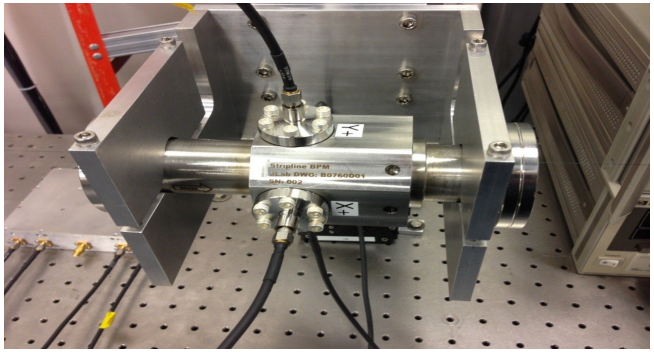
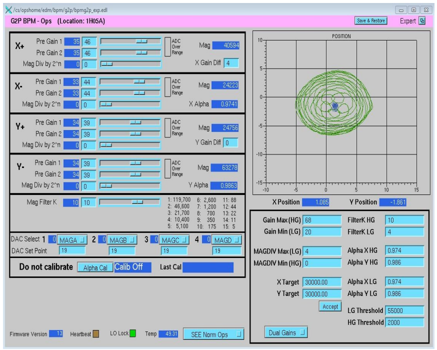
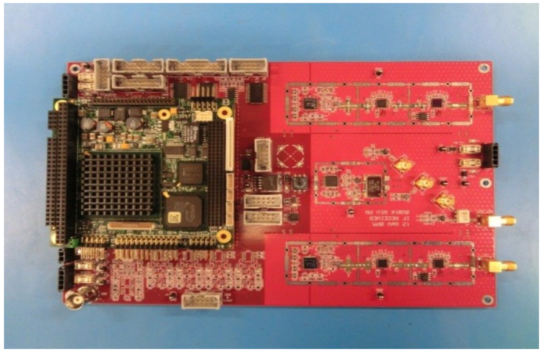
  

Overview and Expected Performance of RF Beam Diagnostics

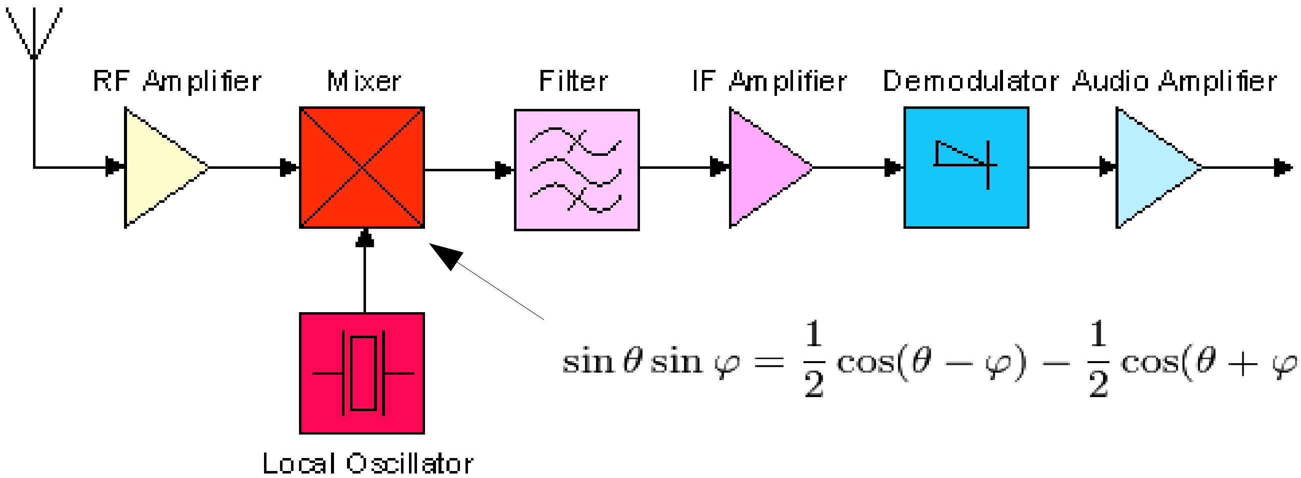
Trent Allison, Brian Bevins, Keith Cole, Roger Flood, Omar Garza, John Musson, and Dave Williams

8/6/2015

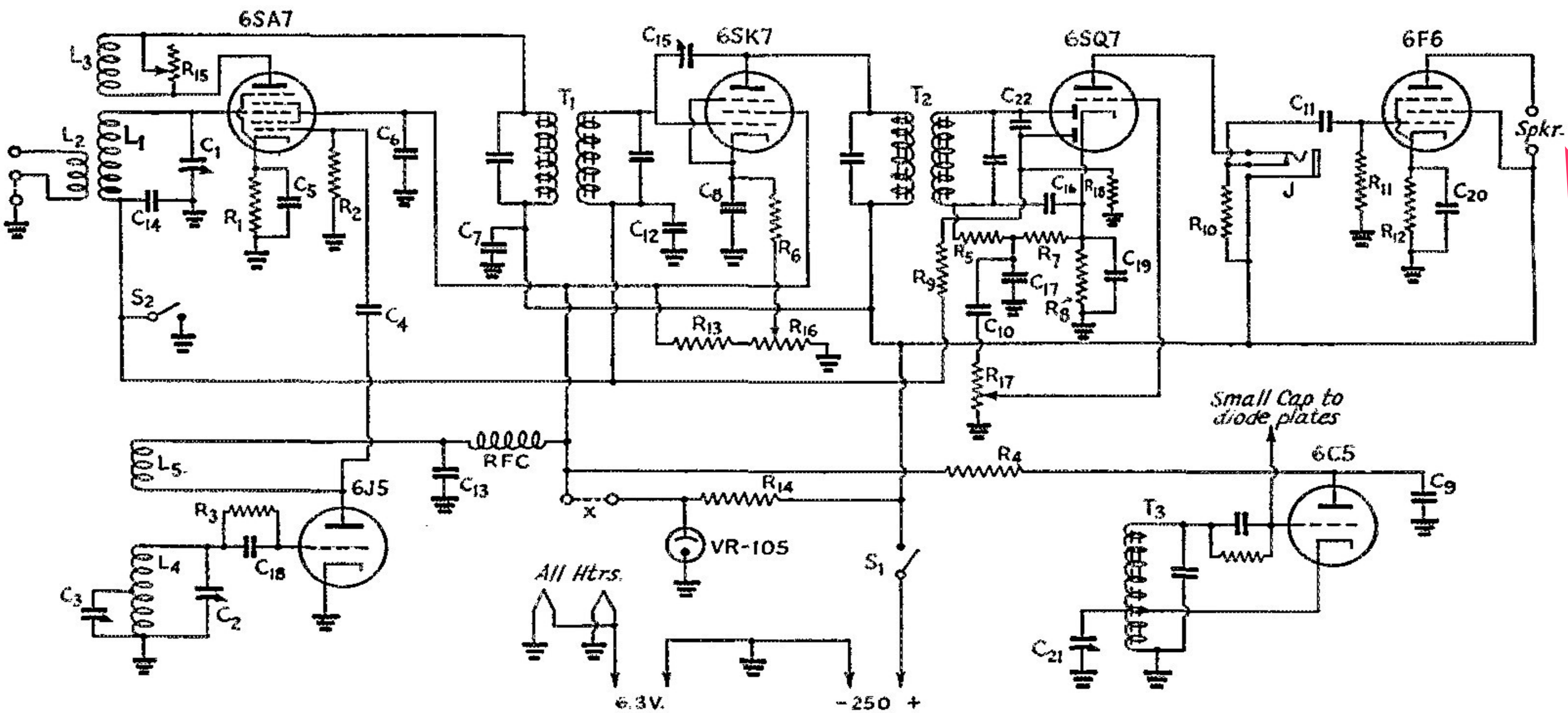
Overview

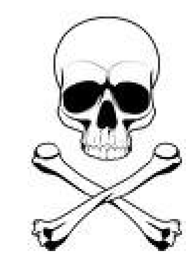
- Receiver Architecture
- Stripline BPMs
- Cavity BPMs
- BCM
- Goubau Line Testing
- Conclusions
- References

Superheterodyne Architecture



$$\sin\theta\sin\varphi = \frac{1}{2}\cos(\theta-\varphi) - \frac{1}{2}\cos(\theta+\varphi)$$





Digital Receiver

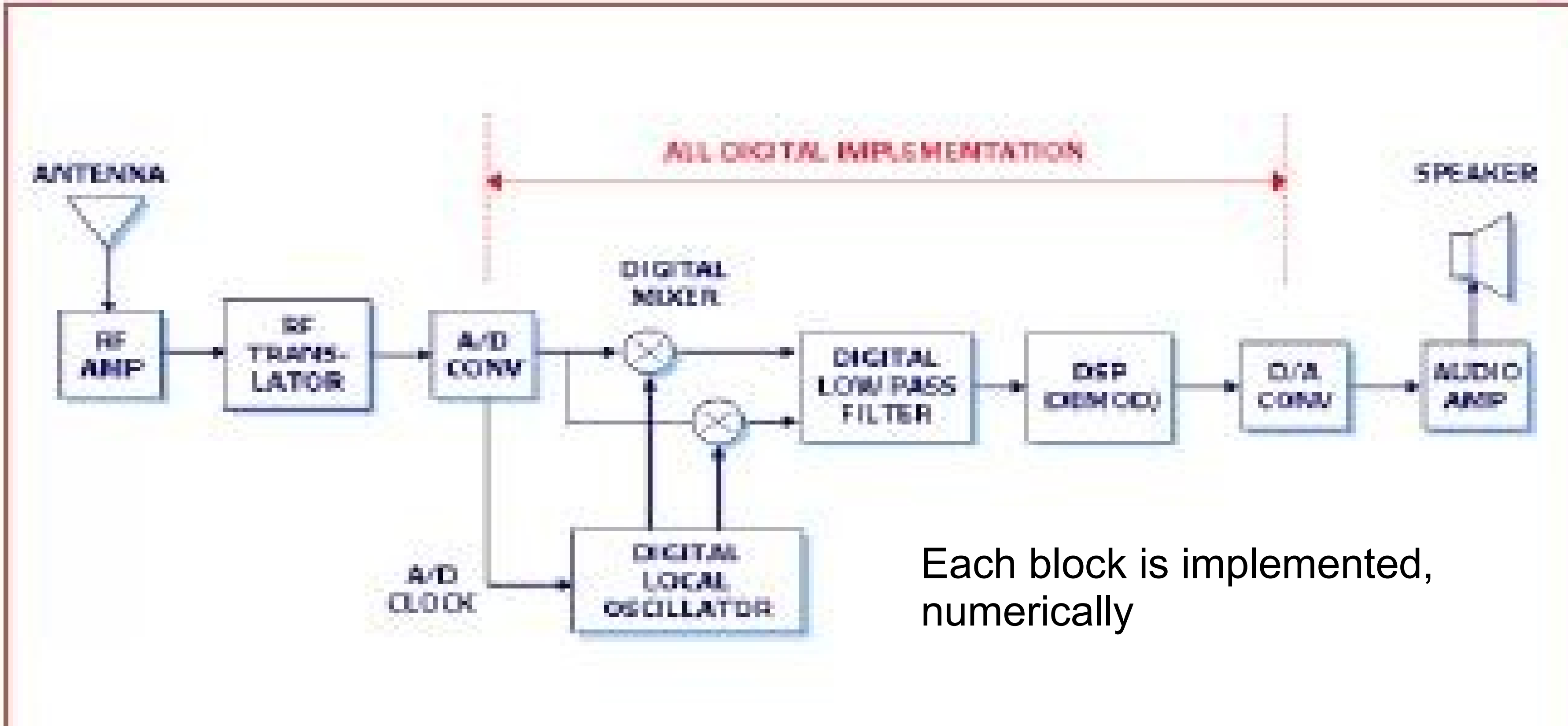
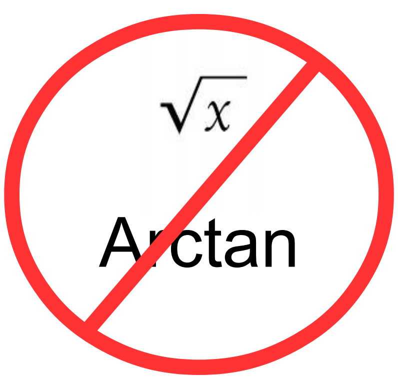


Figure 3

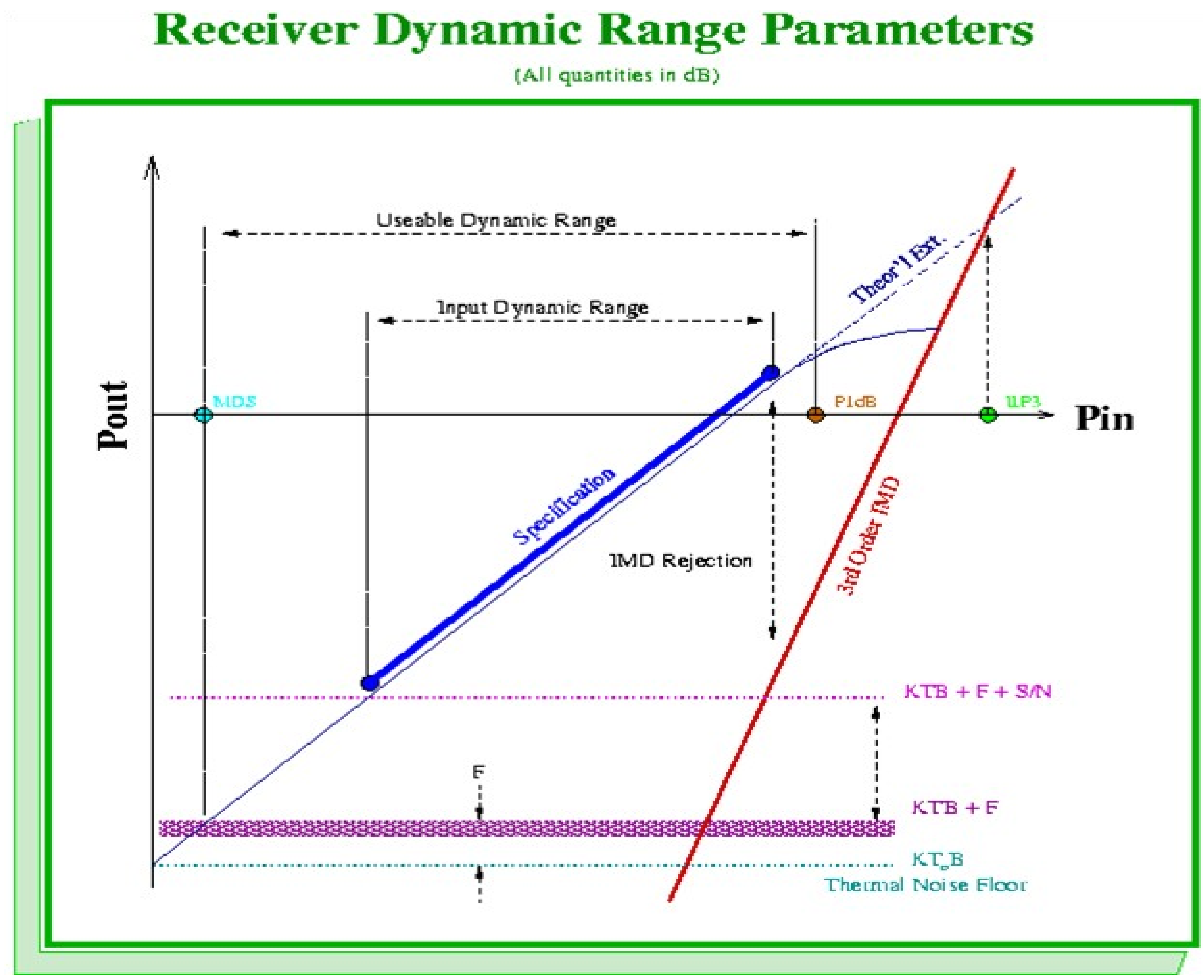
Each block is implemented, numerically



Nearly always integer math!!!

JLAB-TN-14-028. "Functional Description of Algorithms Used in Digital Receivers"
https://jlabdoc.jlab.org/docushare/dsweb/View/Collection-21302

System Linearity



RECEIVER MODEL

Cal Cell | Downconverter

Input Field

	Coax	LNA	Filter	Amp	Coax	LNA	Filter	Amp	Filter	Mixer	IF Filter	Amp		
Noise Figure	4.00	1.30	3.00	5.40	10.00	1.30	3.00	5.40	1.00	8.00	6.00	2.70	2.70	**dB**
Gain: Passband	-4.00	13.00	-3.00	18.00	-10.00	13.00	-3.00	18.00	-1.00	-8.00	-6.00	15.00	15.00	**dB**
Gain: Reject-band	-4.00	13.00	-20.00	18.00	-10.00	13.00	-20.00	18.00	-20.00	-8.00	-30.00	15.00	15.00	**dB**
IIP3	200.00	28.00	200.00	26.00	200.00	28.00	200.00	26.00	200.00	34.00	200.00	21.00	23.00	**dBm**
P1dB	200.00	23.00	200.00	20.00	200.00	23.00	200.00	20.00	200.00	22.00	200.00	20.00	20.00	**dBm**
Return Loss	8.00	20.00	6.00	20.00	20.00	20.00	6.00	20.00	2.00	16.00	12.00	25.00	25.00	**dB**

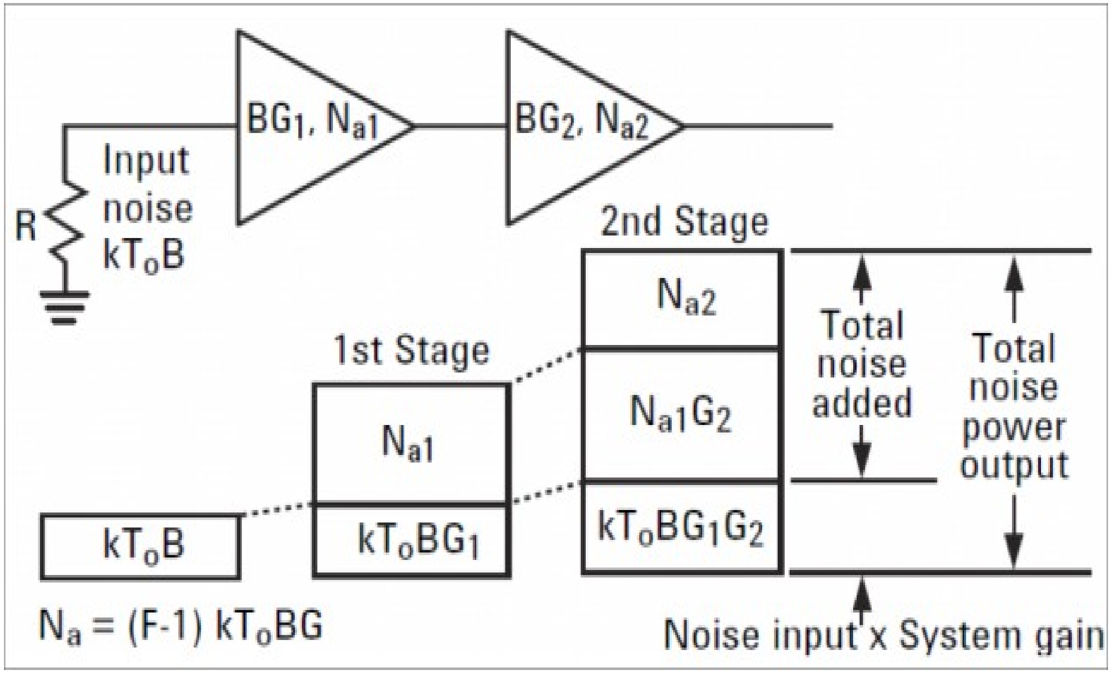
Pin Interference		-33.00	**dBm**	
Pin Passband	-100	-33.00	**dBm**	
Input Noise BW	50	50.00	**dB-Hz**	(System IF BW)
Input Noise Temperature	290	290.00	**K**	(IEEE definition = 290K for Physical Temperature)
Input Noise Level		-124.0	**dBm**	
Required C/N	60	0.00	**dB**	(Modulator / BER -dependent…see BER sheet)
Required Sensitivity	164	-120.00	**dBm**	(From "Specifications" or "Standards")

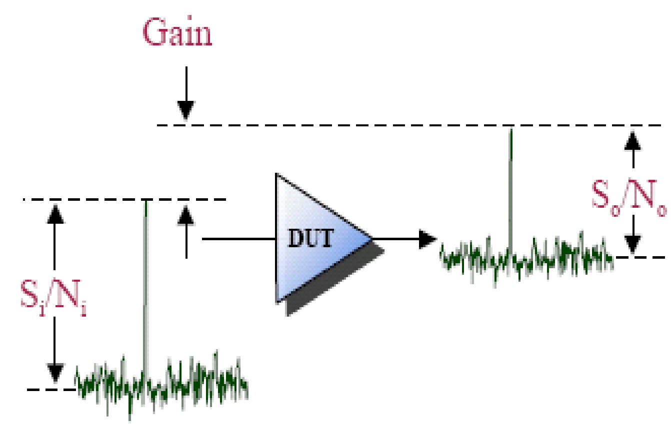
Calculation Field

System Noise Figure	4.00	5.30	5.46	6.16	6.20	6.22	6.22	6.23	6.23	6.23	6.23	6.24	6.24	**dB**
System Noise Temp	26.42	28.41	28.63	29.58	29.63	29.65	29.66	29.67	29.67	29.67	29.67	29.68	29.68	**dBK**
System Gain: Passband	-4.00	9.00	6.00	24.00	14.00	27.00	24.00	42.00	41.00	33.00	27.00	29.00	44.00	**dB**
System Gain: Reject-band	-4.00	9.00	-11.00	7.00	-3.00	10.00	-10.00	8.00	-12.00	-20.00	-50.00	12.00	27.00	**dB**
IIP3: Passband	200.00	32.00	32.00	19.73	19.73	12.97	12.97	1.67	1.67	-7.55	-7.55	6.77	-6.22	**dBm**
IIP3: Reject-band	200.00	32.00	32.00	30.81	30.81	27.89	27.89	27.27	27.27	27.21	27.21	23.18	10.74	**dBm**
Input Spurious-Free Dynamic Range	213.32	100.45	100.35	91.70	91.67	87.16	87.15	79.61	79.61	73.46	73.46	83.01	74.34	**dB**
Pout: Passband	-37.00	-24.00	-27.00	-9.00	-19.00	-6.00	-9.00	9.00	8.00	0.00	-6.00	-4.00	11.00	**dBm**
Pout: Reject-band	-37.00	-24.00	-44.00	-26.00	-36.00	-23.00	-43.00	-25.00	-45.00	-53.00	-83.00	-21.00	-6.00	**dBm**
Output Noise Power	-123.98	-109.68	-112.52	-93.81	-103.78	-90.76	-93.76	-75.75	-76.75	-84.75	-90.75	-88.74	-73.74	**dBm**
C/N Ratio	86.98	85.68	85.52	84.81	84.78	84.76	84.76	84.75	84.75	84.75	84.75	84.74	84.74	**dB**
Saturation?	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	
IIM3	-499.00	-163.00	-163.00	-160.61	-160.61	-154.78	-154.78	-153.54	-153.54	-153.42	-153.42	-145.35	-120.49	**dBm**
C/I Ratio	466.00	130.00	130.00	127.61	127.61	121.78	121.78	120.54	120.54	120.42	120.42	112.35	87.49	**dB**
Total Return Loss	8.00	28.00	34.00	54.00	74.00	94.00	100.00	120.00	122.00	138.00	150.00	99.00	124.00	**dB**

Calculated Receiver Sensitivity:	-117.74	**dBm**
Required Receiver Sensitivity:	-120.00	**dBm**
Margin:	-2.26	**dB**

Noise Calibration





$$F_{sys} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \ldots$$

If loads are characterized, a 2-point calibration is possible:

Hot load: Room temperature (300 K), or noise source (3770 K)

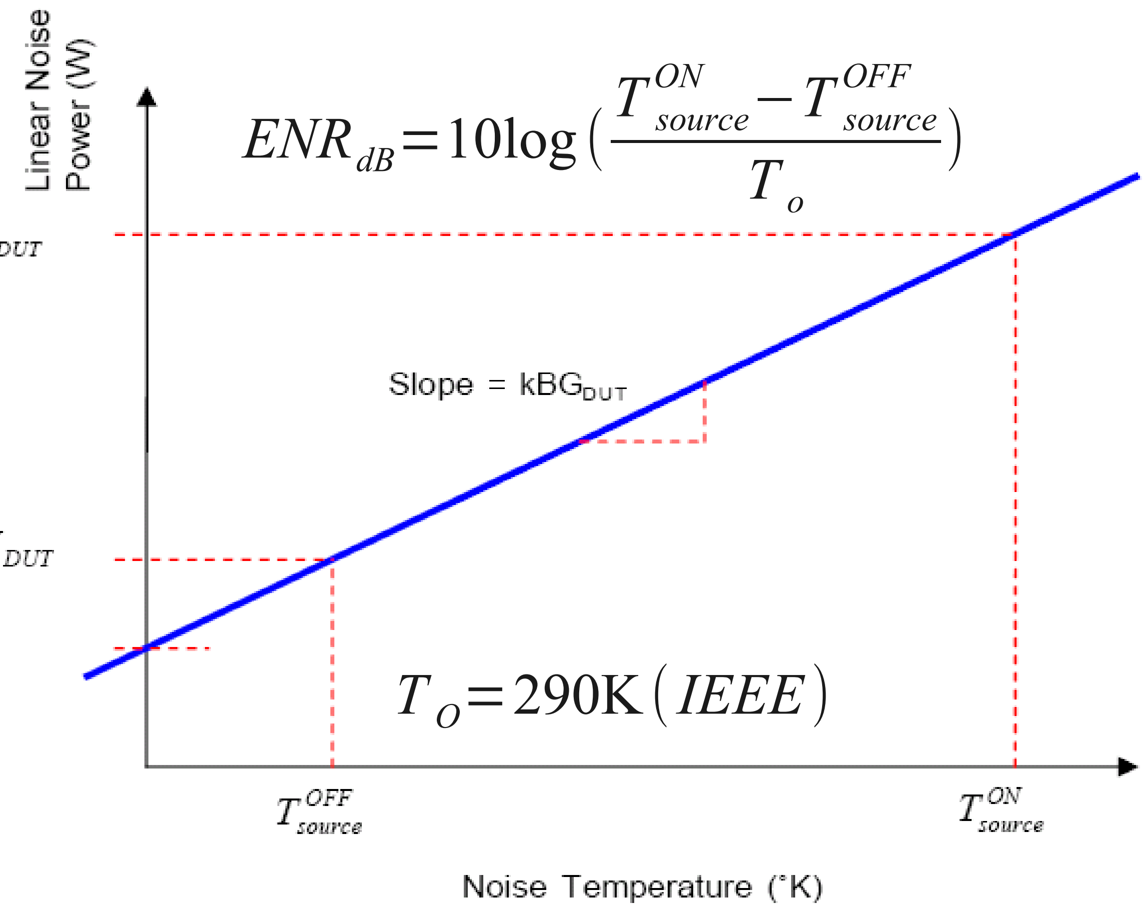
Cold load: LN2 or room temperature (300 K)

Y-Factor Calibration Method

$$N_{on} = kT^{ON}_{source} B G_{DUT} + N_{DUT}$$

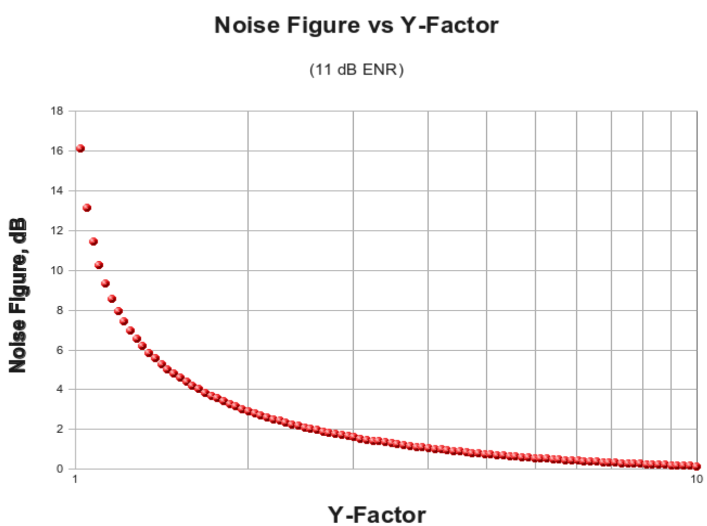
$$N_{off} = kT^{OFF}_{source} B G_{DUT} + N_{DUT}$$

$$N_{DUT} = kT_{DUT} B G_{DUT}$$



$$ENR_{dB} = 10\log\left(\frac{T^{ON}_{source} - T^{OFF}_{source}}{T_o}\right)$$

$$T_O = 290\text{K}\,(IEEE)$$

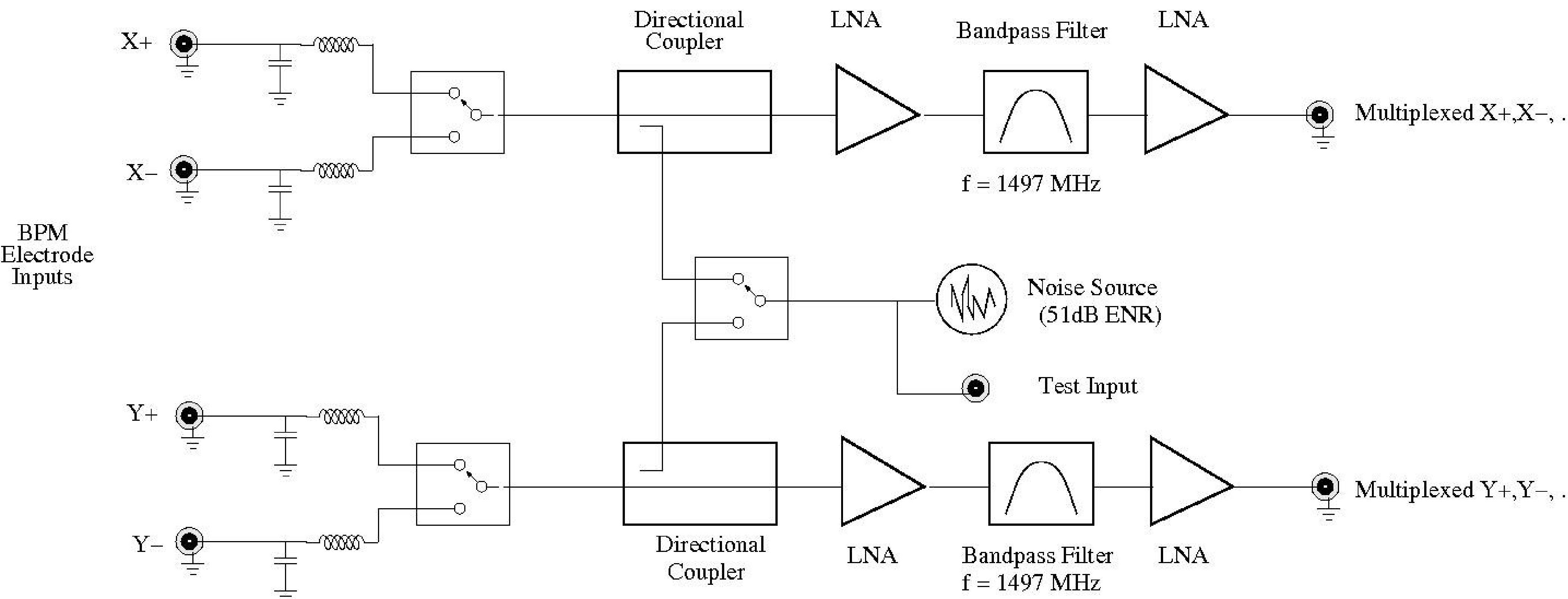


$$slope = kGB = \frac{N_{ON} - N_{OFF}}{T^{ON}_{source} - T_o}$$

$$Y = \frac{N_{ON}}{N_{OFF}}$$

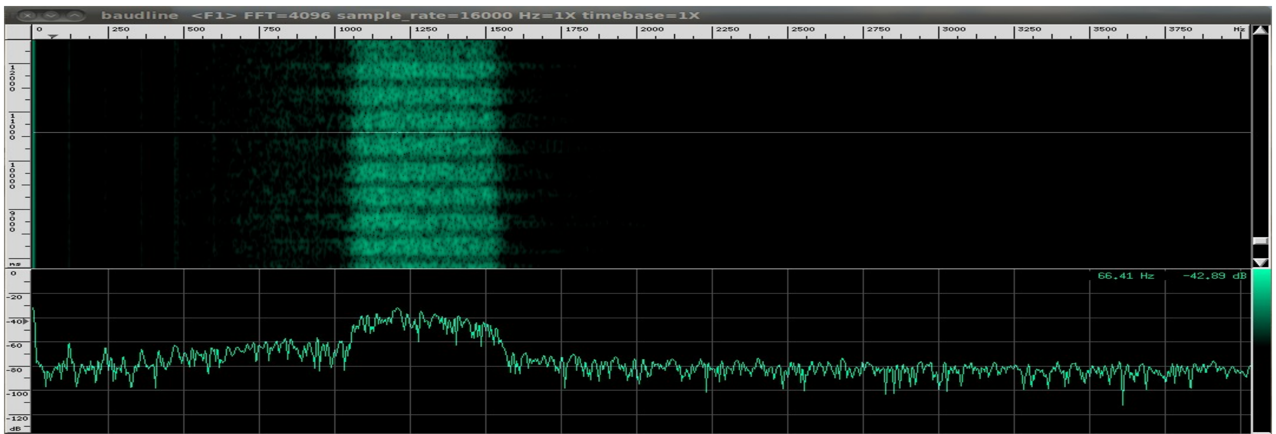
$$F_{dB} = ENR_{dB} - 10\log(Y - 1)$$

Implementation: Calibration Cell

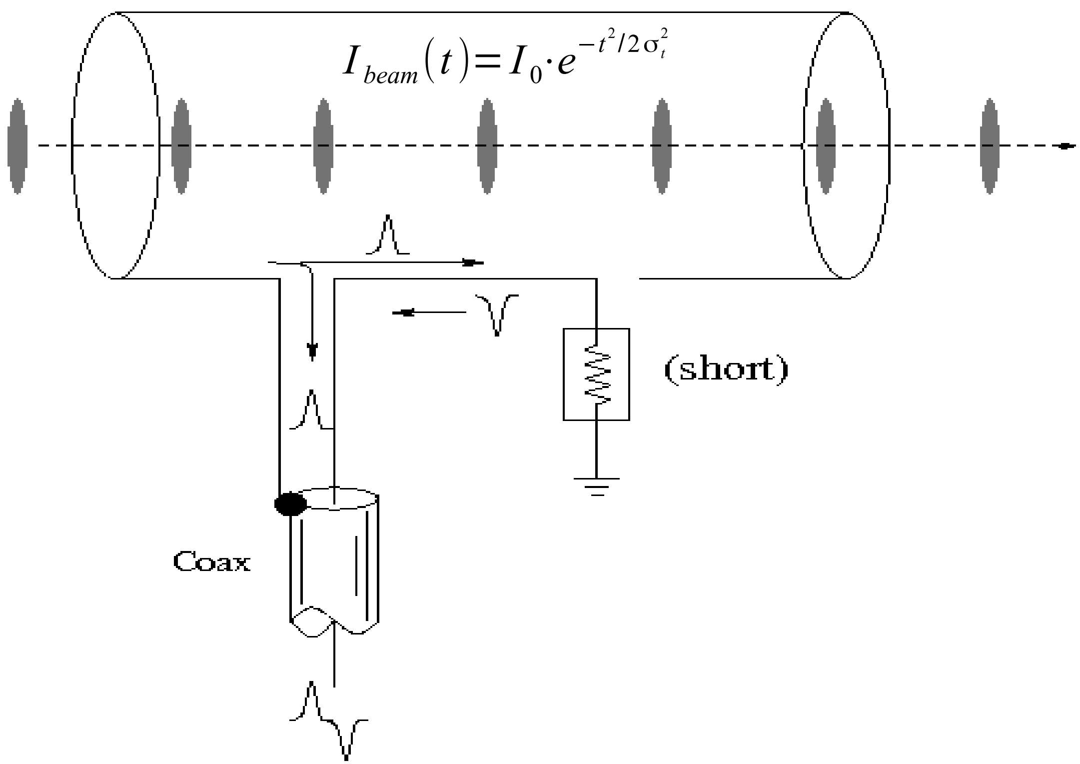


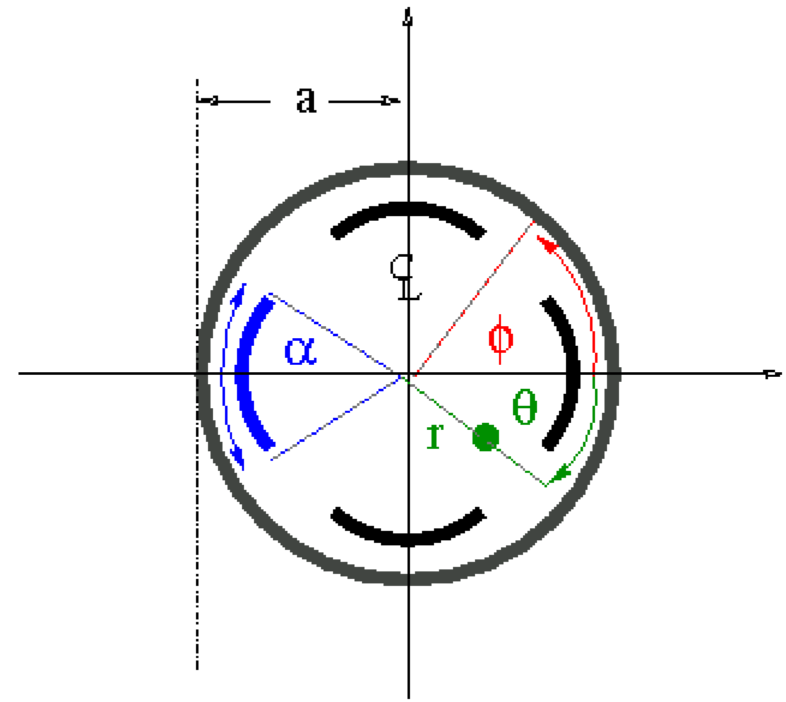
$$Gain \approx \log\left(N_{ON} - N_{OFF}\right)$$

$$NF \approx \log\left(\frac{N_{ON}}{N_{OFF}}\right)$$



Stripline BPMs





Voltage

$$U_1(t)=\frac{1}{2}\frac{\alpha}{2\pi}\cdot R_1\left(I_{beam}(t)-I_{beam}\left(t-\frac{2l}{c}\right)\right)$$

$$U_1(t)=\frac{Z_{strip}}{2}\frac{\alpha}{2\pi}\cdot\left(e^{-t^2/2\sigma_t^2}-e^{-(t-2l/c)^2/2\sigma_t^2}\right)\cdot I_0$$

Current

$$j_{\Im}(\varphi)=\frac{I_{beam}}{2\pi a}\cdot\left(\frac{a^2-r^2}{a^2+r^2-2ar\cdot\cos(\varphi-\theta)}\right)$$

$$I_{\Im}=\int_{-\alpha/2}^{+\alpha/2} a\cdot j_{\Im}(\varphi)\,d\varphi$$

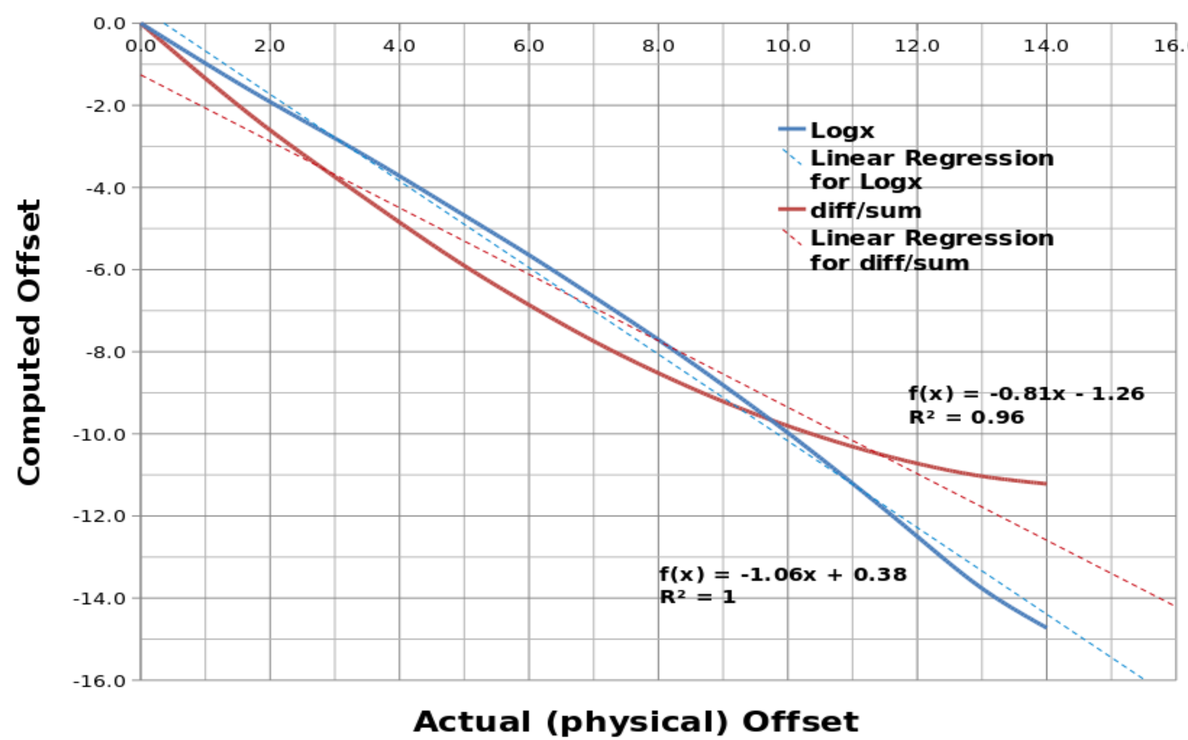
$$Z_t(\omega)=\frac{Z_{strip}\cdot\alpha}{4\pi}\cdot e^{-\omega^2\sigma_t^2/2}\cdot\sin(\omega l/c)\cdot e^{i(\pi/2-\omega l/c)}$$

Transfer Impedance

Resolution Analysis

Difference-over-sum

$$X = \frac{a}{2} \cdot \frac{V_L - V_R}{V_L + V_R}$$



$$\frac{\partial X}{\partial V_R} = \frac{a \cdot V_L}{(V_R + V_L)^2}$$

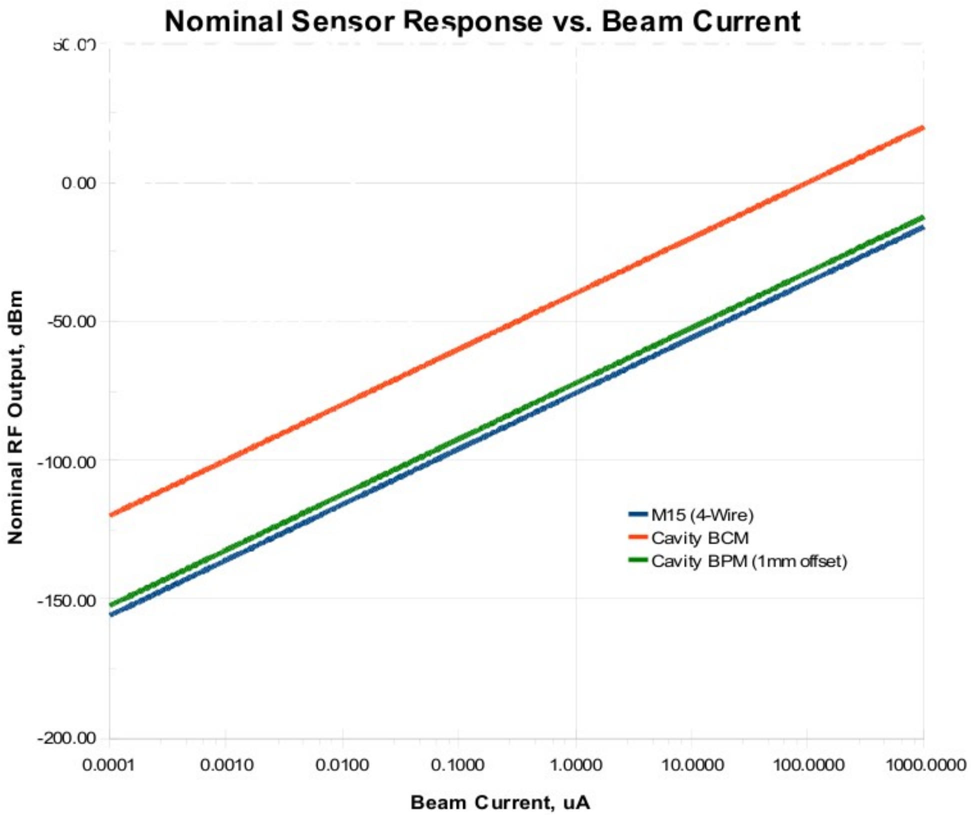
$$\frac{\partial X}{\partial V_R} = \frac{-a \cdot V_L}{(V_R + V_L)^2}$$

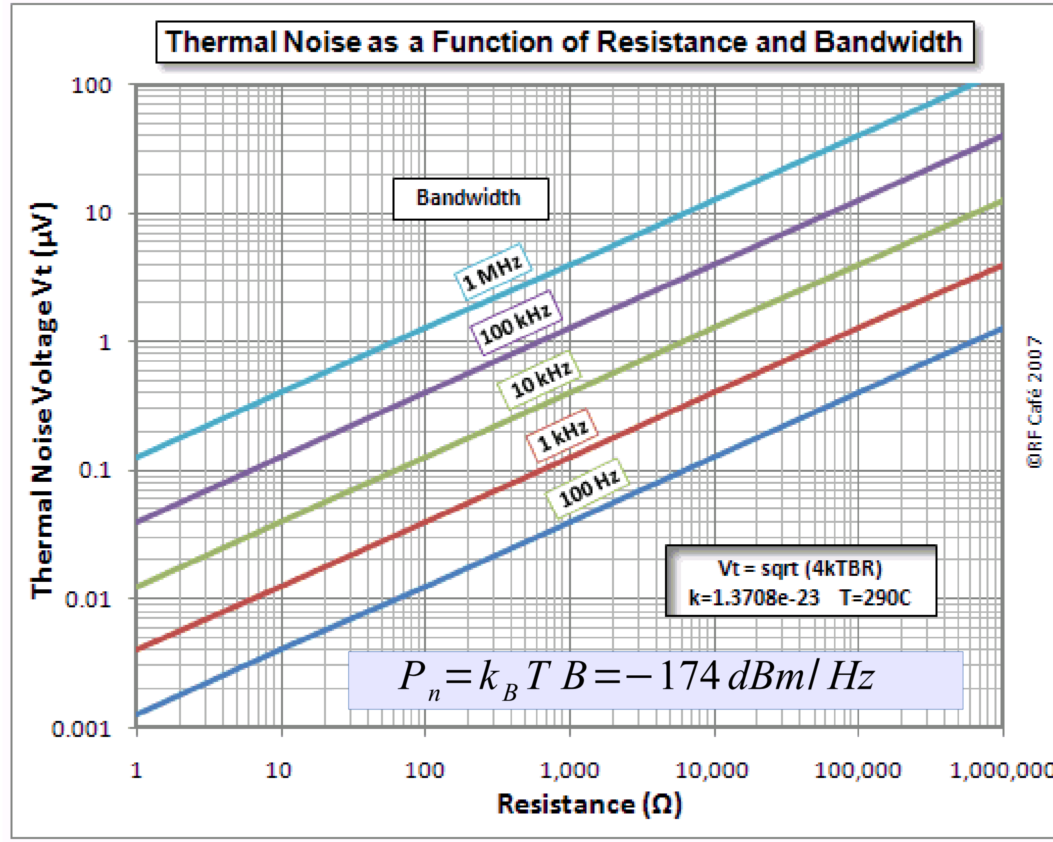
$$\sigma_X = \frac{a}{(V_R + V_L)^2} \cdot \sqrt{V_L^2 \delta V_R^2 + V_R^2 \delta V_L^2}$$

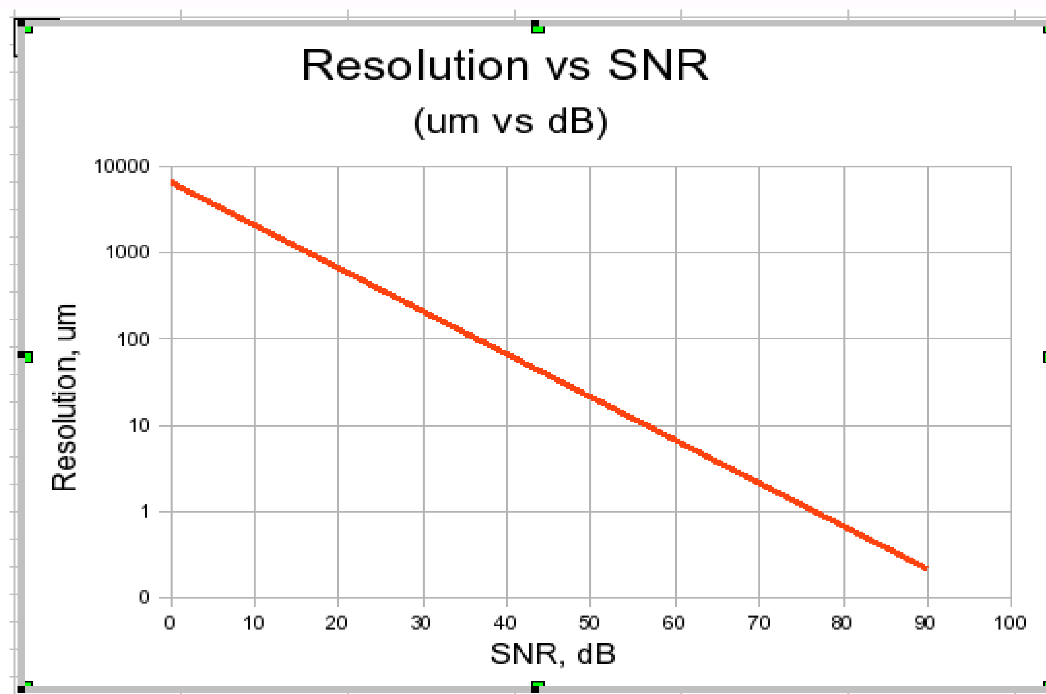
At boresight....

$$\sigma_X = \frac{a}{2} \cdot \frac{\sqrt{2}\sigma_v}{2\mathrm{V}} = \frac{a}{2\sqrt{2}} \cdot \frac{1}{\sqrt{SNR}}$$

$$SNR = \frac{P_s}{P_n} = \frac{V_s^2}{V_n^2}$$







Typical SL output power = -102 dBm - 100nA

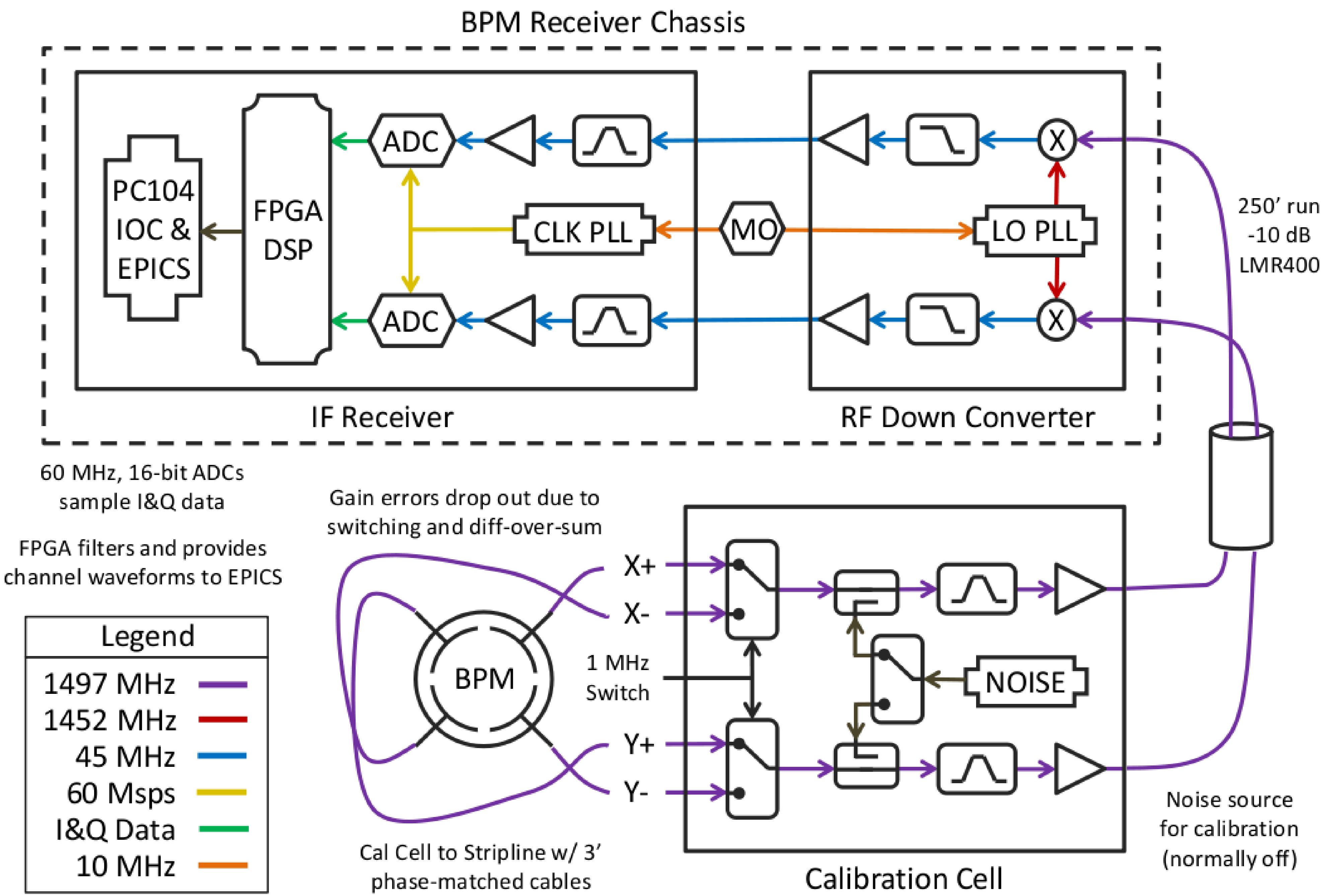
Expected noise power = -160 dBm - 10 Hz

SNR = 58 dB (B = 10 Hz)

σ = 10 um, I = 100 nA, B = 10 Hz

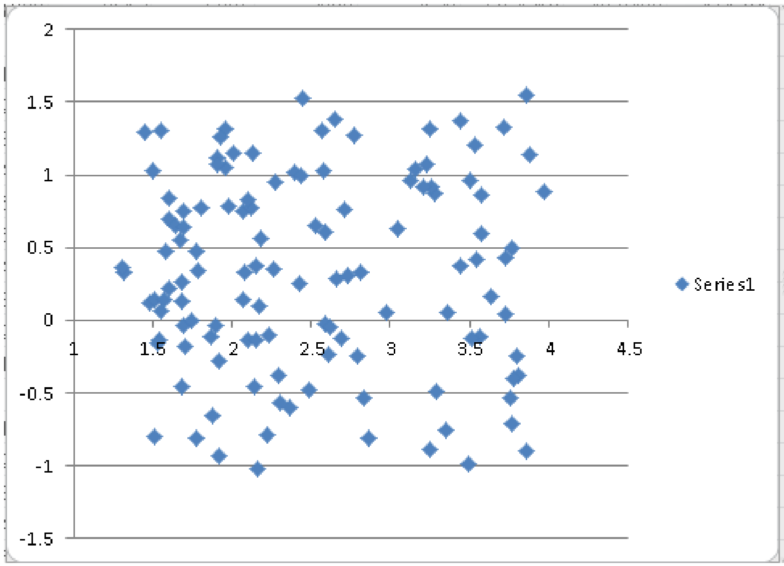
Note: Resolution is NOT accuracy!!

Stripline BPM Electronics

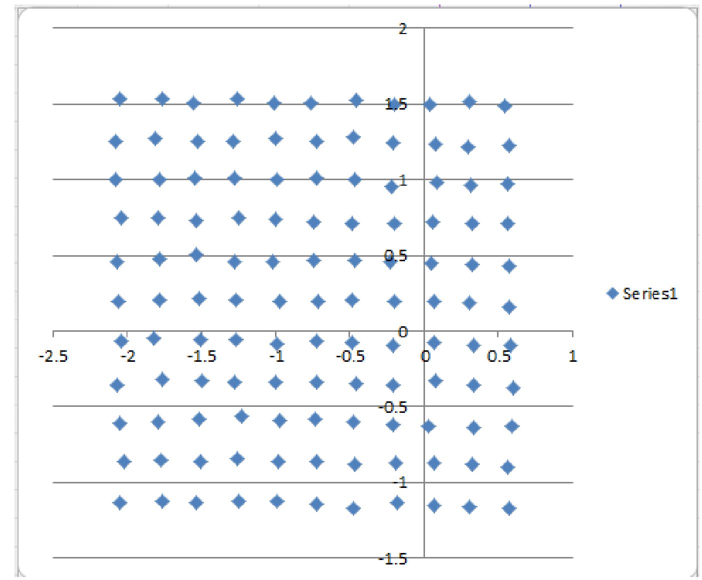


BPM Test Stand Stripline Electronics Testing

~30nA @ 10 Hz

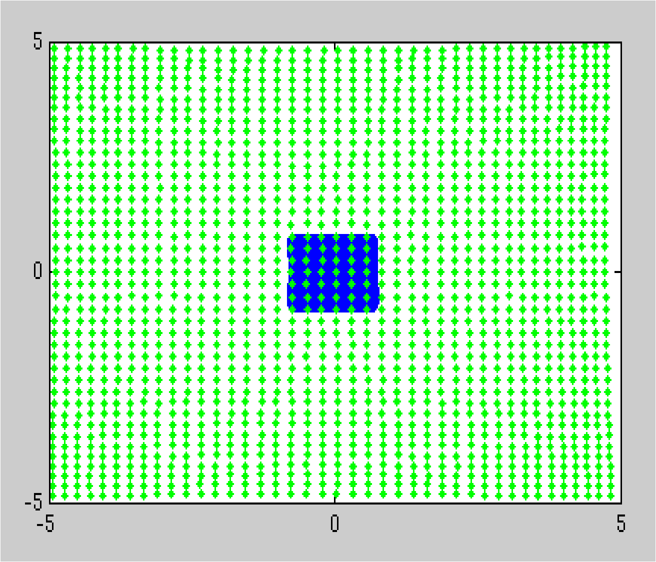


~30 nA @ 1 Hz

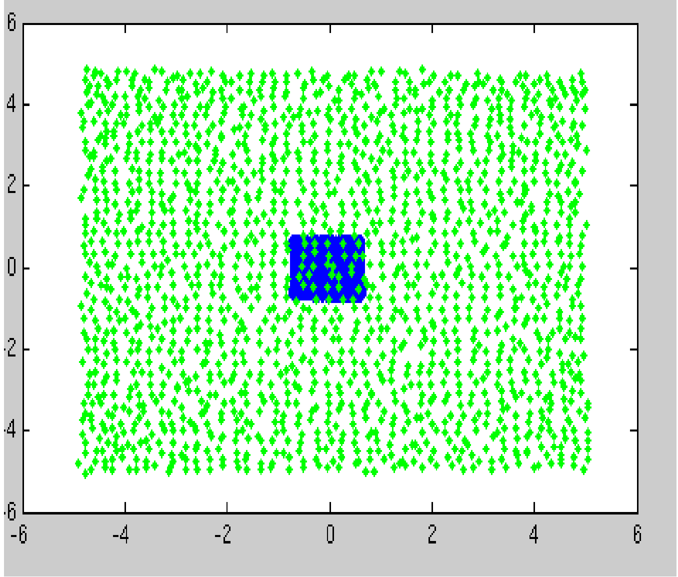


- Improving the signal-to-noise improves performance
- Filtering down to 1 Hz instead of 10 Hz gives an improvement factor of about 3 (excessive noise is due to algorithm)
- This square root of bandwidth improvement holds true as long as the noise is Gaussian
- Scan: 250 um/step, yielding 10s of um resolution (per calc)

Resolution

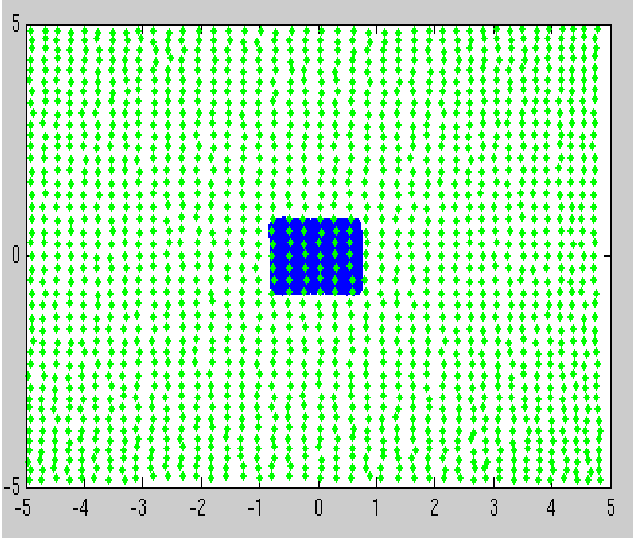


I ~ 800nA; B = 10 Hz

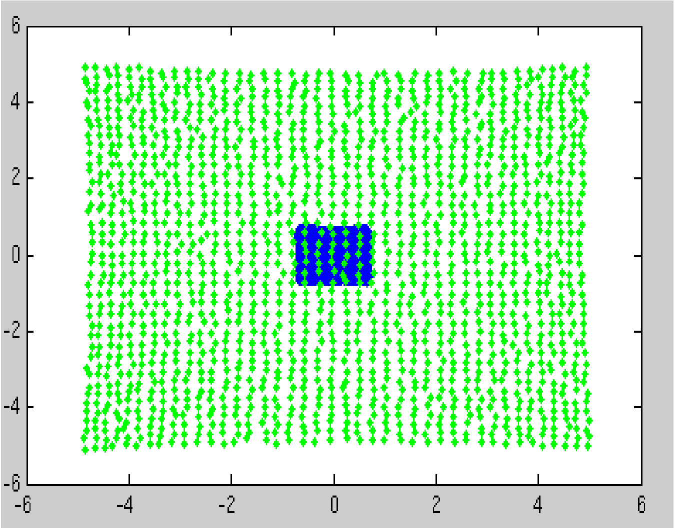


I ~ 100nA; B = 100 Hz

Step = 250 um



I ~ 100nA; B = 10 Hz

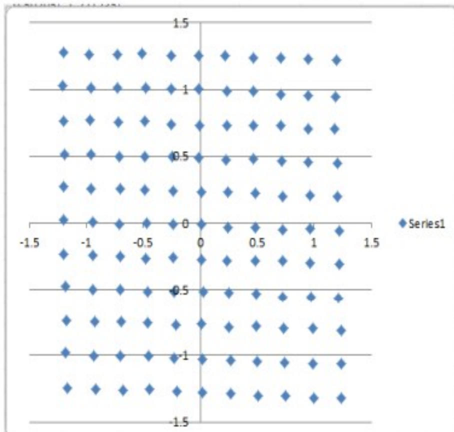


I ~ 70nA; B = 10 Hz

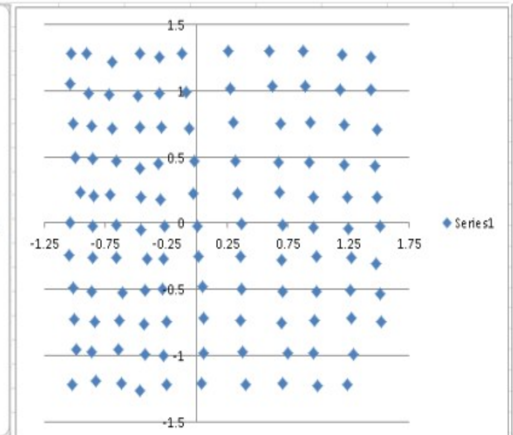
Resolution (cont.)

SEE Electronics with M15 (Pulsed, -59dBm @ source = 800nA, -75dBm)

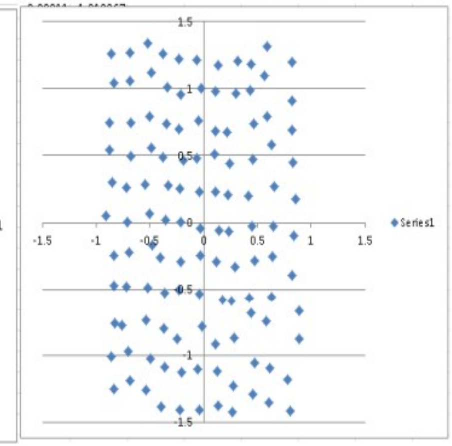
-65dBm = 400 nA



-71dBm = 200nA

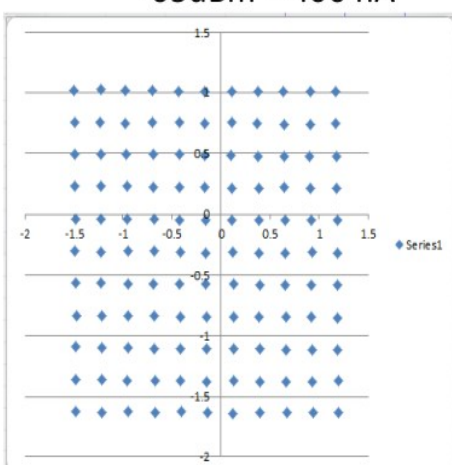


-77dBm = 100nA

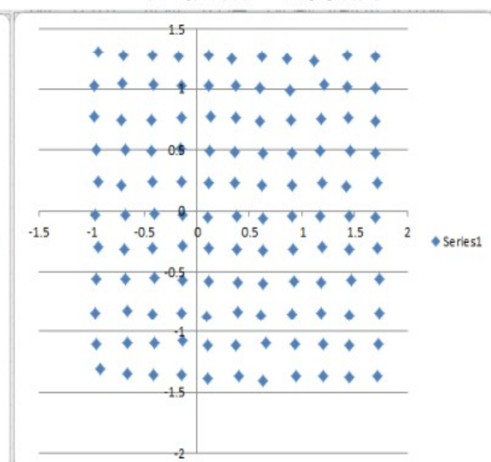


12 GeV Electronics with Stripline (10Hz)

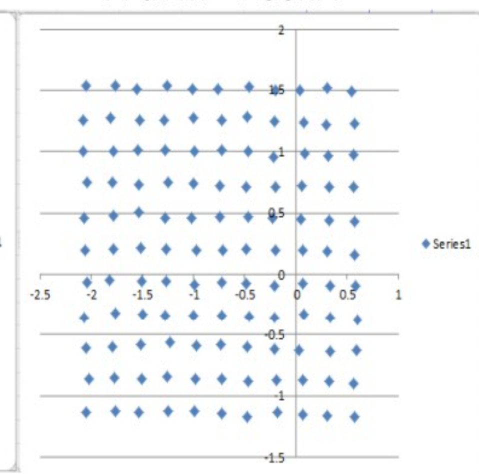
-65dBm = 400 nA



-71dBm = 200nA



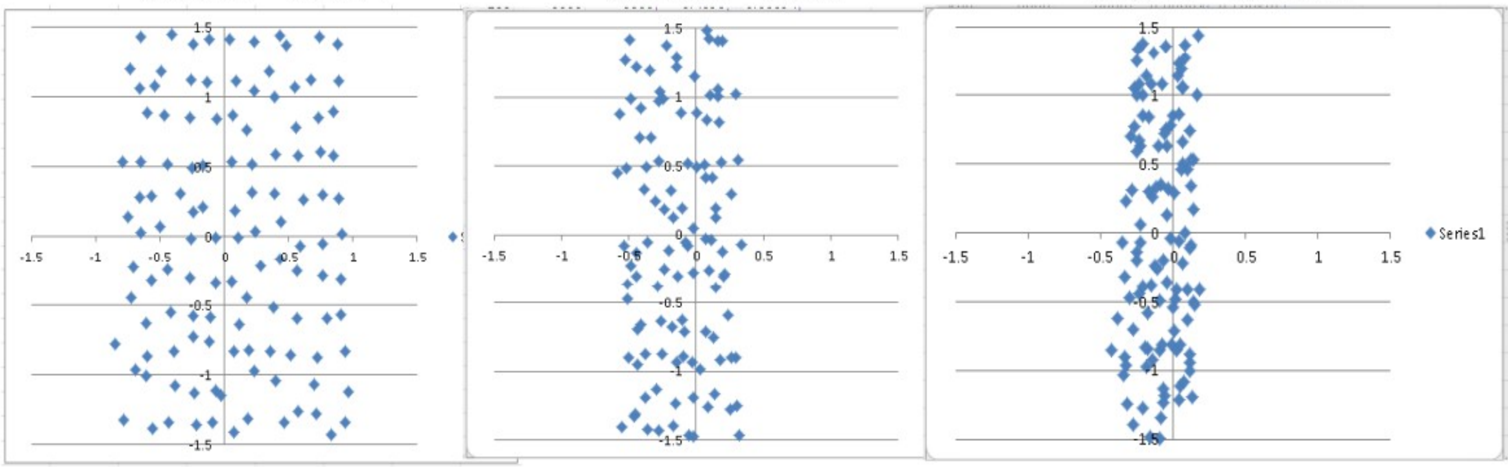
-77dBm = 100nA



Resolution (cont.)

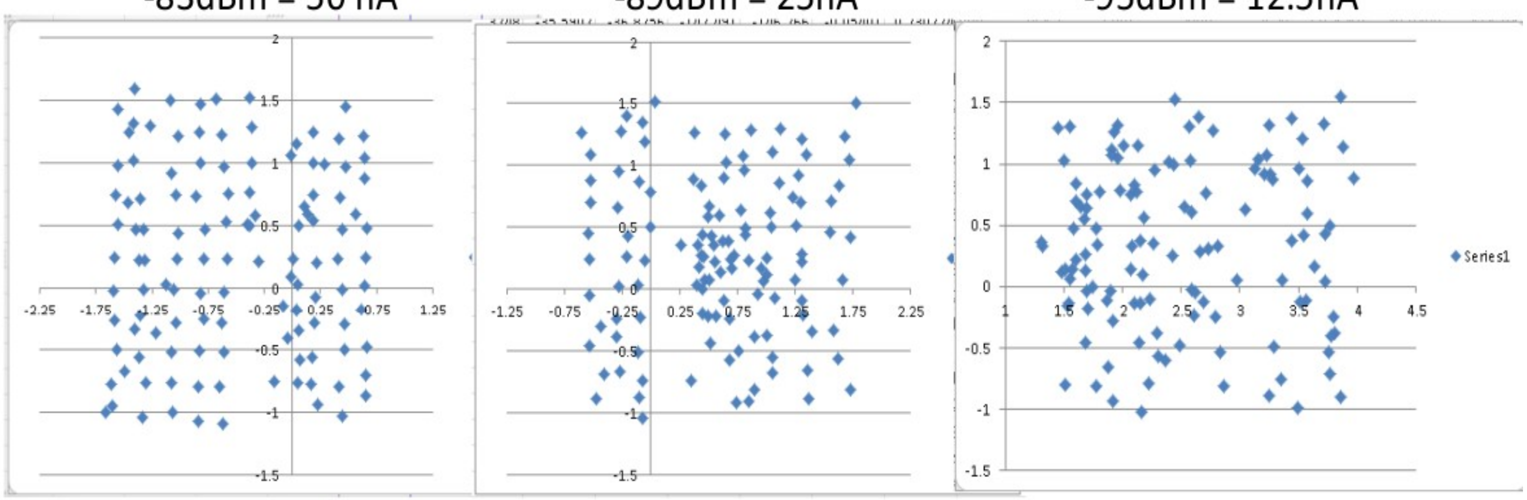
SEE Electronics with M15 (Pulsed, -59dBm @ source = 800nA, -75dBm)

-83dBm = 50 nA | -89dBm = 25nA | -95dBm = 12.5nA



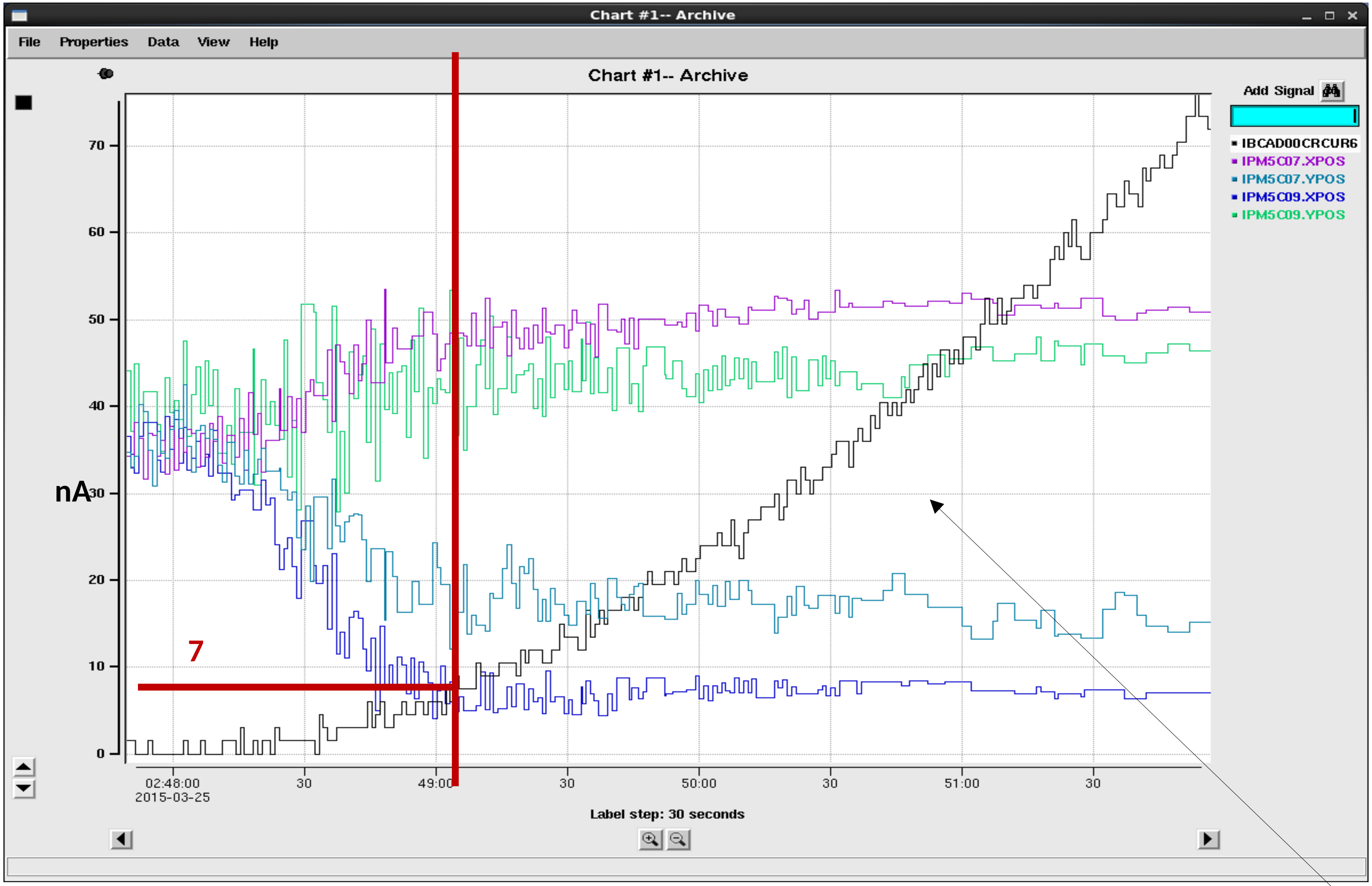
12 GeV Electronics with Stripline (10Hz)

-83dBm = 50 nA | -89dBm = 25nA | -95dBm = 12.5nA



Premature signal breakup mainly due to algorithm inefficiencies.....

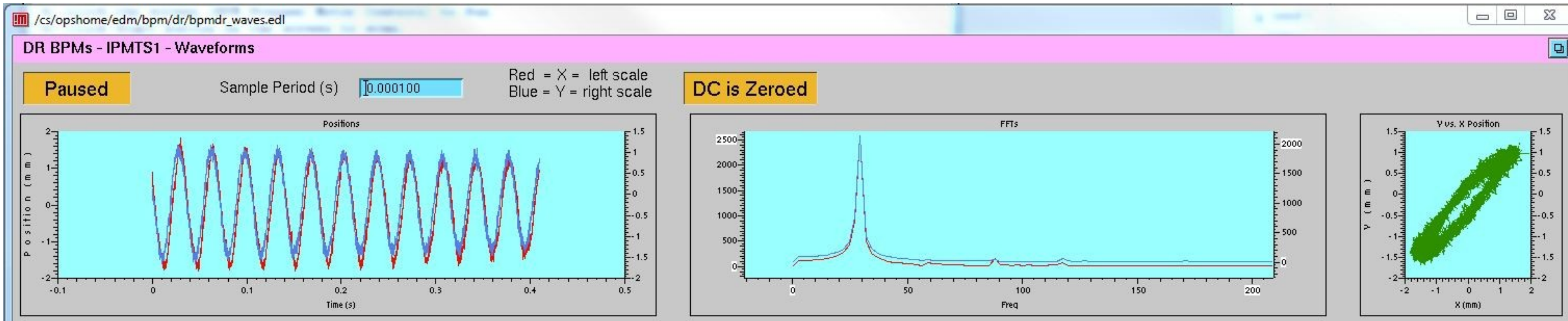
Stripline BPM Testing

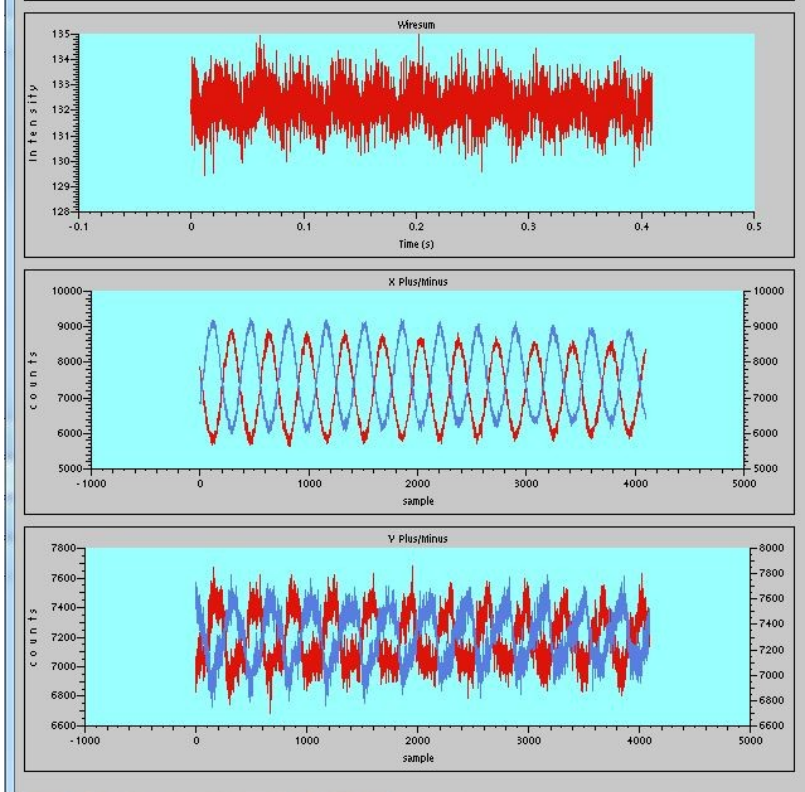


- Hall D current in black ramping from 0 to 75 nA
- The 5C07 and 5C09 BPM positions settle at ~7nA and accuracy improves as the signal-to-noise goes up (bandwidth of ~1Hz)

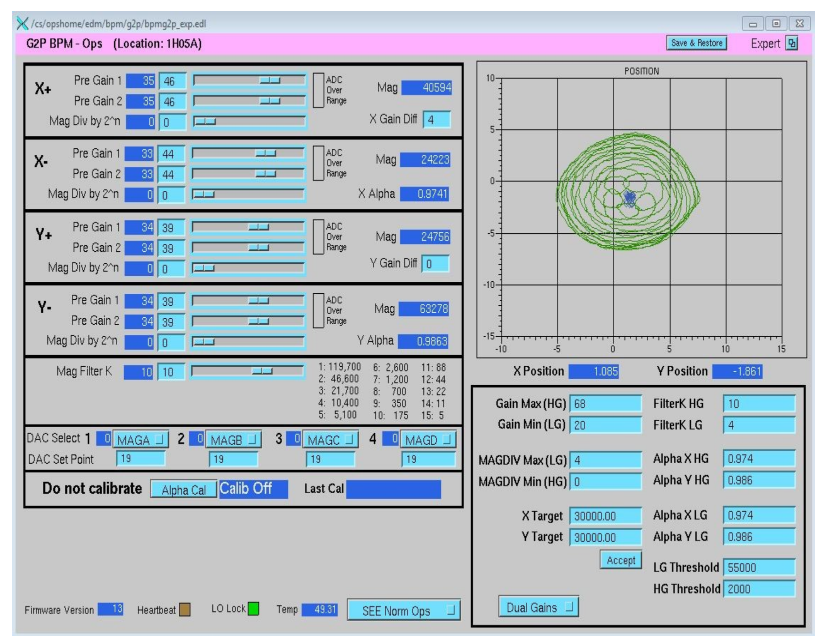
Stripline BPM Software

Screen Shot of ~30Hz Oscillation (Time & Frequency Plots)

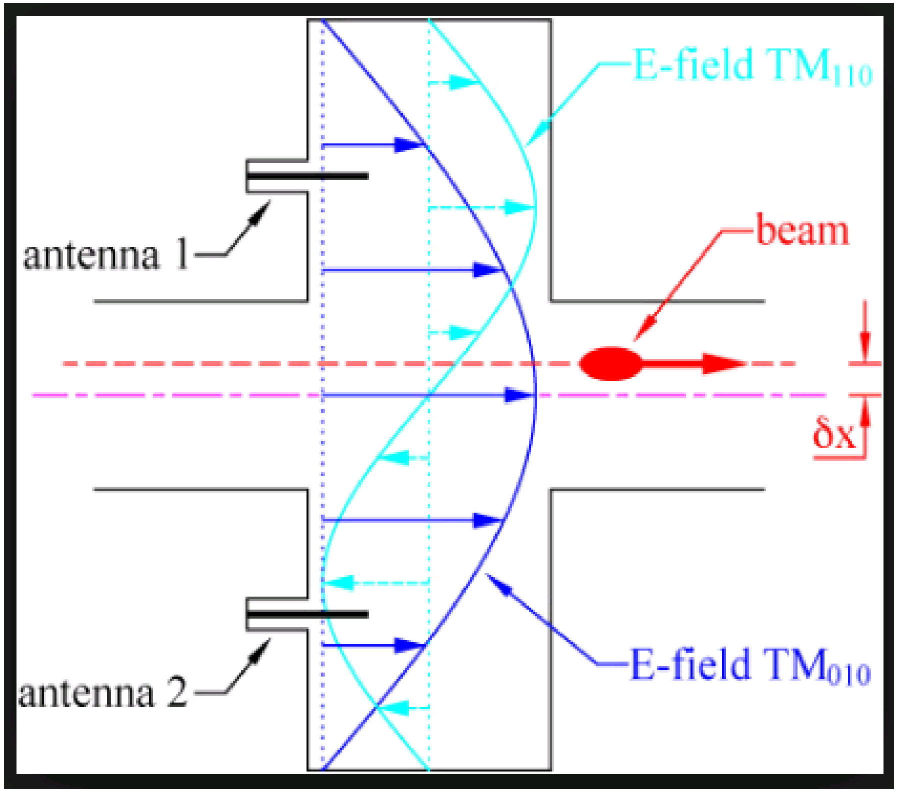


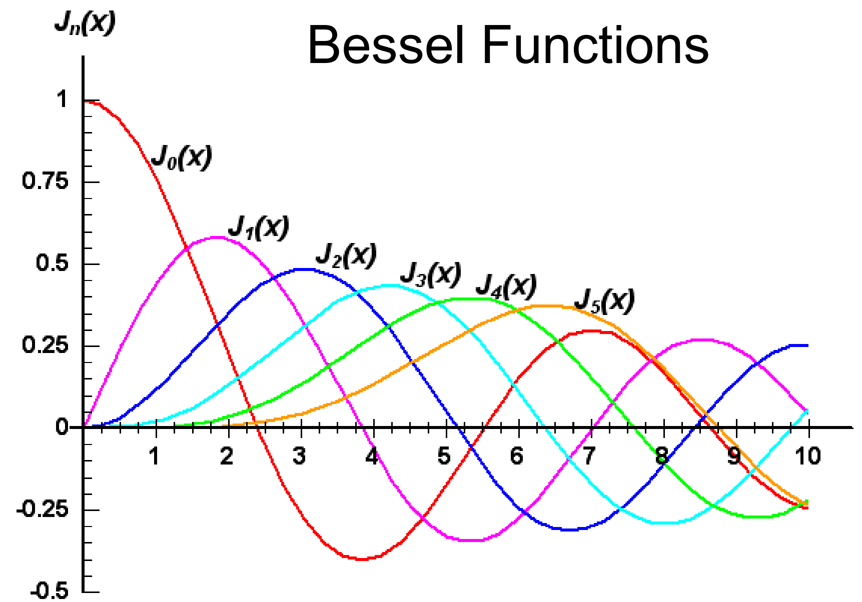


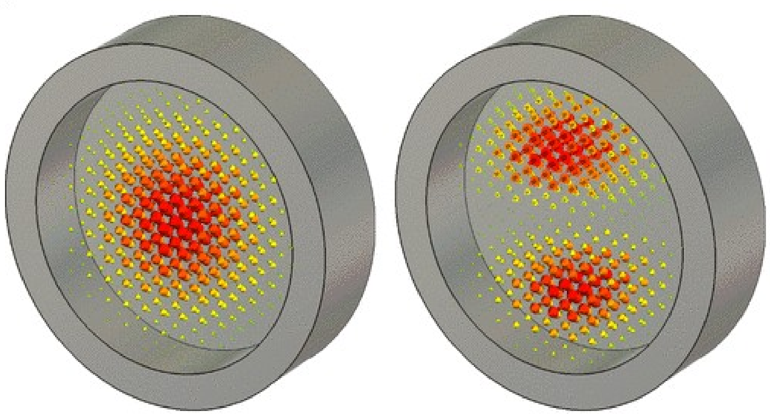
G2P Rastered Position



Cavity Modes







(a)TM_{010}. (b)TM_{110}.

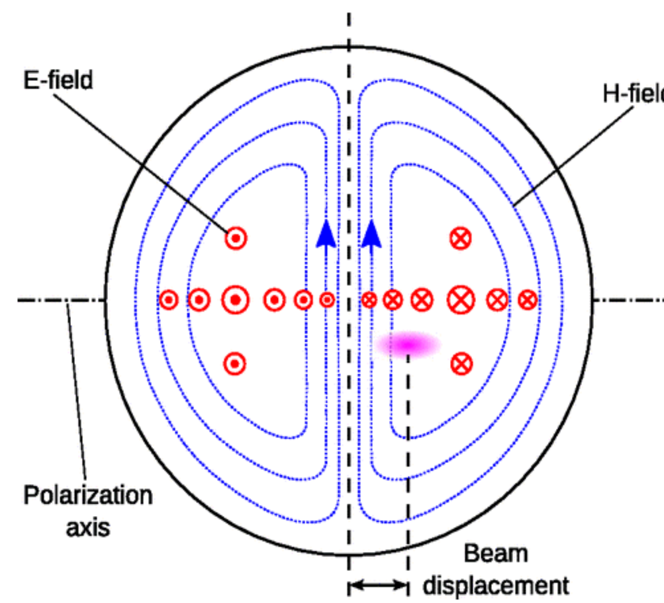
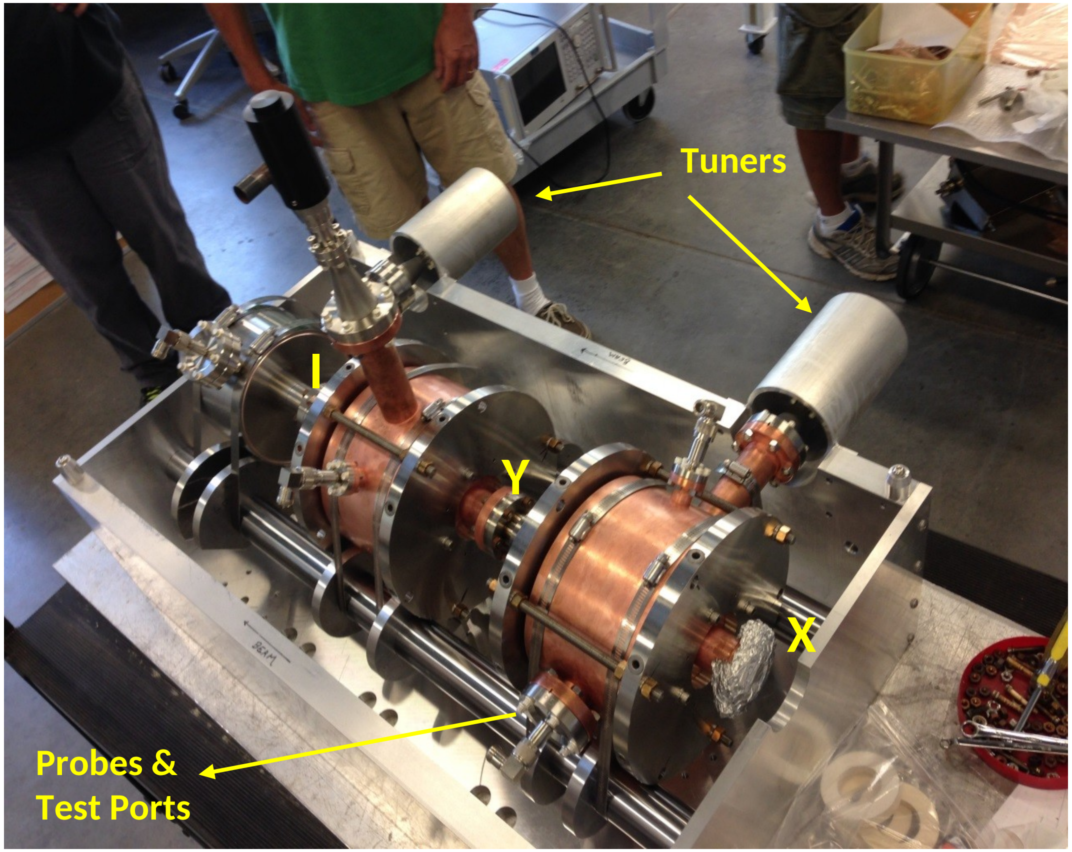


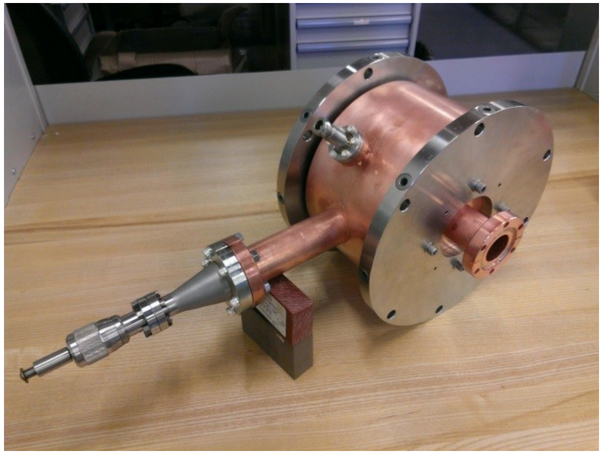
Figure 1

Cavity Beam Position Monitors

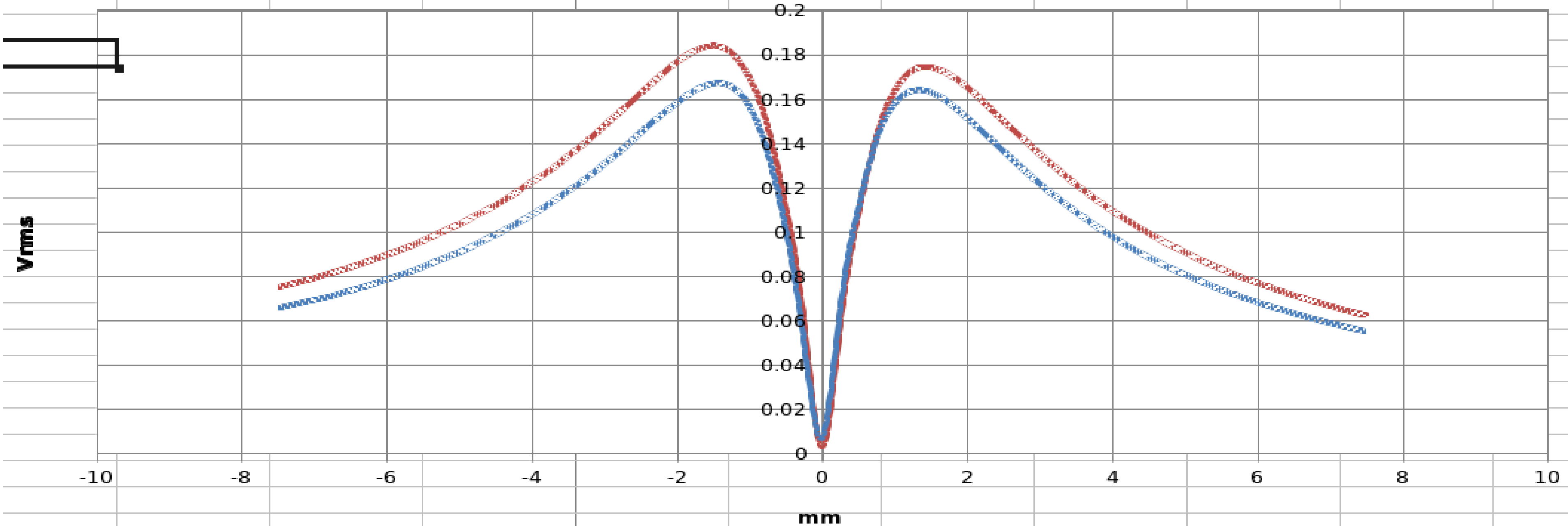
- Electromagnetic field excited by beam
  - TM110 Mode
  - Probe antenna picks up field
  - Test also used to excite field
  - Copper coated to increase Q
  - **Signal disappears at boresight!**
- Tuning port for centering at 1497MHz
  - Annually/vacuum broken
  - Temperature stabilized
- 1497 MHz Probe signals get down converted
- Positions go as X/I and Y/I
- IPM5C11A & IPM5C11C

P = - 92 dBm @ 100um - uA

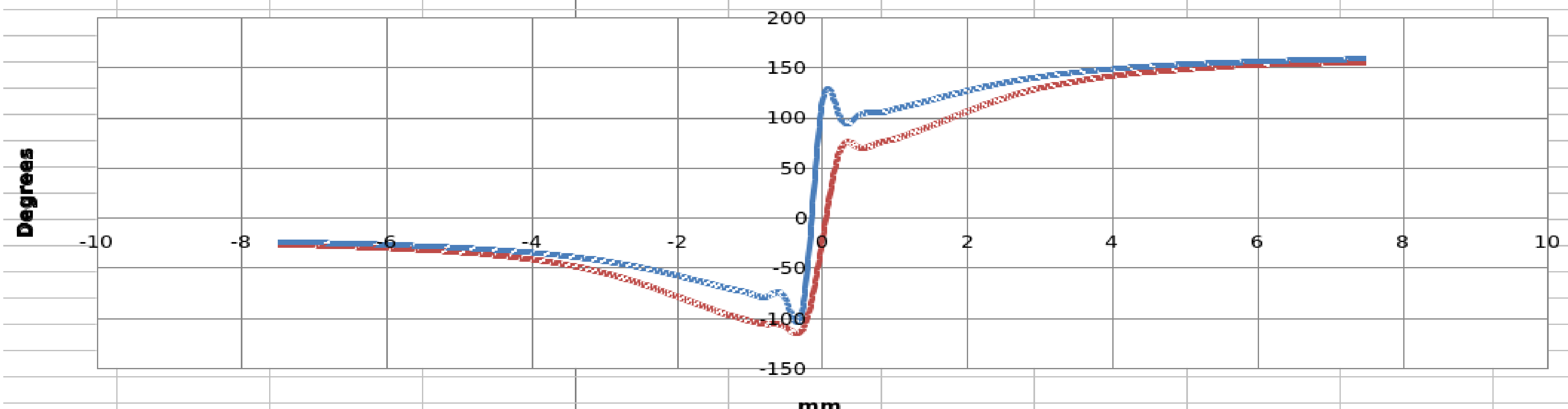




Magnitude Response From +10dBm G-Line Scan (Vector Voltmete



Phase Response From +10dBm G-Line Scan (Vector Voltmeter)



Resolution Analysis

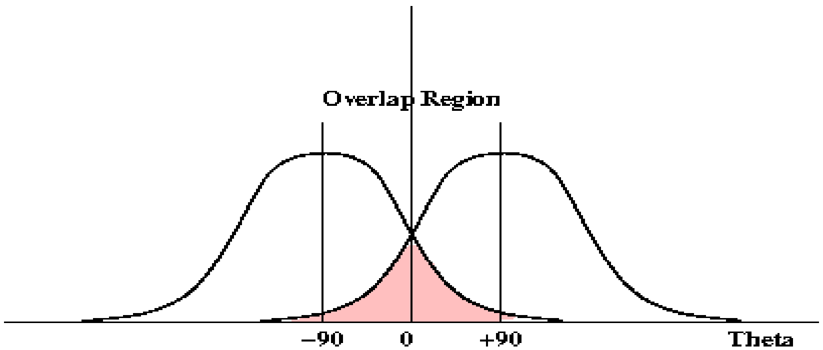
$$X = \frac{18.7 \cdot V_{meas}}{I_{beam}}$$, microns

(k = 18.7 derived from MAFIA simulations, SS304)

$$V_{meas} = uVolts$$
$$I_{beam} = uAmps$$

Compared to stripline, cavity performance is *potentially* ~24 times better (100 nA, B = 10 Hz)

$$\sigma_X = \frac{18.7 \cdot dV}{I_{beam}}$$



For NF = 4 dB, B = 10 Hz, I = 100 nA:

$$\sigma_X = 0.417\, um$$

"Baggage" imposed by non-linear phase detection

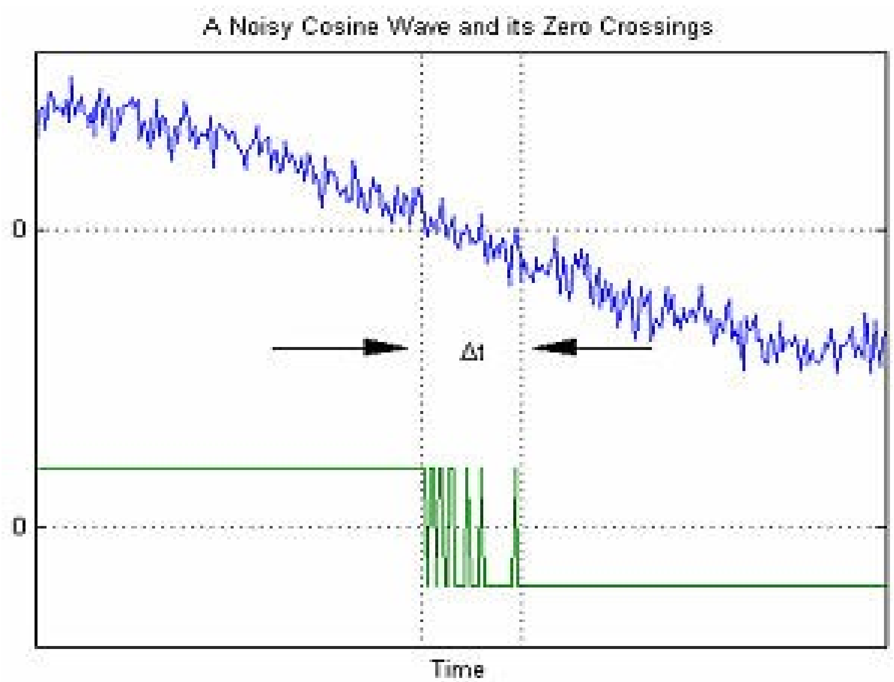
Dead-band at boresight = 2σ_X

Performance scales as I, sqrt(B)

Cu plating improves Q by 10, with (theoretically) equal improvement in resolution

Phase Detection Penalty

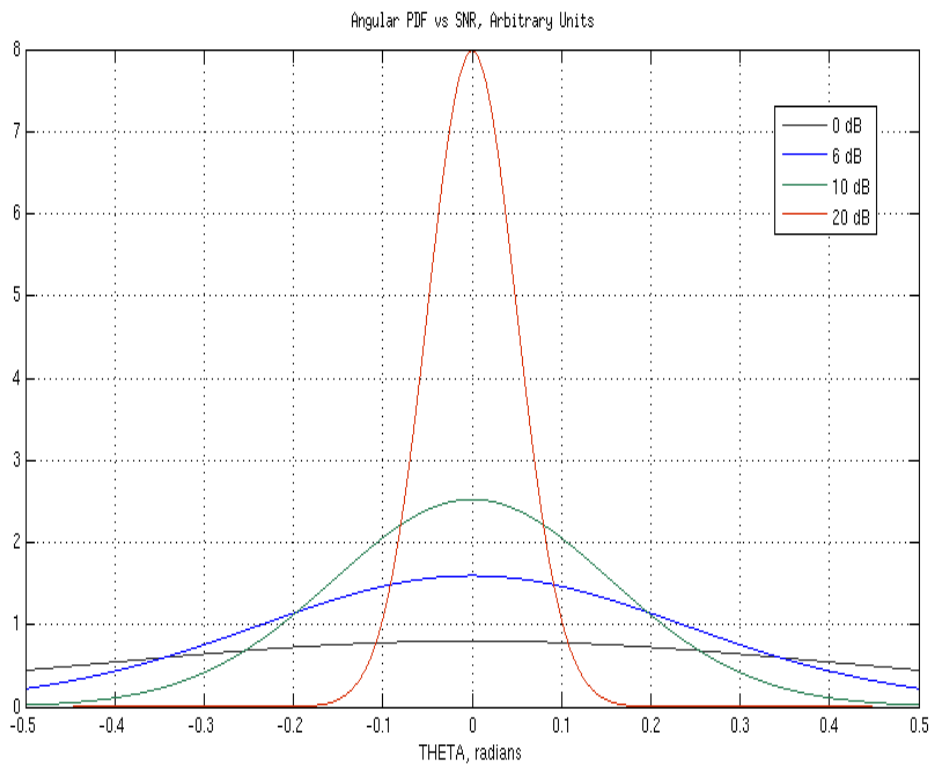
(Tech Note pending...)

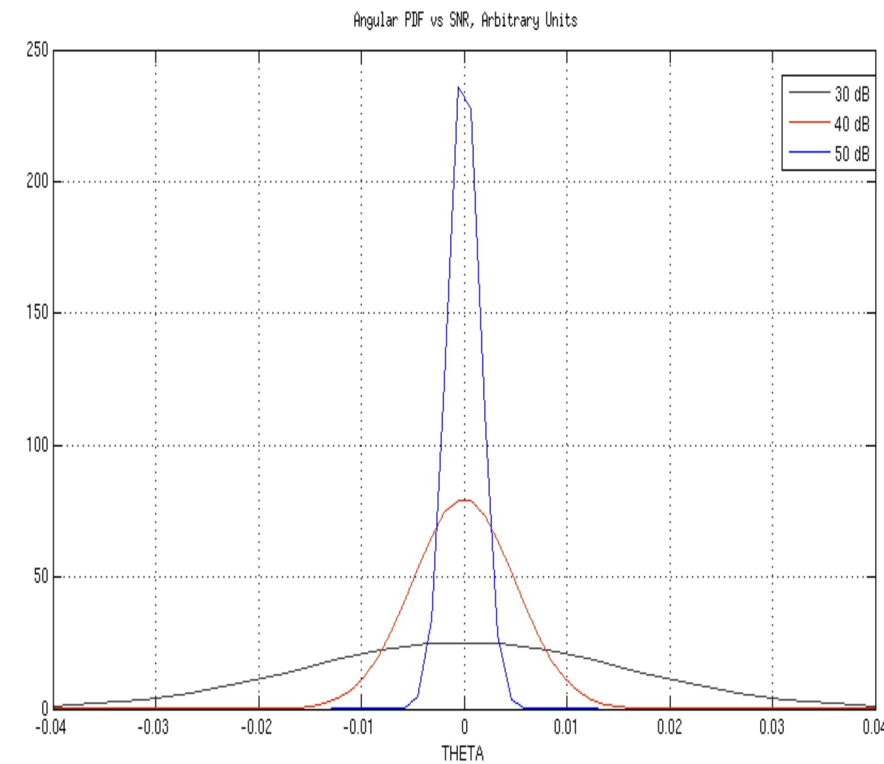


Angular PDF vs SNR.

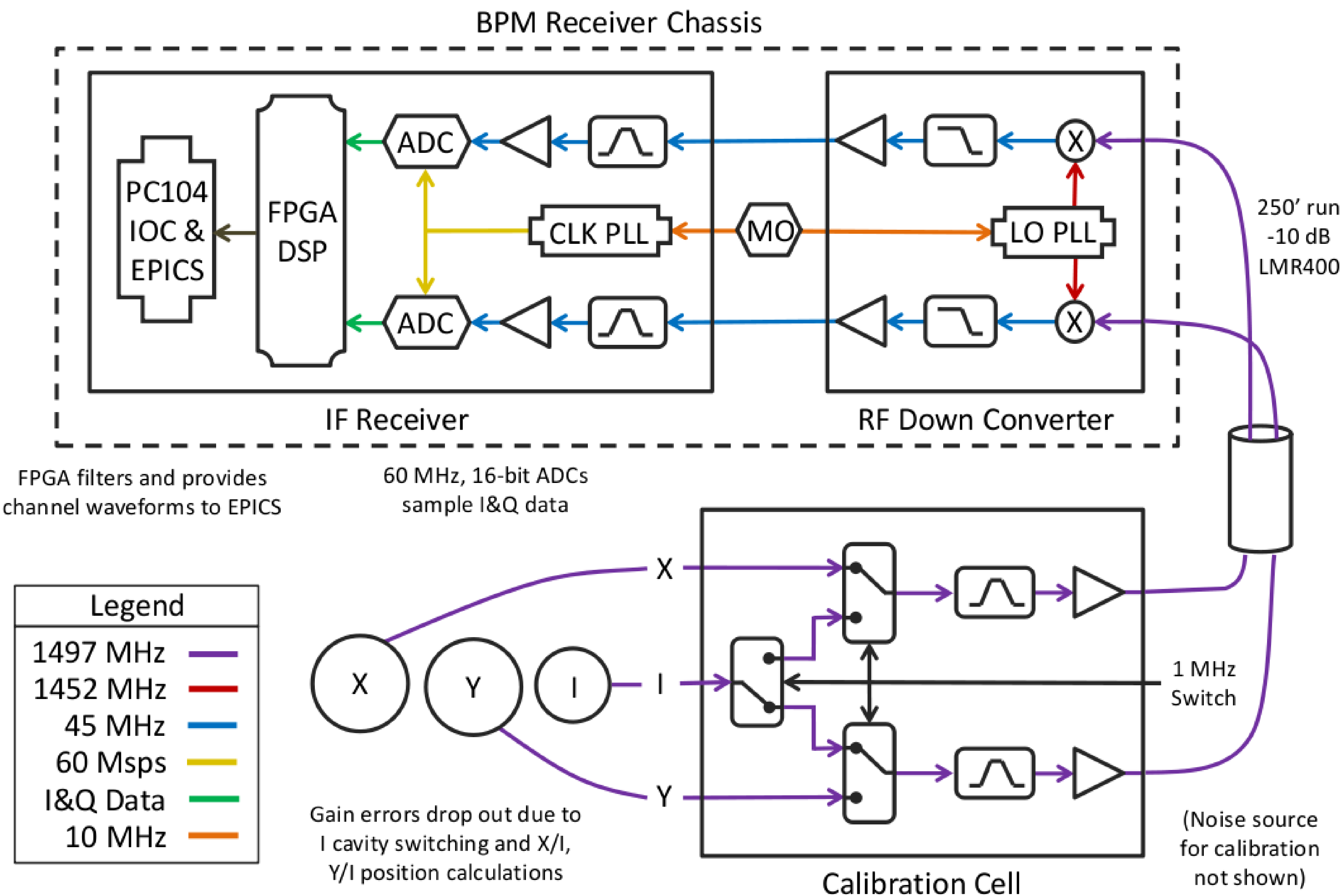
$$p_{\theta_r}(\theta_r)=\frac{1}{2\pi}e^{-2\gamma_s \sin^2\theta_r}\int_0^{\infty} V_r e^{-\frac{(V_r-2\sqrt{\epsilon_s}\cos(\theta_r))^2}{2}}dV$$

~ 6-10 dB req'd to detect phase jump



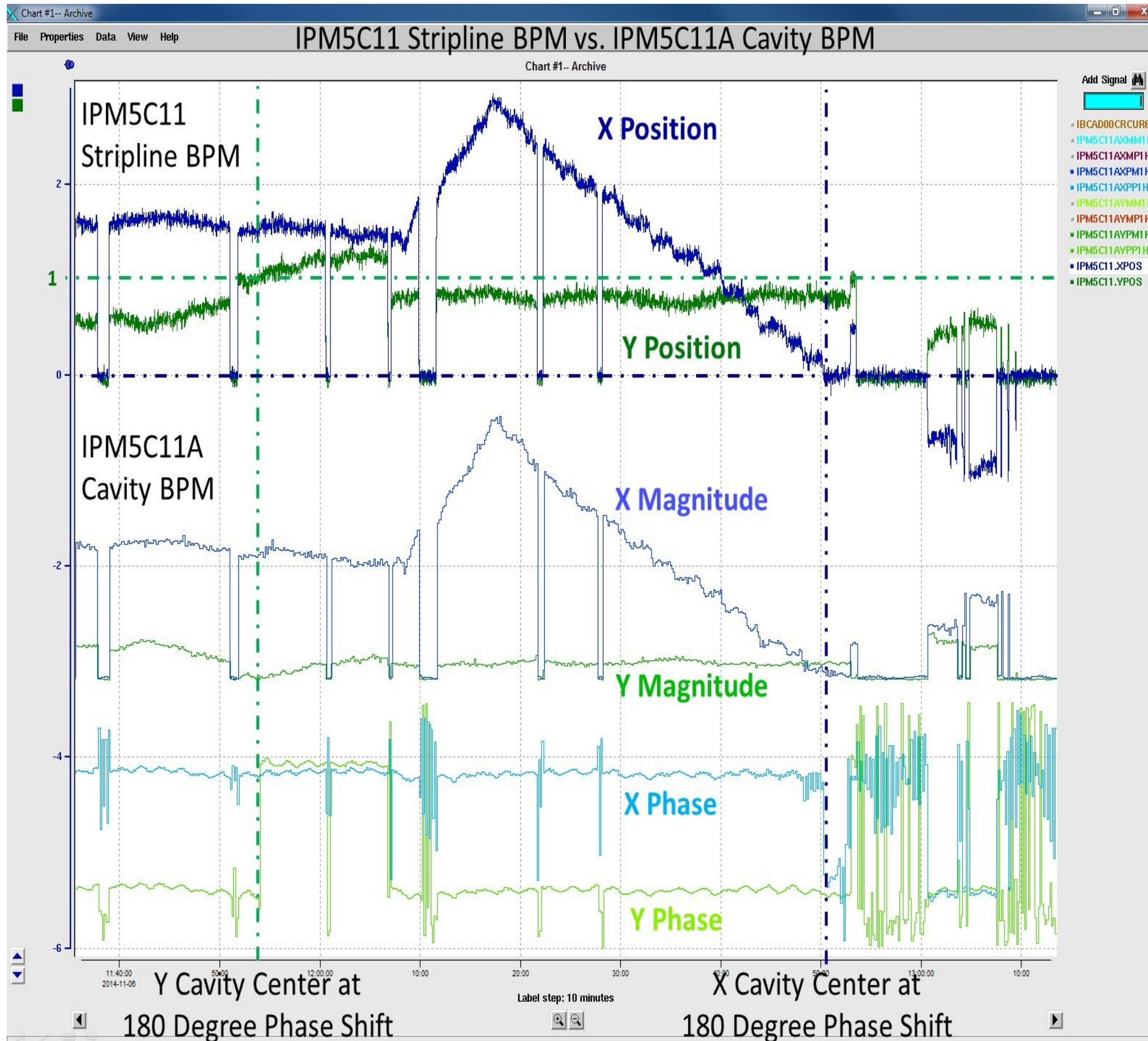


Cavity BPM Electronics



Cavity BPM Testing ('5C11)

- Behaves as expected vs. Stripline BPM
- Signal goes to zero at cavity center
  - Phase shifts 180 degrees
  - Phase used to determine sign of position
- More commissioning time needed
- Aim to have valid positions down to 100pA beam currents at 1Hz



Hall A BCM Commissioning Run, 4/15

<u>"Double-Difference"</u>

$$DD = \frac{V_{I1} - V_{I2}}{V_{I1} + V_{I2}}$$

$$\sigma_I = \frac{1}{2} \cdot \frac{\sqrt{2}\sigma_V}{2V} = \frac{1}{2\sqrt{2}} \cdot \frac{1}{\sqrt{SNR}}$$

Linearity

SNR Convergence

<0.5% @ 40 uA

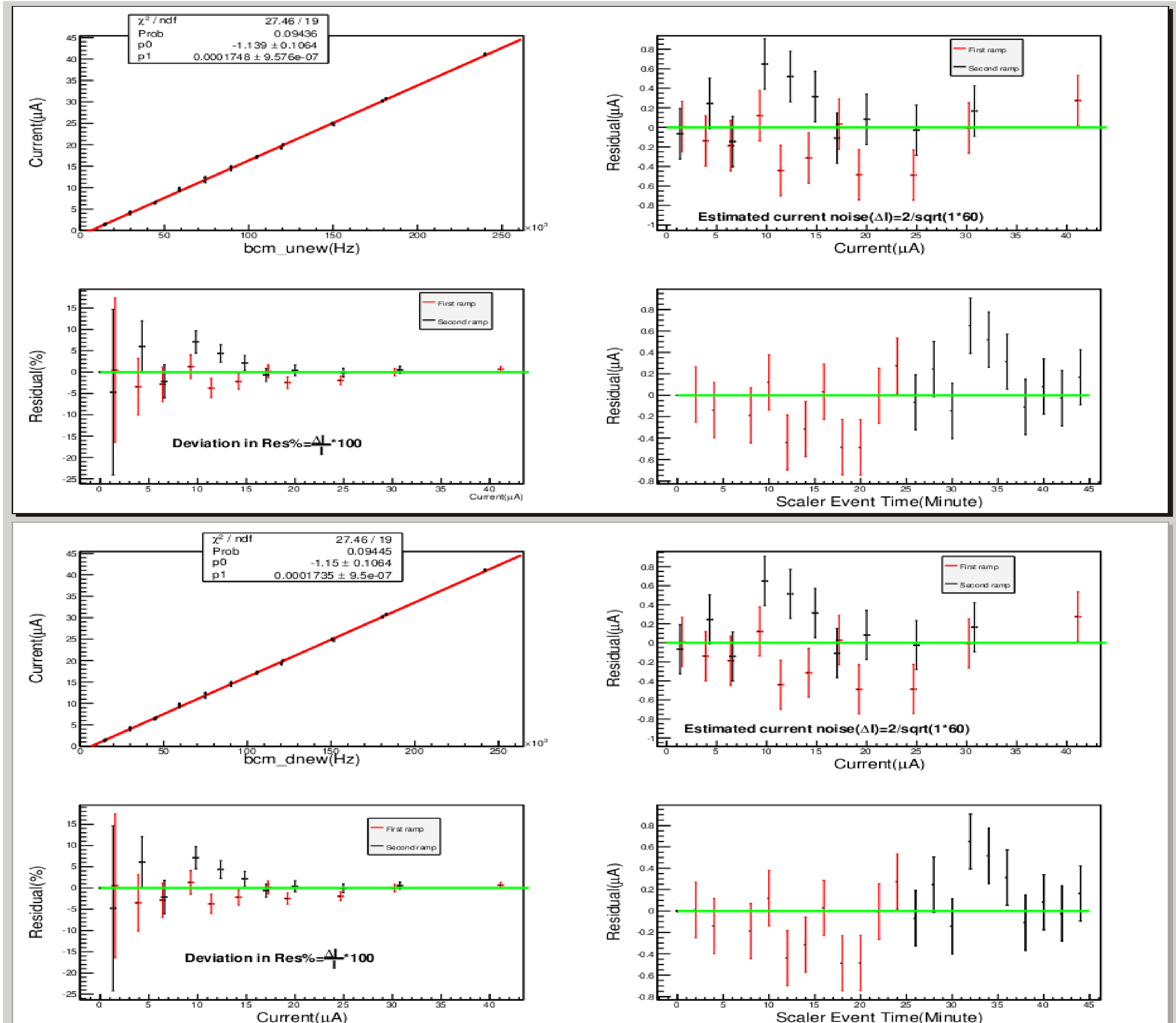
B = 10kHz

40 dB coupling

18-bit DAC

~40 dB eff. SNR

<0.5% @ 40 uA



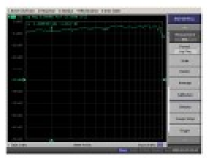
Application Of Goubau Surface Wave Transmission Line For Improves Bench Testing Of Diagnostic Beamline Elements*

J. Musson, K. Cole, Thomas Jefferson National Accelerator Facility, Newport News, VA
S. Rubin, Rubytron, Port Chester, NY

Abstract

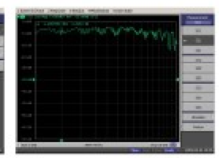
In-air test fixtures for beamline elements typically utilize an X-Y positioning stage, and a wire antenna excited by an RF source. In most cases, the antenna contains a standing wave, and is useful only for coarse alignment measurements in CW mode. A surface-wave (SW) based transmission line permits RF energy to be launched on the wire, travel through the beamline component, and then be absorbed in a load. Since SW transmission lines employ travelling waves, the RF energy can be made to resemble the electron beam, limited only by ohmic losses and dispersion. Although lossy coaxial systems are also a consideration, the diameter of the coax introduces large uncertainties in centroid location. A SW wire is easily constructed out of 200 micron magnet wire, which more accurately approximates the physical profile of the electron beam. Benefits of this test fixture include accurate field mapping, absolute calibration for given beam currents, Z-axis independence, and temporal response measurements of sub-nanosecond pulse structures. Descriptions of the surface wave launching technique, transmission line, and instrumentation are presented, along with measurement data.

Goubau Line/BPM Test Fixture



Insertion Loss (S21) plot of 1.6 mm diameter RadWire

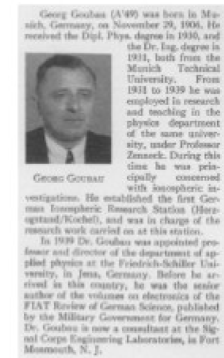
Return Loss (S11) plot of 1.6 mm diameter RadWire



Insertion Loss (S21) plot of 160 um diameter RadWire

Return Loss (S11) plot of 160 um diameter RadWire

Goubau

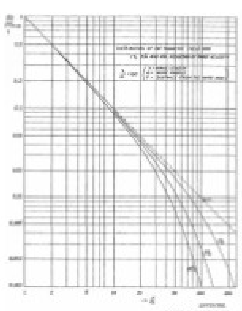


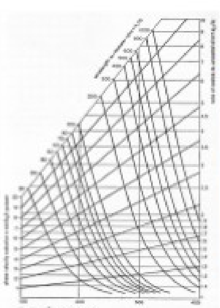
Georg Goubau (A'49) was born in Munich, Germany, on November 29, 1906. He received the Dipl. Phys. degree in 1930, and the Dr. Ing. degree in 1931, both from the Munich Technical University. From 1931 to 1939 he was employed in research and teaching in the physics department of the same university, under Professor Zenneck. During this time he was principally concerned with ionospheric investigations. He established the first German Ionospheric Research Station (Herzogstand/Kochel), and was in charge of the research work carried on at this station.

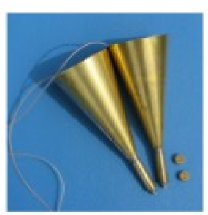
GEORG GOUBAU

In 1939 Dr. Goubau was appointed professor and director of the department of applied physics at the Friedrich-Schiller University, in Jena, Germany. Before he arrived in this country, he was the senior author of the volumes on electronics of the FIAT Review of German Science, published by the Military Government for Germany. Dr. Goubau is now a consultant at the Signal Corps Engineering Laboratories, in Fort Monmouth, N. J.

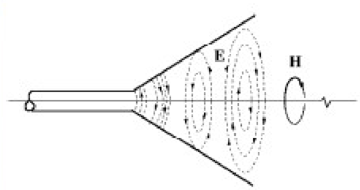
Development Of Surface Wave Lancher







.30 Caliber Brass Prototype



Surface wave evolution inside the launcher

Commercial Rubytron Inc. RadWire Lancher

Conclusions

Traditional bench testing of beamline components will be inadequate to characterize and assess performance of the 12 GeV upgrade at Jefferson lab. The use of the G-line facilitates measurements which more accurately mimic electron beam conditions. This system is particularly well-suited for our bench system, due to ease of fabrication, low-cost, and choice of operating frequency range. In addition, due to the flat 8 GHz frequency response, pulsed beam structures can be replicated, providing a platform for receiver development. Further reduction of VSWR is planned, in order to minimize dispersion of pulses resulting from reflections. Finally, the use of ~1 um X-Y stages presents a system which can be automated, improving repeatability and simplifying test procedures.

*Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

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Jefferson Lab

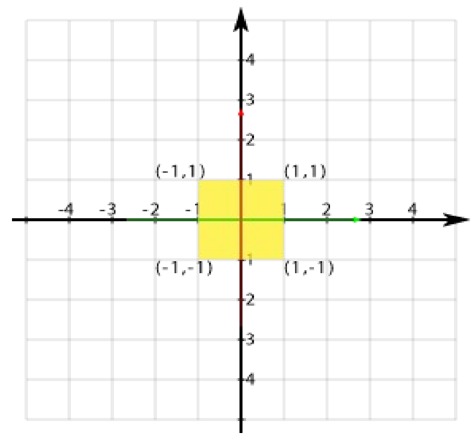
LMS 2-D Field Map Transformations

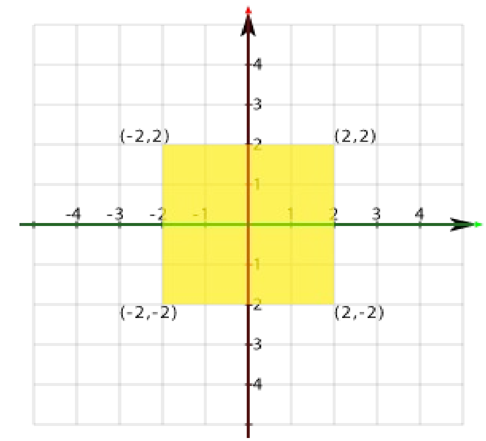
- Translation

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & d_x \\ 0 & 1 & d_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

- Scaling

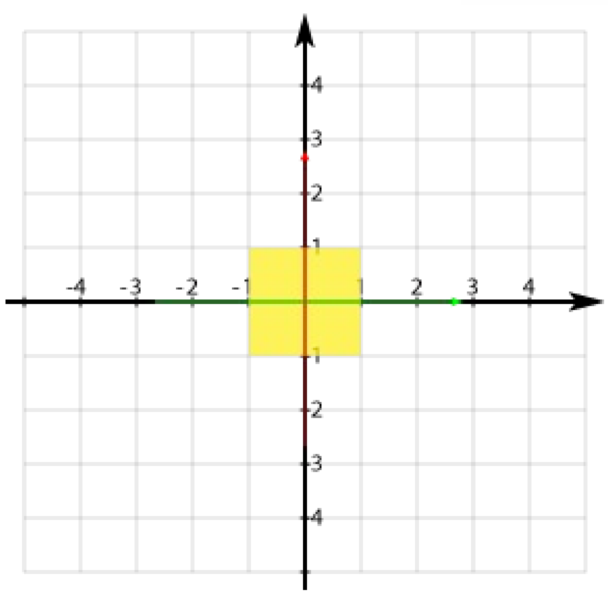
$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} s_x & 0 & 0 \\ 0 & s_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

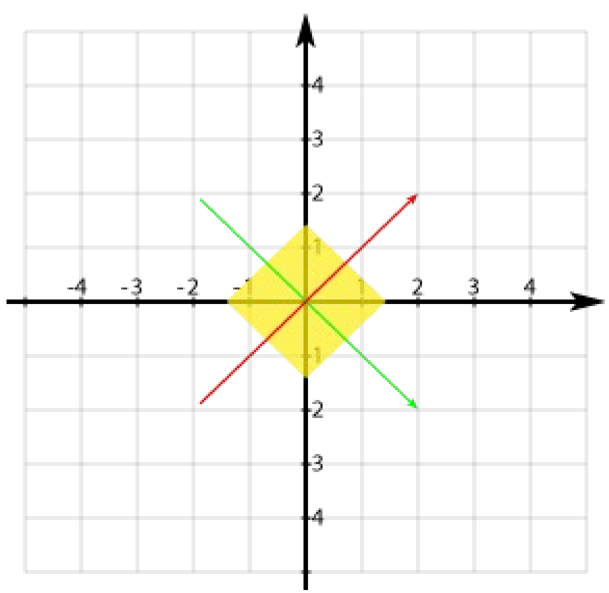


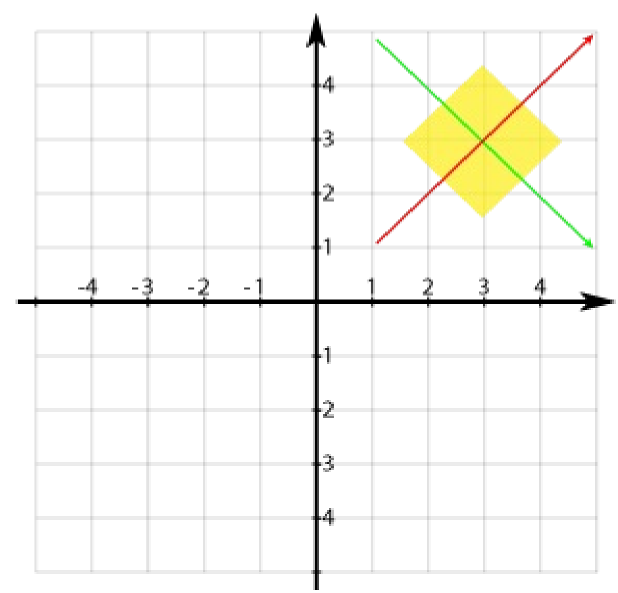


- Rotation

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$







Physical Significance

$$X_{scale\ factor} = \sqrt{\alpha_x^2 + \beta_x^2}$$

$$Y_{scale\ factor} = \sqrt{\alpha_y^2 + \beta_y^2}$$

Scale factors for X and Y directions

$$\theta_x = \tan^{-1}\left(\frac{\beta_x}{\alpha_x}\right)$$

$$\theta_y = \tan^{-1}\left(\frac{\beta_y}{\alpha_y}\right)$$

X and Y “effectively” rotated individually

$$\Delta\theta = \theta_y - \theta_x$$

Differences in thetas represents X-Y coupling

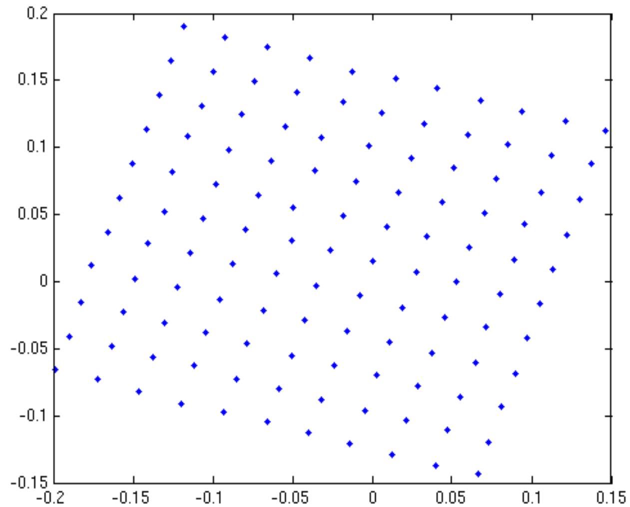
$$\Delta_x, \Delta_y$$

Arbitrary field offset;

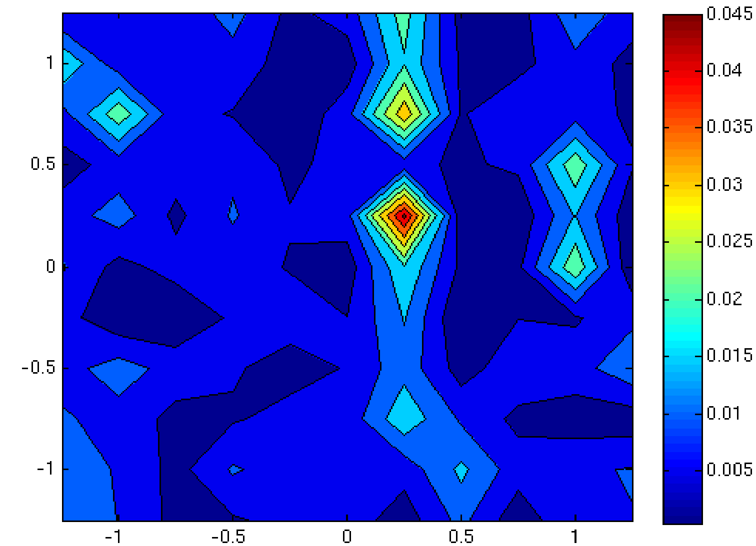
Merely tells us where we “should” have started the scan

Not related to physical vs. electrical centers (obtained later)

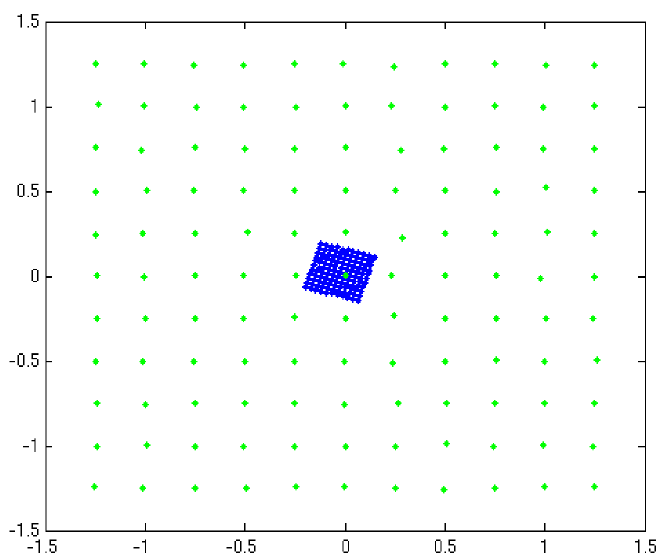
Algorithm Verification



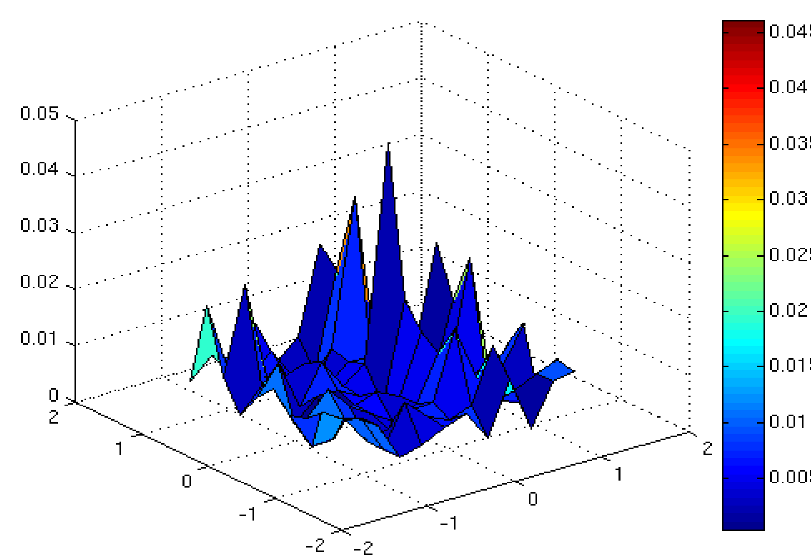
Raw Field Measurement



RMS Error Vector Magnitudes

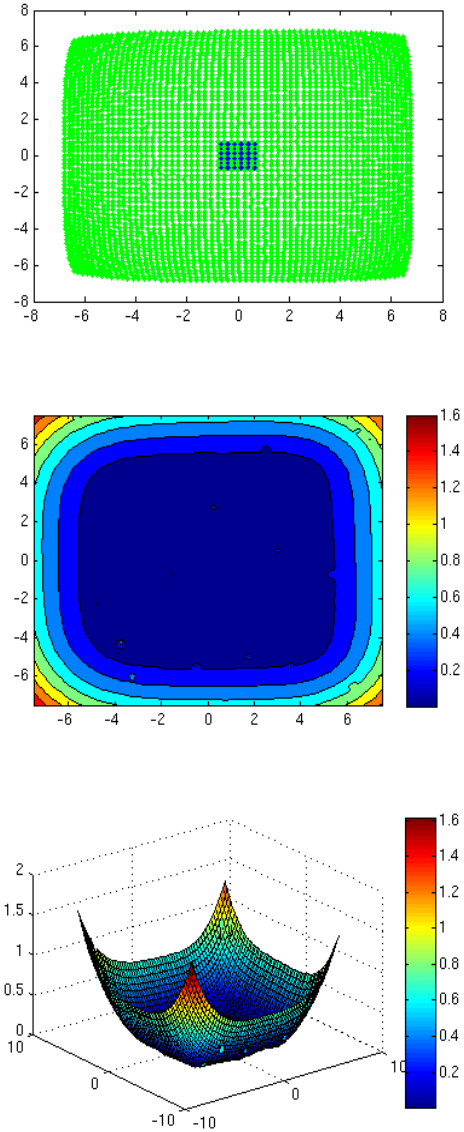


Scaled, Rotated, Translated....

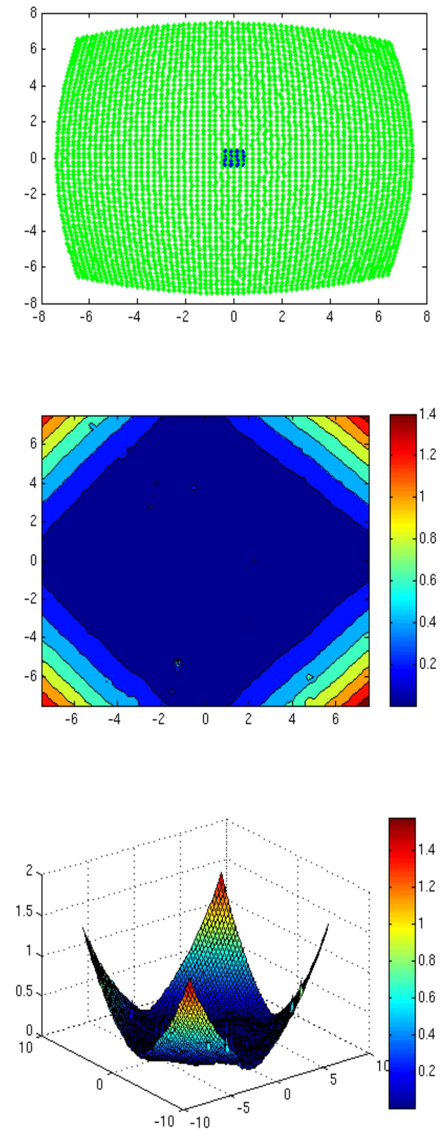


SPM vs M15 Scans

LMS per 1cm x 1cm



SPM

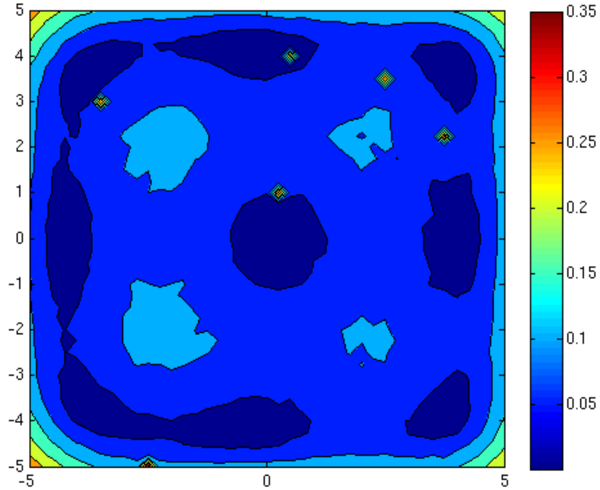


M15

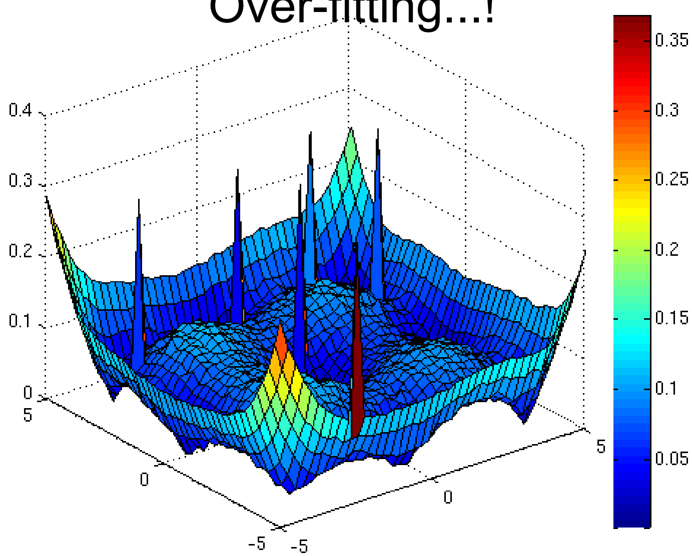
Step size = 250 um

LMS Fit: 1 cm^2 (SPM 26)

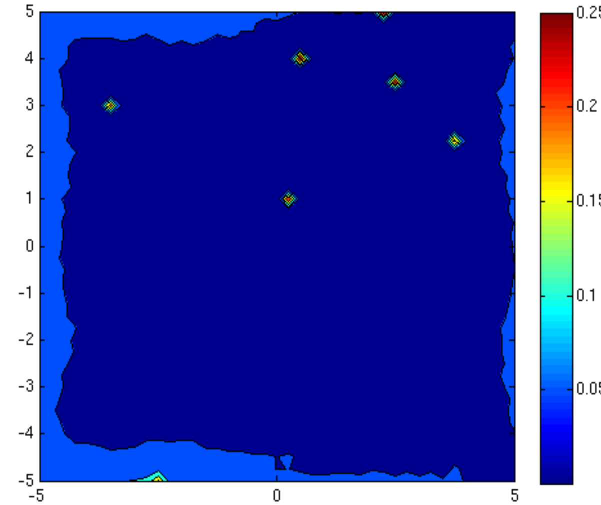
Linear Fit

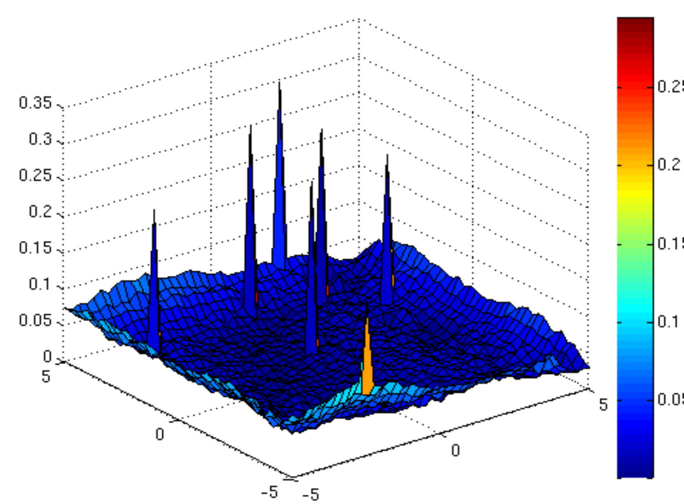


Over-fitting...!



Log Fit





Position Accuracy (SPM)

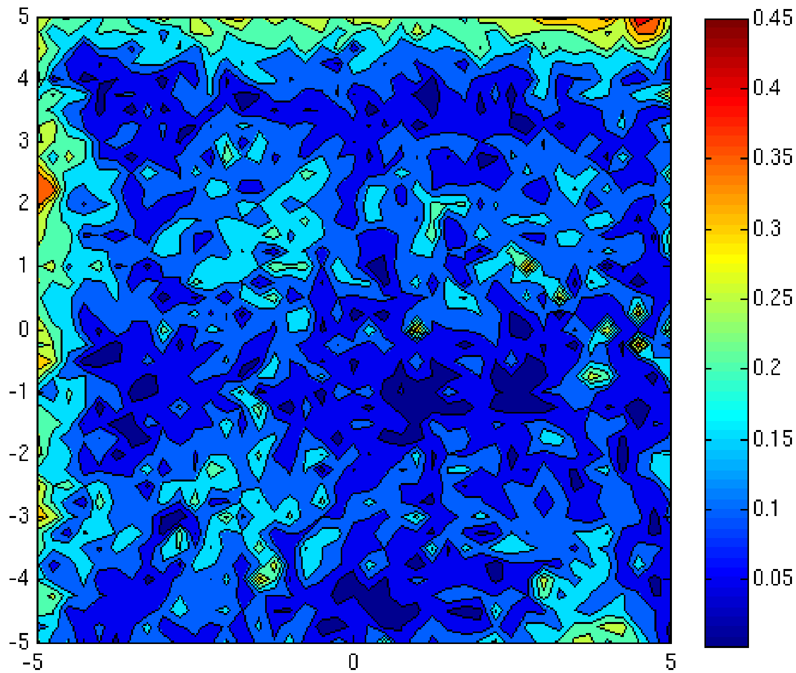
$$f(x;\sigma) = \frac{x}{\sigma^2} e^{-x^2/2\sigma^2}, \quad x \geq 0,$$

Rayleigh Distribution

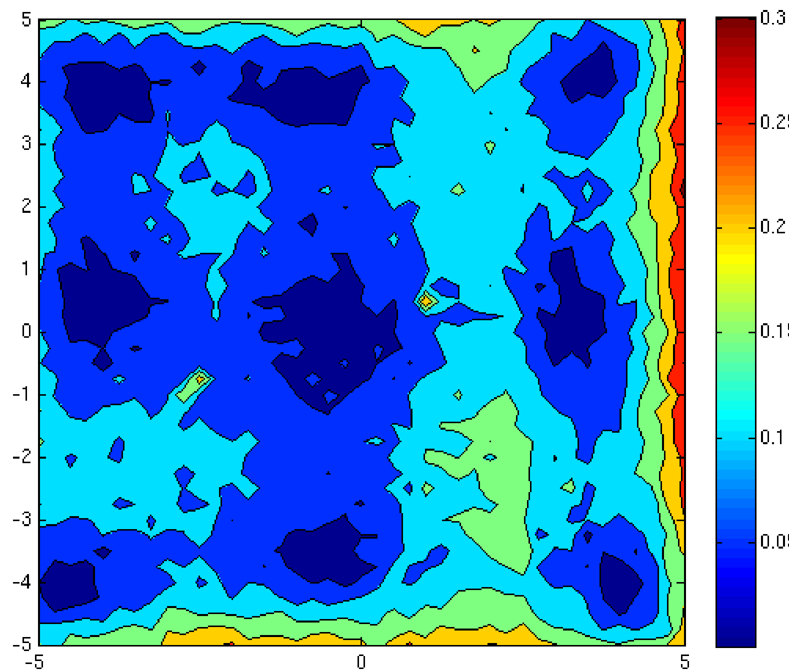
Ibeam ~ 100nA
B = 100 Hz
$\sigma = 100\,um$

← Composite resolution →

Ibeam ~ 100nA
B = 10 Hz
$\sigma = 85\,um$



1cm x 1cm



1cm x 1cm

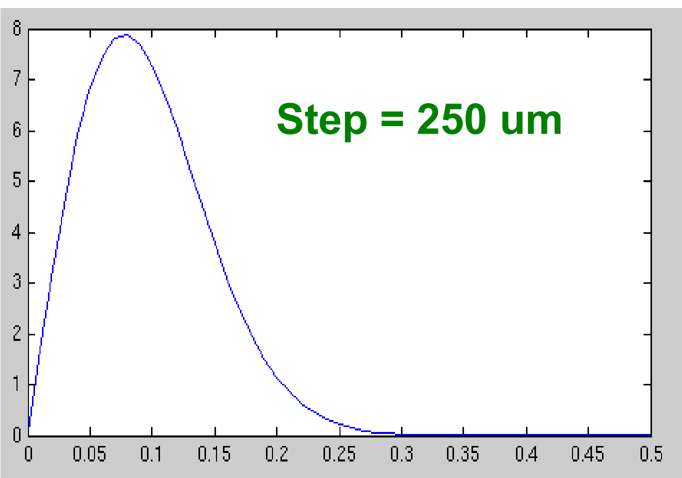
Position Accuracy (cont.)

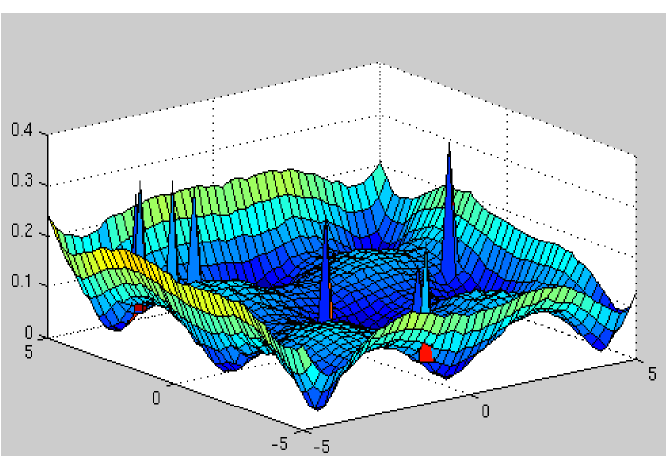
Ibeam ~ 500nA

B = 10 Hz

$\sigma = 77\,um$

R = 120 um



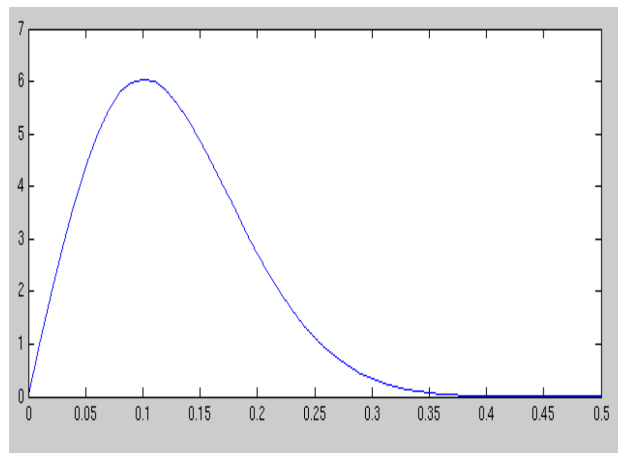


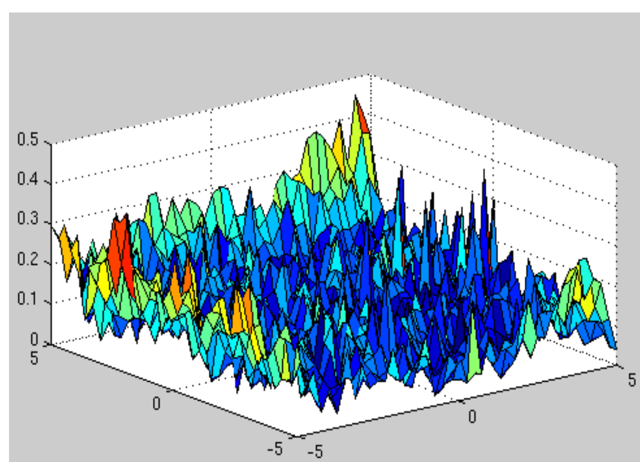
Ibeam ~ 100nA

B = 100 Hz

$\sigma = 100\,um$

R = 158 um



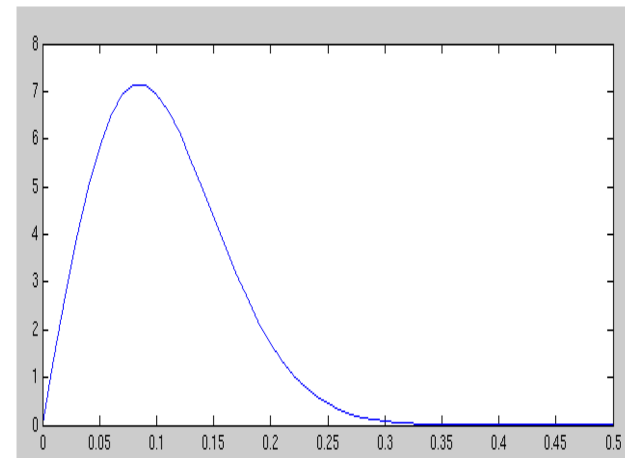


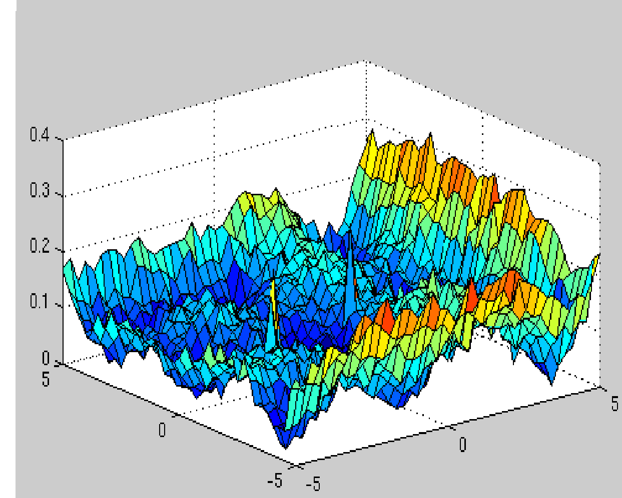
Ibeam ~ 100nA

B = 10 Hz

$\sigma = 85\,um$

R = 133 um





Conclusions

- SL BPM is a relative sensor, with resolution dependent on SNR
- Cavity system has better magnitude response, but contains phase detection “baggage”
- Realized improvement at 100 nA, 10 Hz is ~8x (no Cu plating)
- Cavity calibration is rather involved, requiring additional beamline elements as fiducials
- New electronics are vastly more configurable:
  - Resolution (NF), Lineartity (DR), and output BW are competing factors
- Important numbers:
  - Pn = -174 dBm / Hz
  - SL BPM -80 dBm @ 1uA (scales 20log for I, 10log forB)
  - Cavity -92 dBm @ 100um – 1 uA
  - Electronics: $5k per system
  - Elements:
    - SL ~$1K
    - Cavity system ~$100k!
- SL BPM > 7nA (1 Hz)
- Cavity BPM >100 pA (1 Hz, Cu-plated)
- Cavity BCM already confirmed to 100s of pA (see Grames ELOG)

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