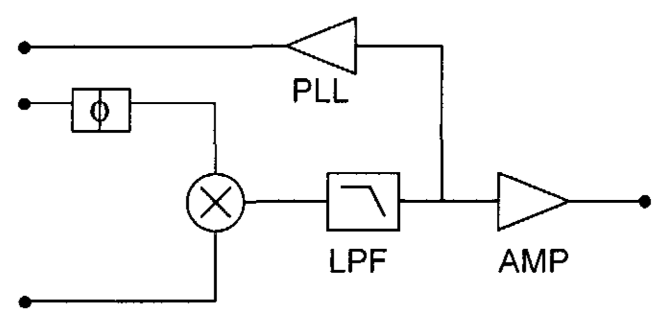


## NIST PM/AM noise measurement system

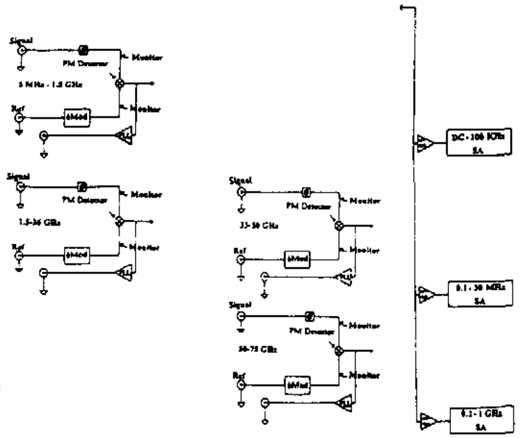
- Separates PM from AM noise
- Measures carrier frequencies from 5 MHz to 75 GHz
- Extends Fourier analysis to 1GHz
- Measurement accuracy: 0.3 - 3 dB
- Calibrates most PM/AM measurement error models



## Basic phase noise measurement

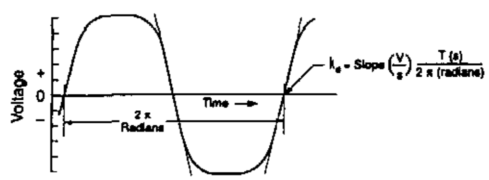


## NIST wideband measurement system





## Determination of Kd




- Determines Gain at single frequency
- Does not calibrate pll effects

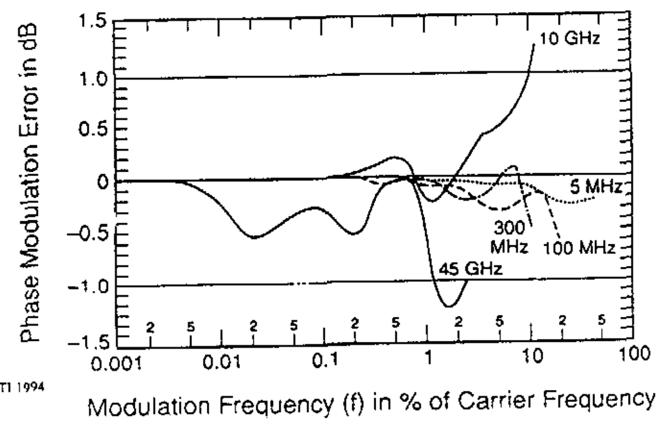


## NIST modulator

- Can be adjusted for pure PM or AM modulation
- Extremely flat frequency response
- Calibrates Kd(f) with system locked



## Errors in the NIST modulator



## Tips for measuring gain Vs Fourier frequency

- Measure power spectrum not PSD
- Use flattop windows for FFT
- Only small number of averages required
- Use zero span width on spectrum analyzers
- 3-5 points per decade
- create gain curve with cubic spline

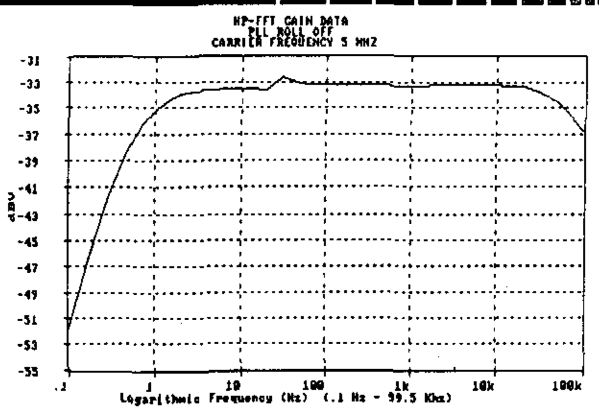


## Tips for measuring noise

- Use PSD on FFT
- Using Hanning window
- Confidence interval depends on number of averages
- Confidence interval depends also on resolution and video bandwidth for swept analyzers
- Keep level of system noise floor in mind

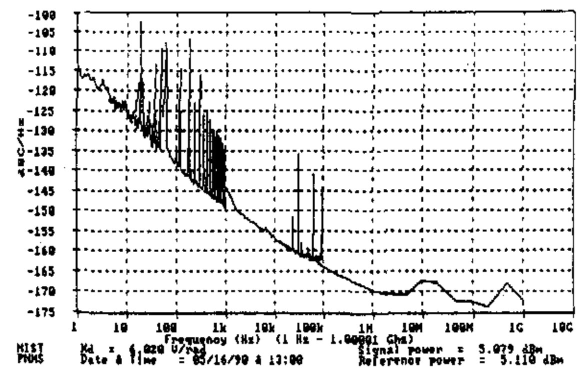


## Sample gain curve at X-band

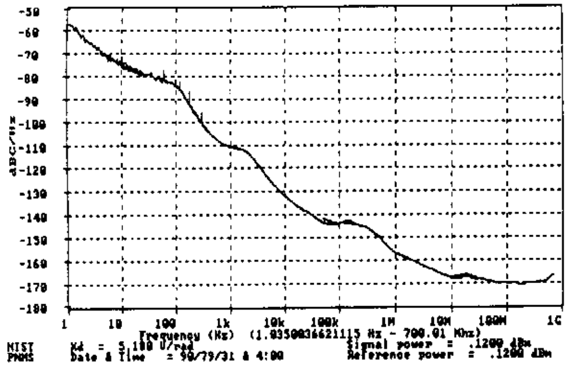





## Noise floor of NIST system at 42 GHz



## Phase noise of X-band synthesizer

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## Integral PM and AM noise standards

- Low noise signal source
- Two outputs with extremely low differential AM and PM noise
- Calibrated noise source
- Greatly simplifies AM and PM measurements

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## Current performance of NIST phase noise measurement system

| Noise Floor | Accuracy |
|---|---|
| **5 to 1500 MHz** | |
| -140 dBc/Hz at 1Hz | ±0.5 dB 1Hz to 32 MHz |
| -173 dBc/Hz Floor | ±1 dB 32 MHz to 150 MHz |
| **1.5 to 26 GHz** | |
| -135 dBc/Hz at 1 Hz | ± 1dB 1Hz to 500 MHz |
| -170 dBc/Hz Floor | ±2 dB 500 MHz to 1GHz |

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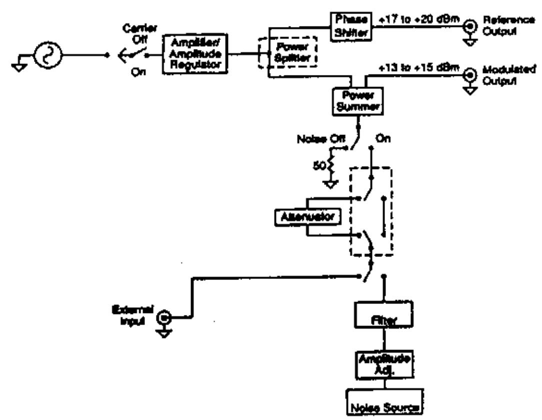
## Block diagram of NIST PM/AM noise standard

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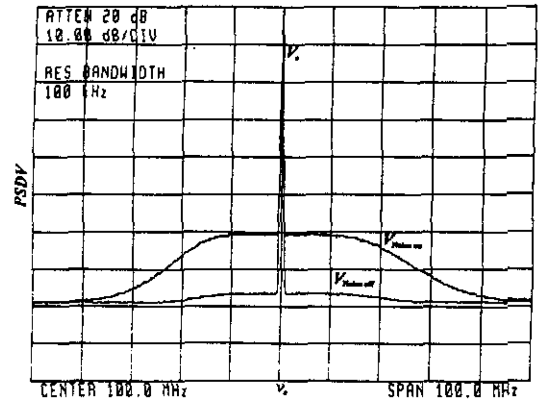
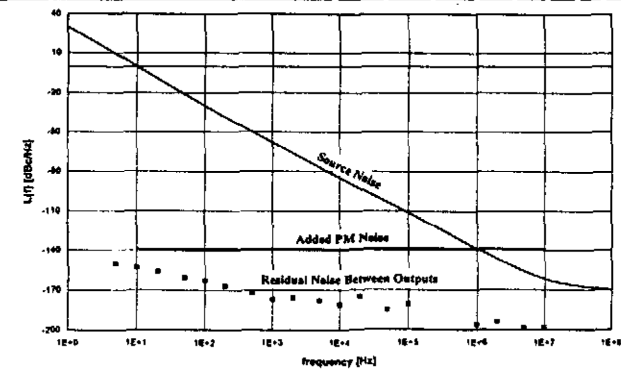
## Addition of noise to carrier



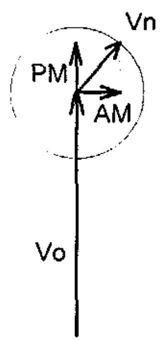



## Phase noise of NIST X-band PM/AM standard





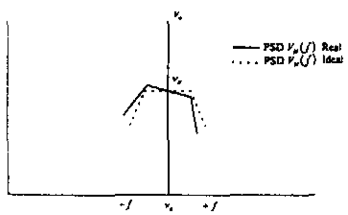

## Added noise appears as equal amounts of AM and PM




$$S_a(f) = S_\phi(f) = \frac{PSDV_n(\nu_0 - f) + PSDV_n(\nu_0 + f)}{2V_0^2}$$

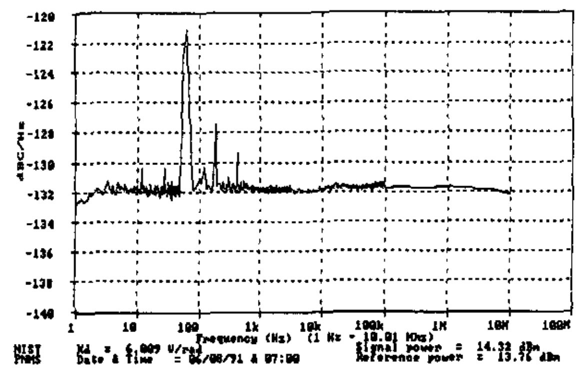
While

$$\int_0^\infty S_\phi(f) << 0.1$$

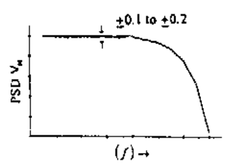




## Added PM noise at 100 MHz



# Stability of noise standard



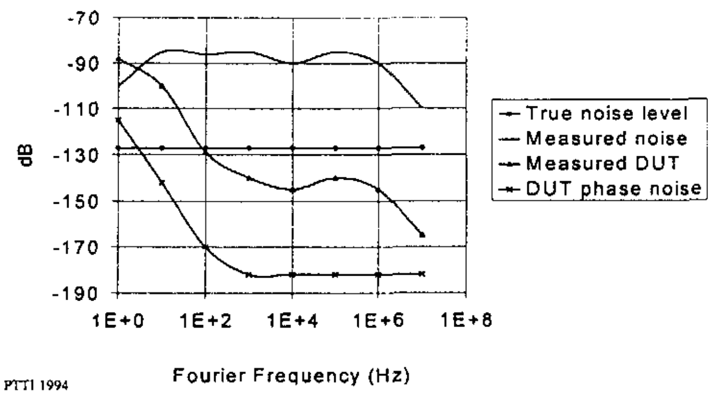

$$\frac{dS_\phi(f)}{dTemp} < 0.02\,dB/^\circ C$$

$$\frac{dS_\phi(f)}{dtime} < 0.2\,dB/year$$

$$accuracy/_{calib.} \pm 0.15\,dB$$

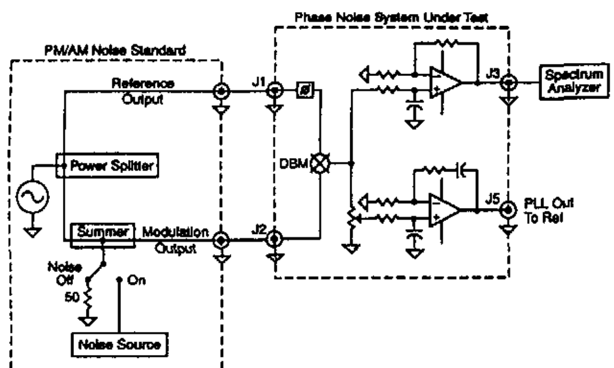


# Use of noise calibration level






# System noise floor for PM






# Calibration of noise floor and system accuracy

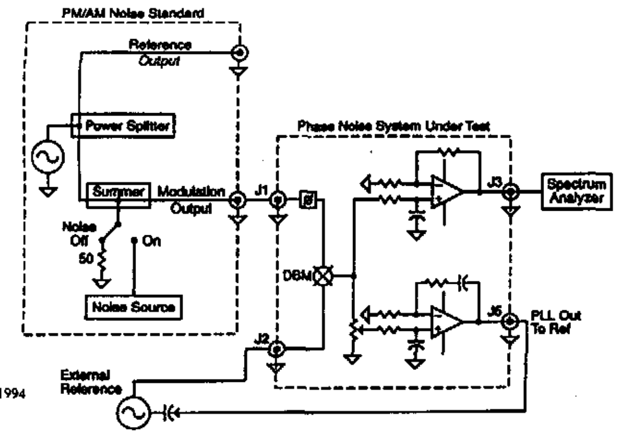
MAXIMUM RESIDUAL NOISE BETWEEN CHANNELS dBc/Hz

| SOURCE FREQUENCY | 1 Hz | 10 Hz | 100 Hz | 1 kHz | 10 kHz | 100 kHz | 1 MHz | 10 MHz |
|---|---|---|---|---|---|---|---|---|
| 5 MHz | -162 | -172 | -182 | -190 | -194 | -191 | | |
| 10 MHz | -161 | -176 | -183 | -191 | -197 | -194 | | |
| 100 MHz | -152 | -162 | -172 | -182 | -193 | -193 | -194 | |
| 10.6 GHz | | -153 | -163 | -173 | -181 | -181 | -196 | -198 |

DIFFERENTIAL PM/AM NOISE LEVEL ± 0.2 dBc/Hz

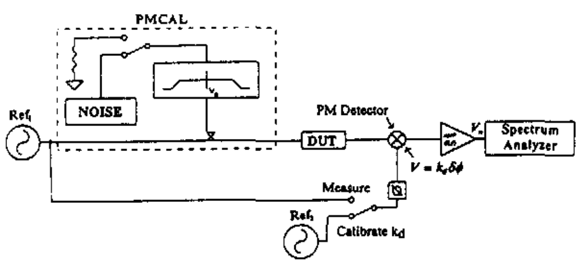
| SOURCE FREQUENCY | 1 Hz | 10 Hz | 100 Hz | 1 kHz | 10 kHz | 100 kHz | 1 MHz | 10 MHz |
|---|---|---|---|---|---|---|---|---|
| 5 MHz | -127.3 | -127.3 | -127.3 | -127.3 | -127.3 | -127.3 | | |
| 10 MHz | -128.4 | -128.4 | -128.4 | -128.4 | -128.4 | -128.4 | -128.4 | |
| 100 MHz | -129.5 | -129.5 | -129.5 | -129.5 | -129.5 | -129.5 | -129.5 | -129.8 |
| 10.6 GHz | -138.9 | -138.9 | -138.9 | -138.9 | -138.9 | -138.9 | -138.9 | -138.9 |

# Measurement of an external oscillator



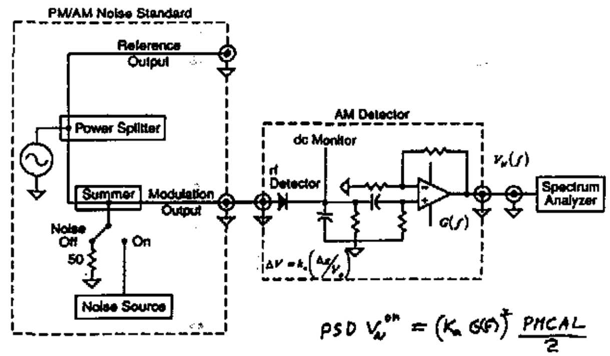



# Measurement of other devices






# Calibration of a simple AM measurement



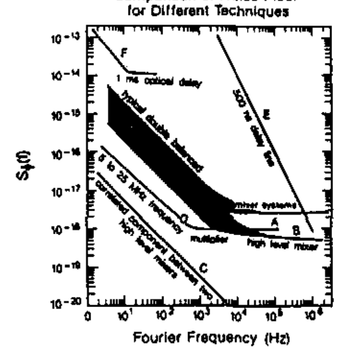

$$PSD\ V_N^{ch} = (K_a G(f))^2 \frac{PMCAL}{2}$$



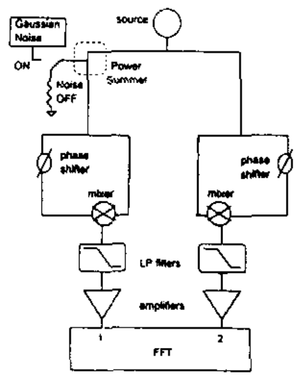
# Ultra low PM and AM measurement systems

■ Cross-Correlation

Comparison of Noise Floor for Different Techniques

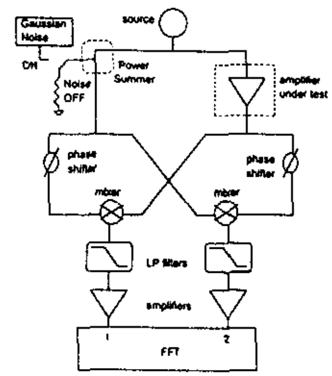


## Cross-correlation PM noise floor measurement






## Cross-correlation PM noise system for amplifier measurements



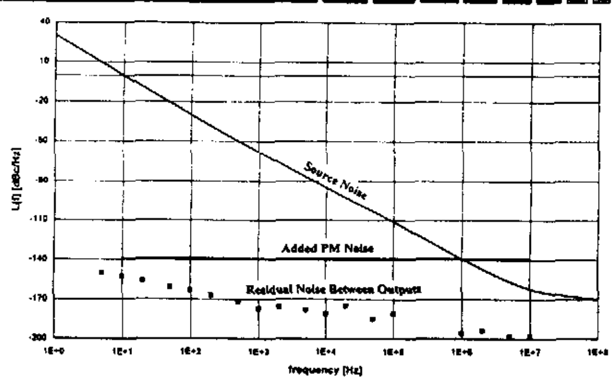

$$PSD1 = PM_{amplifier} + NOISE_{channel1}$$

$$PSD2 = PM_{amplifier} + NOISE_{channel2}$$

$$PSD(CROSS) = PM_{amplifier}$$

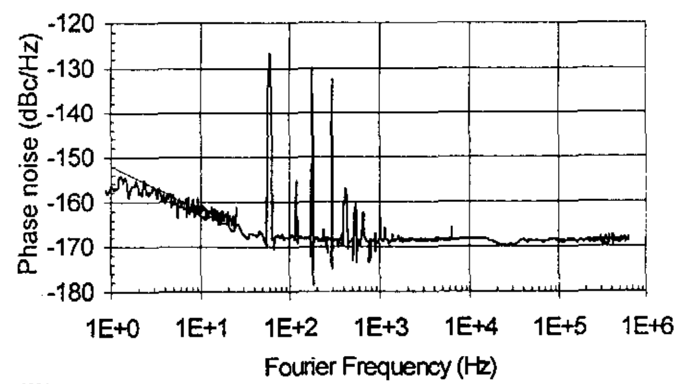


## Residual noise between channels of NIST phase noise standard






## Ultra-low noise amplifier measurement



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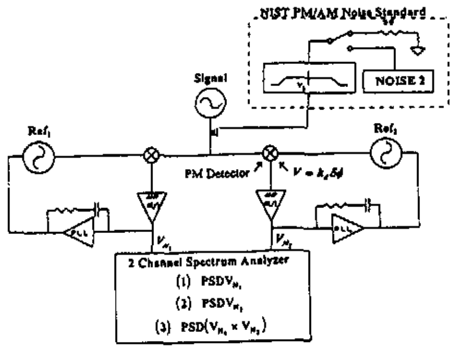
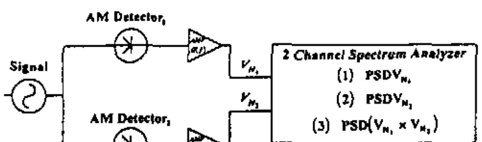
# Cross-correlation oscillator measurements






# Cross-correlation AM measurements



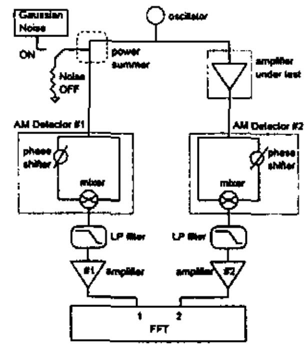

(1) $\frac{PSDV_{N_1}}{[k_a G(f)]^2}$ measures $S_a(f)$ of the signal plus System$_1$ noise.

(2) $\frac{PSDV_{N_2}}{[k_a G(f)]^2}$ measures $S_a(f)$ of the signal plus System$_2$ noise.

(3) $\frac{PSD(V_{N_1} \times V_{N_2})}{[k_a G(f)]^2}$ measures $S_a(f)$ of only the signal since, System$_1$ noise is uncorrelated with System$_2$ noise.



# Cross-correlation AM amplifier measurements




$PSD1 = NOISE_{channel\ 1} + AM_{source}$

$PSD2 = NOISE_{channel\ 2} + AM_{source} + AM_{amplifier}$

$PSD1 - PSD2 = AM_{amplifier} + NOISE_{channel\ 1} - NOISE_{channel\ 2}$

$PSD(CROSS) = AM_{source}$



# Noise floor of AM measurement system