EESICS – Intro & Moller Diagnostics Plans

Talk Outline:

- Introductions
- Moller Plan of Record
- Diagnostic Systems Overview
- Status & Plans
- Topics For Future Discussions
- Questions

Nate Rider, EESICS Group Leader

Thursday, January 26, 2023

Introductions

- Who am I?
  - Electrical Engineer
  - Started at Jefferson Lab as the Electrical Engineering Systems Instrumentation and Control Systems (EESICS) Group Leader in January 2022.
  - Designed instrumentation and controls for the Cornell Laboratory for Accelerator Based Sciences and Education for 14 years.
    - CESR, CHESS, ILC, muon G-2, LHC
  - Prior to that, developed mixed signal embedded systems in industry for 12 years.
- What is EESICS?
  - Formerly known as I&C
  - Part of the Electrical Engineering Systems Department within the Engineering Division
  - Responsible for diagnostics and controls in CEBAF, UITF, LERF and the experimental halls

Major Development Projects FY23-24:
- RTP Pockels cell driver (CIS)
- IA Pockels cell driver (CIS)
- Helicity magnet controller (CIS)
- Next generation JLAB BPM

Group Leader:
- Nate Rider

Supervisors:
- Keith Cole
- Scott Windham

Senior Engineers:
- John Musson
- Chad Seaton
- Jim Kortze

Junior Engineers:
- Xuan Nguyen
- Paolo Maltez

Field Engineers:
- Leo Ketchum
- Joe Sawyer

Technicians:
- Tony Dela Cruz
- Mathew Almodovar Mercado
- Seth Green
- Matt Mueller
- TBD

Systems:
- Beam Position Monitors
- Viewers
- Harps
- Beam dump instrumentation
- Vacuum controls
- Fast feedback systems
- Beam Loss Accounting
- Beam current monitors
- Cryo diode readbacks
- Timing & synchronization
- Misc

*Fun Fact: Within the past 18 months 6/15 group members are new to JLab

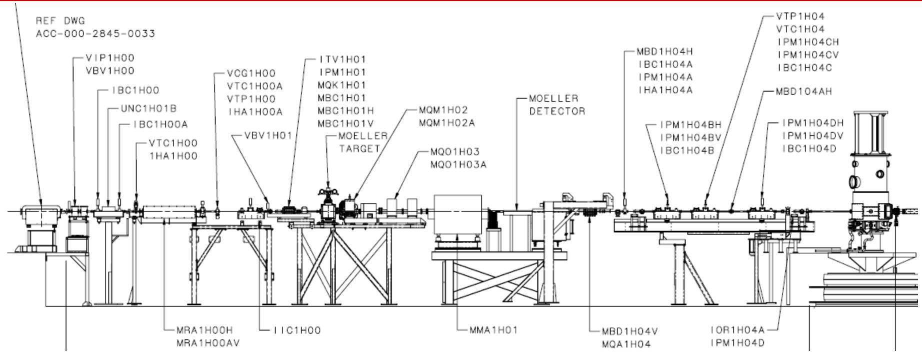
Motivation For This Presentation

- Establish a connection with the collaboration:
  - ✓ Understand the experimental requirements
  - ✓ Develop specifications which reflect our systems
  - ✓ Help us meet the needs of the experiment in a timely manner

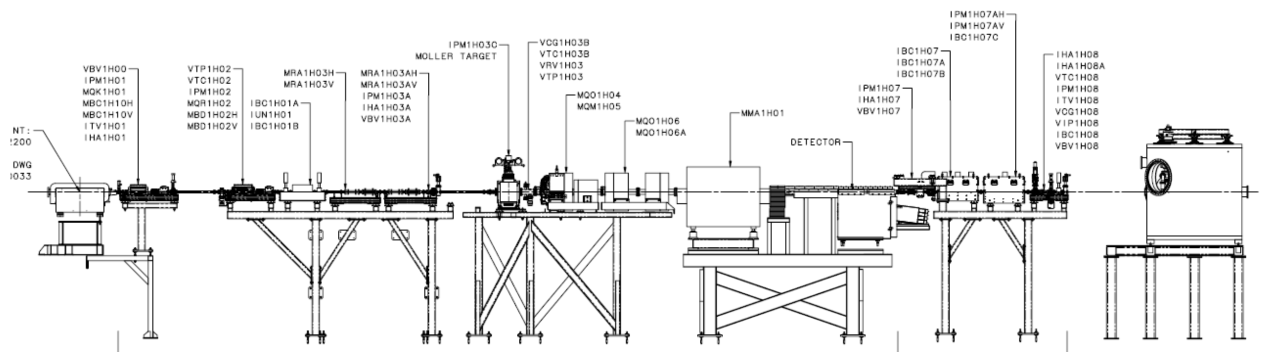
- Present my understanding of the Moller plan of record and provide status
  - I wasn't here when these decision were made
  - Are we all still on the same page?
- Pose some questions to seed future discussions with the collaboration
- Describe some relevant feasibility studies EESICS will be conducting
- Focus on beam position and current diagnostics

EESICS Moller Plan of Record - Layout

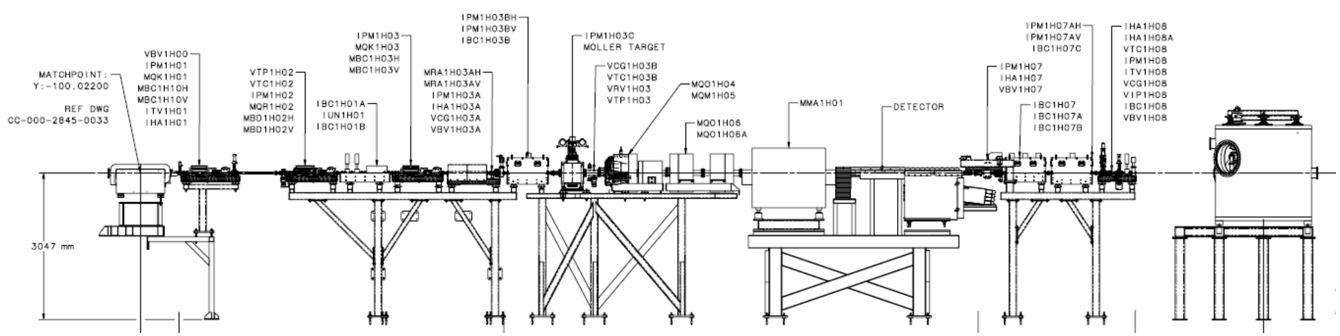
Present



Stage 1



Final



EESICS Moller Plan of Record - Diagnostics

What will be the changes from what you are used to?

- Mechanical:
  - Beam line components get shuffled
  - All antenna BPM pickups replaced by stripline pickups
- Electrical:
  - SEE BPM processors replaced by Digital Receivers
    - SEE hardware is obsolete and no longer available
- Functional:
  - Hall DAQ interfaces will be different
    - Discussed later in this presentation
  - QQQ
  - Some diagnostic element counts change:

Present Day		Stage 1		Final	
BCM	6	BCM	6	BCM	8
Harps	3	Harps	3	Harps	5
BPMs	12	BPMs	15	BPMs	11
Viewers	1	Viewers	1	Viewers	2
UNSER	1	UNSER	1	UNSER	1

Diagnostic Systems - SEE BPM

We presently use Switched Electrode Electronics (SEE) processors for the BPMs

- Antenna BPM pickups
- Designed and manufactured in the mid 1990's
- Obsolete and spare parts are dwindling
- VME based, local muxed RF module, remote IF receiver and hard IOC
- DAQ Interface:
  - Analog Voltage: +/- 10V, effective bandwidth of 24kHz

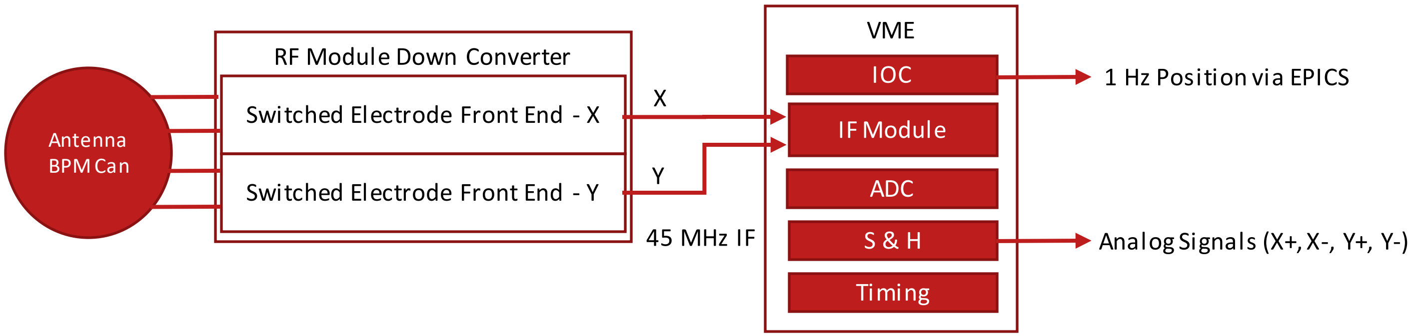
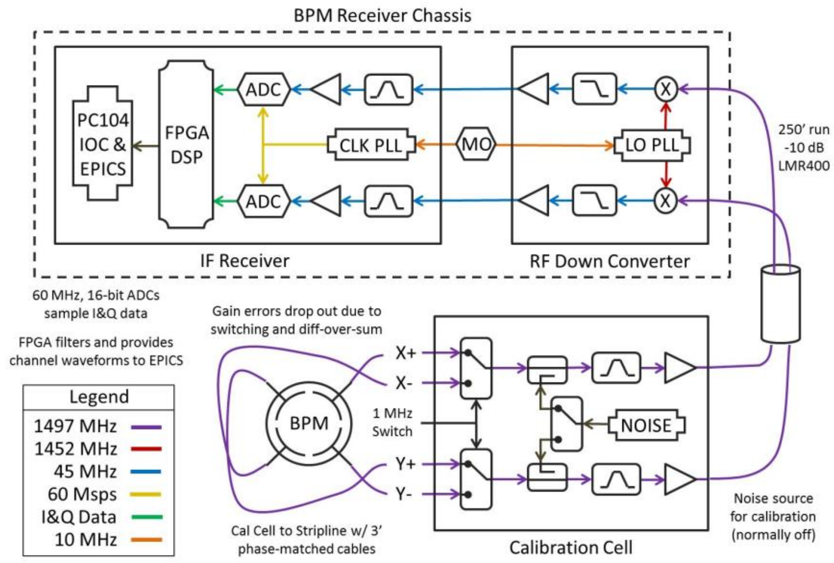


TABLE 1. System Specifications.

Parameter	Linac Style	Transport Style
Dynamic Range	700 nA – 2 mA	70 nA – 200 µA
Nominal Update Rate	1 measurement/second	1 measurement/second
Position Range	|x|. |y| ≤ 5 mm	|x|. |y| ≤ 5 mm
1 Hz Resolution	≤ 0.1 mm	≤ 0.1 mm
Current Dependence	≤ 0.1 mm	≤ 0.1 mm
Multipass Capability	Yes	Not Required
IF Bandwidth	1 MHz	50 kHz
Gated Integrating Filter Bandwidth	170 kHz	14.8 kHz
Effective Analog Bandwidth Due to Switching Effects	57 kHz	3.6 kHz
Maximum Data Rate (Positions)	114 kS/s	7.1 kS/s

Diagnostic Systems - Digital Receiver (BPM, BCM)

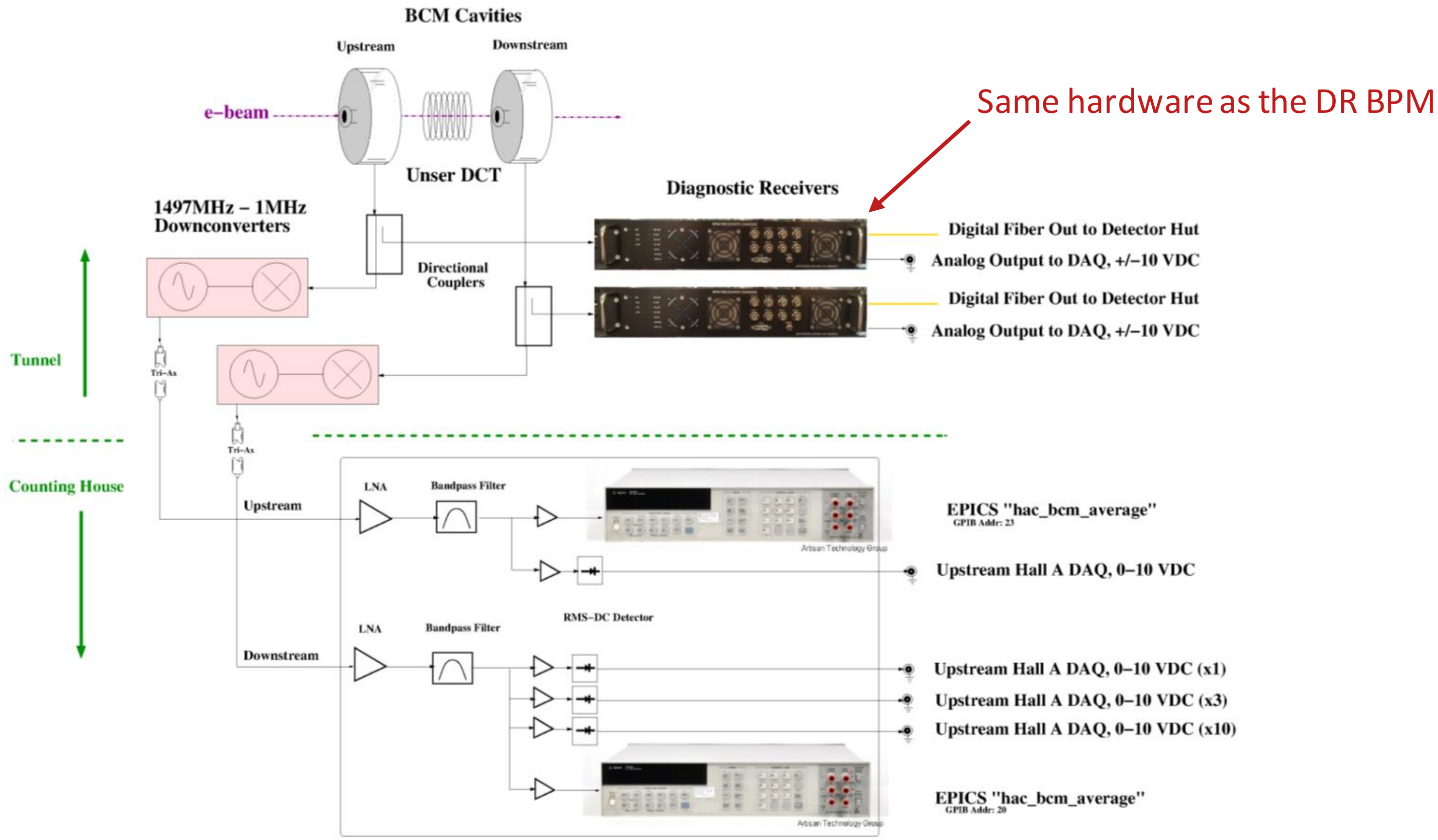
- Newer design mostly available parts
- Flexible firmware allows for different applications
- Stand alone, soft IOC, local muxed calibration cell, remote down converter, IF receiver and processor
- DAQ Interface:
  - Analog Voltage: 18 bit, 1MSPS DAC, +/- 10V, 100kHz effective bandwidth
  - Digital Data: 32 bit, 10KSPS effective bandwidth (BCM only right now)
- Referred to as a DR...not a "Musson Box"



System Specifications:	
Dynamic Range	30 nA – 250 uA
Nominal Update Rate	1 Hz
Position Range	|x|,|y| ≤ 5 mm
1 Hz Resolution	≤ 0.1 mm
Current Dependence	≤ 0.1 mm
IF Bandwidth	45 MHz
Effective Output Bandwidth	100 kHz

*Musson slides in Supporting Section

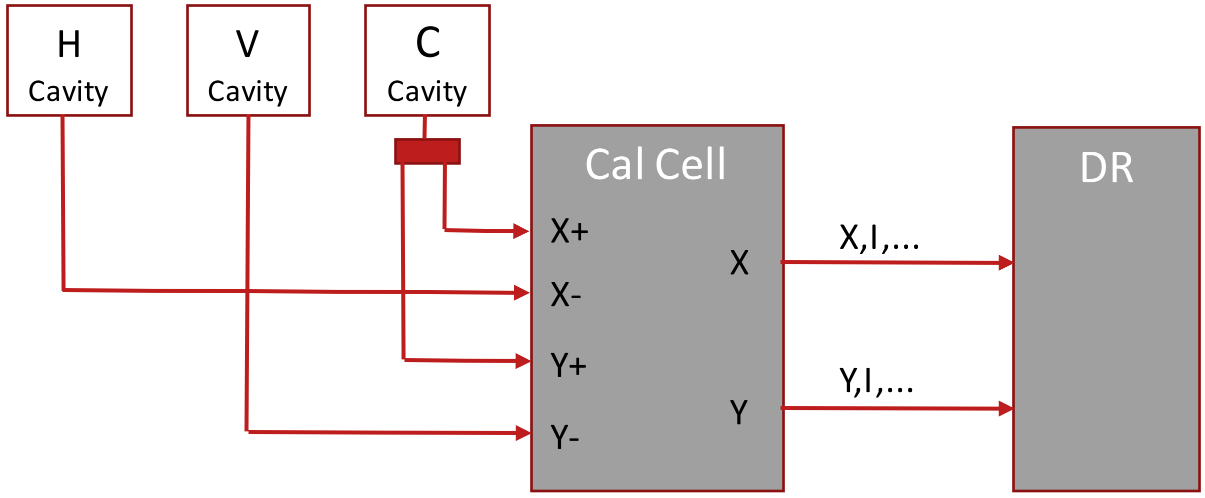
Diagnostic Systems - Unser BCMs



- Instrumented upstream and downstream tuned cavities
- Use directional couplers to split the cavity outputs
  - Modified Vectronics down converters -> DVM + RMS-DC Detector -> EPICS & DAQ
  - Digital Receivers -> Digital & Analog
- Prototype digital output stream to DAQ

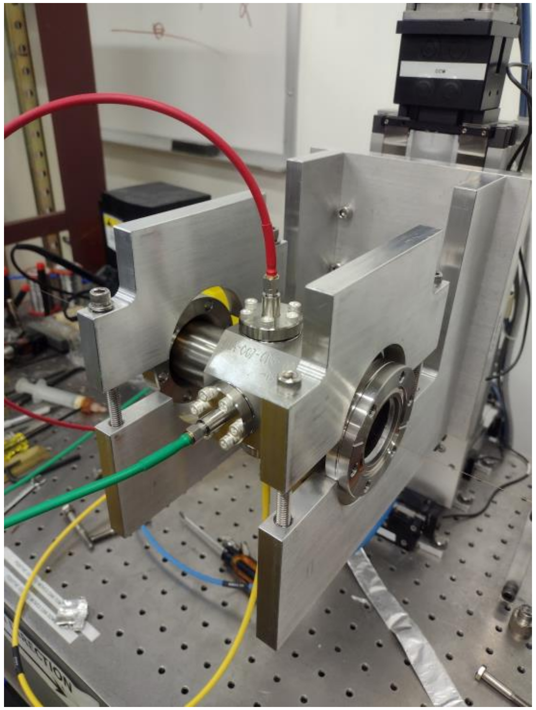
Diagnostic Systems – Cavity BPM, BCM

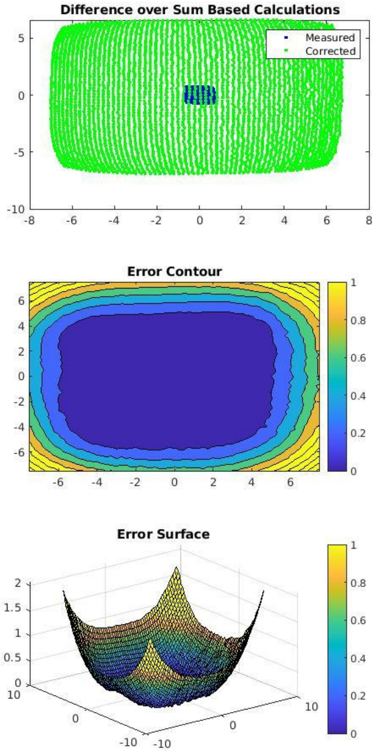
- There are presently 3 sets of cavity bpms
- Consist of three tuned chambers
  - Horizontal position, Vertical position and Current)
- Temperature controlled enclosure
- Connected to cal cell and DR
  - Position and current are muxed
- Presently provide position and current to EPICS
  - Low current capable (~10 nA)
- Require some care and feeding



BPM Striplines

- The first batch of stripline bpm pickups have arrived and we are taking measurements for acceptance. Report to follow.
- In addition to visual inspections, we perform basic network analyzer measurements followed by detailed scans using the Goubau Line Scanner.
- Focus on response errors which will affect our ability to resolve beam position





*Musson slides in Supporting Section

Status & Plans

Status:

- We have procured most of the required hardware for Stage 1
- Presently performing acceptance tests on the stripline pickups

Plans & Feasibility Studies:

- Benchmark the DR vs the SEE processors again
  - Revisit with young eyes
  - Beam based measurements with both strip line and antenna pickups
- Evaluate the quality of the DR analog output
  - This will help inform the choice between a digital and analog interface to the hall DAQ
- Finish the development on the DR digital output (still a prototype, needs a spec)
- If necessary, investigate the suitability of the DR for processing the QQQ signals
- Evaluate the effectiveness of the fast feedback system
  - Position & Energy
  - System is based on the SEE bpm system

Future Topics For Discussion

- Documentation
  - Define the interfaces (Collaboration, EESICS)
  - Formalize requirements (Collaboration)
  - Produce specifications (EESICS)
- BPM Processor Choice
  - Do we need to install any SEE processors?
- Hall DAQ
  - Analog vs digital signals
- QQQ
  - What is our role?
- Support and maintenance roles
- ????

Nate Rider

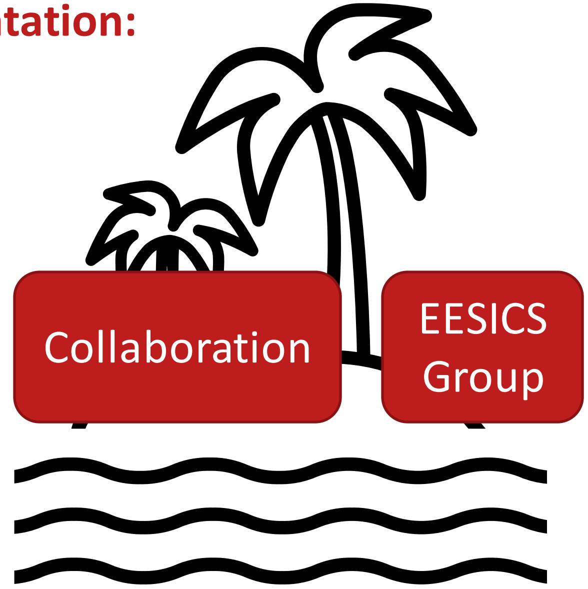
TED2533

nrider@jlab.org 757-269-5145

Thank you for your time!

Thank you for helping me assemble this presentation:

- John Musson
- Jay Benesch
- Chase Dubbe
- EESICS Group

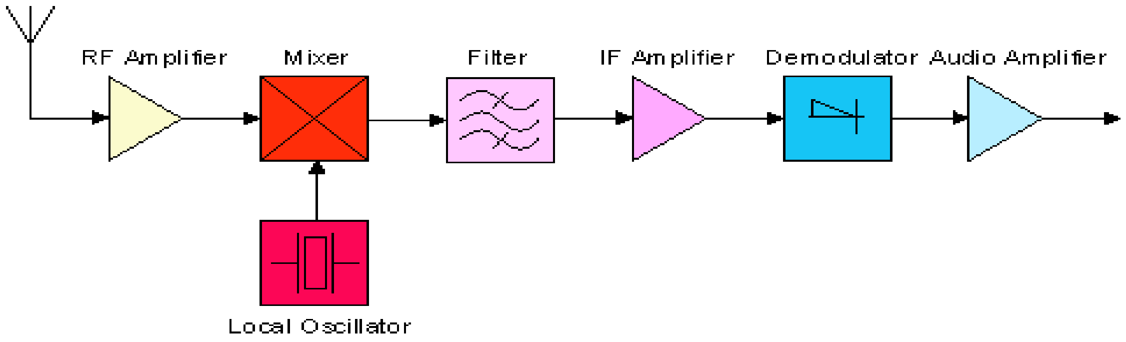


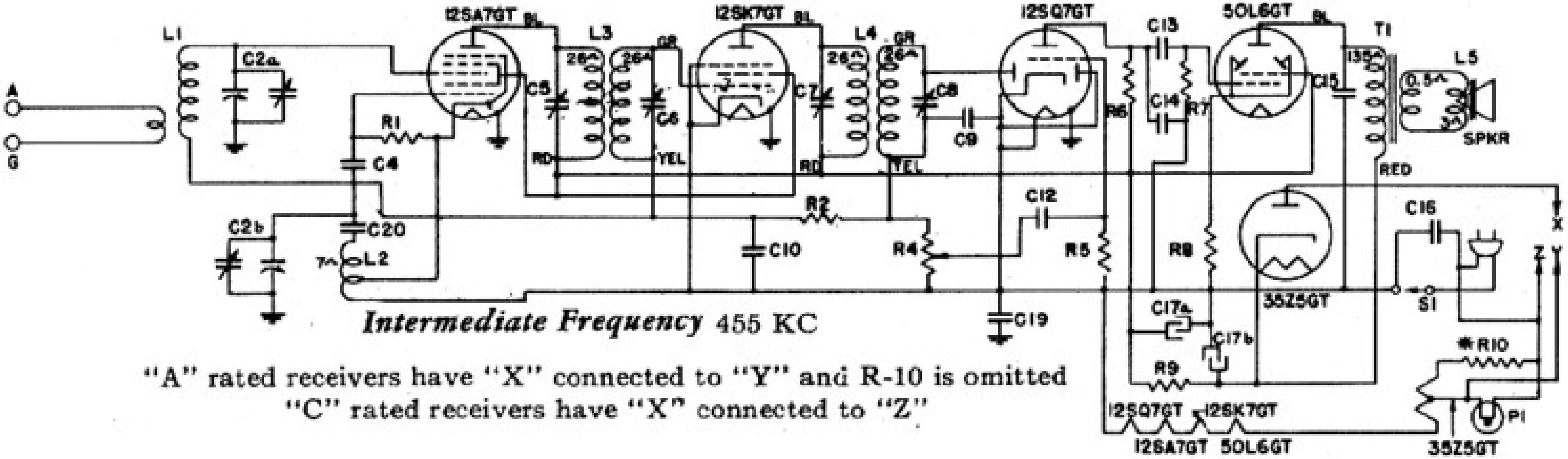
Supporting Slides

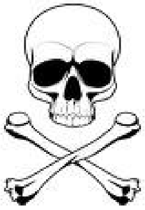
Musson - Digital Receiver

Musson - G Line Stripline Evaluation

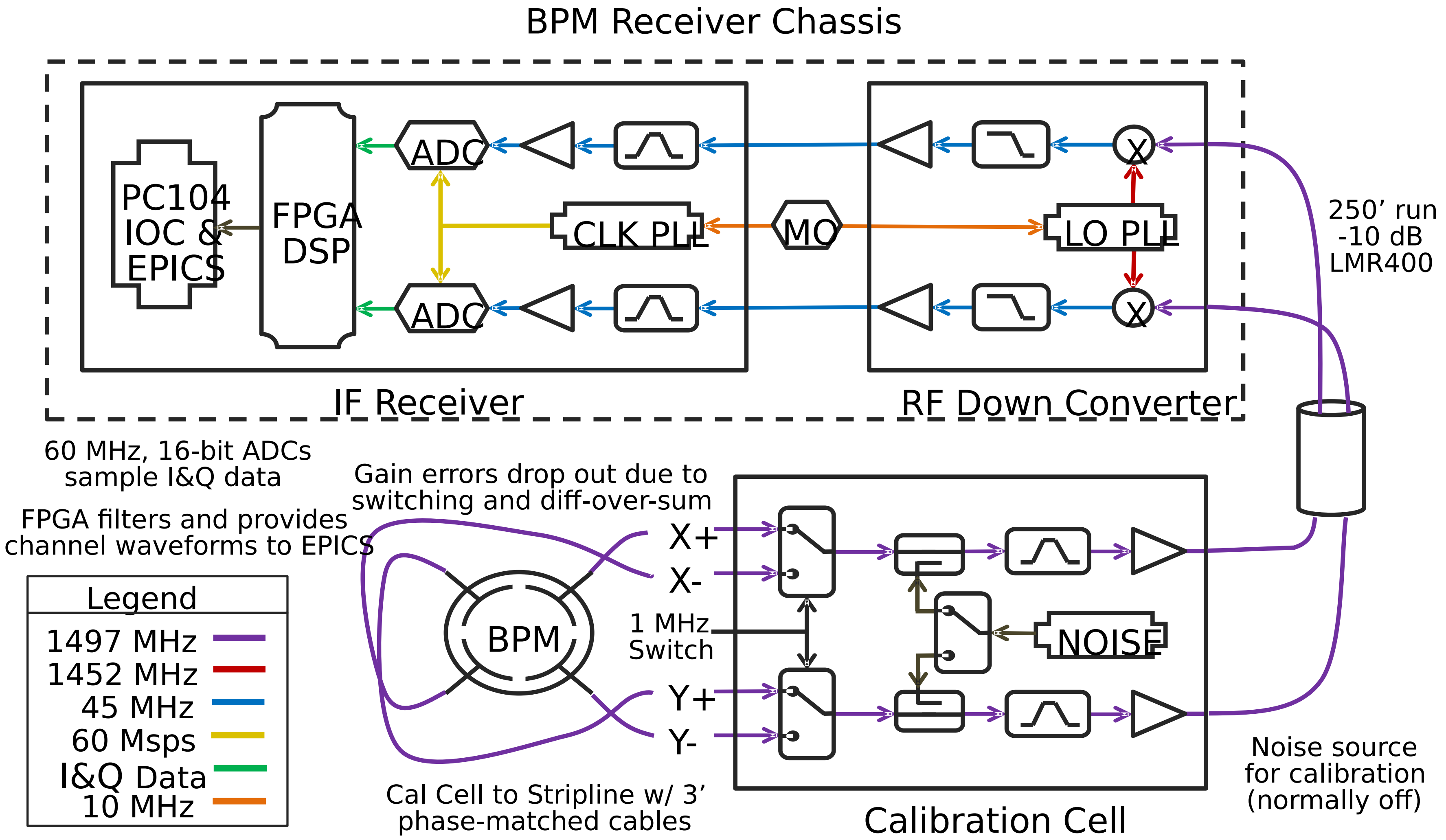
Superheterodyne Architecture



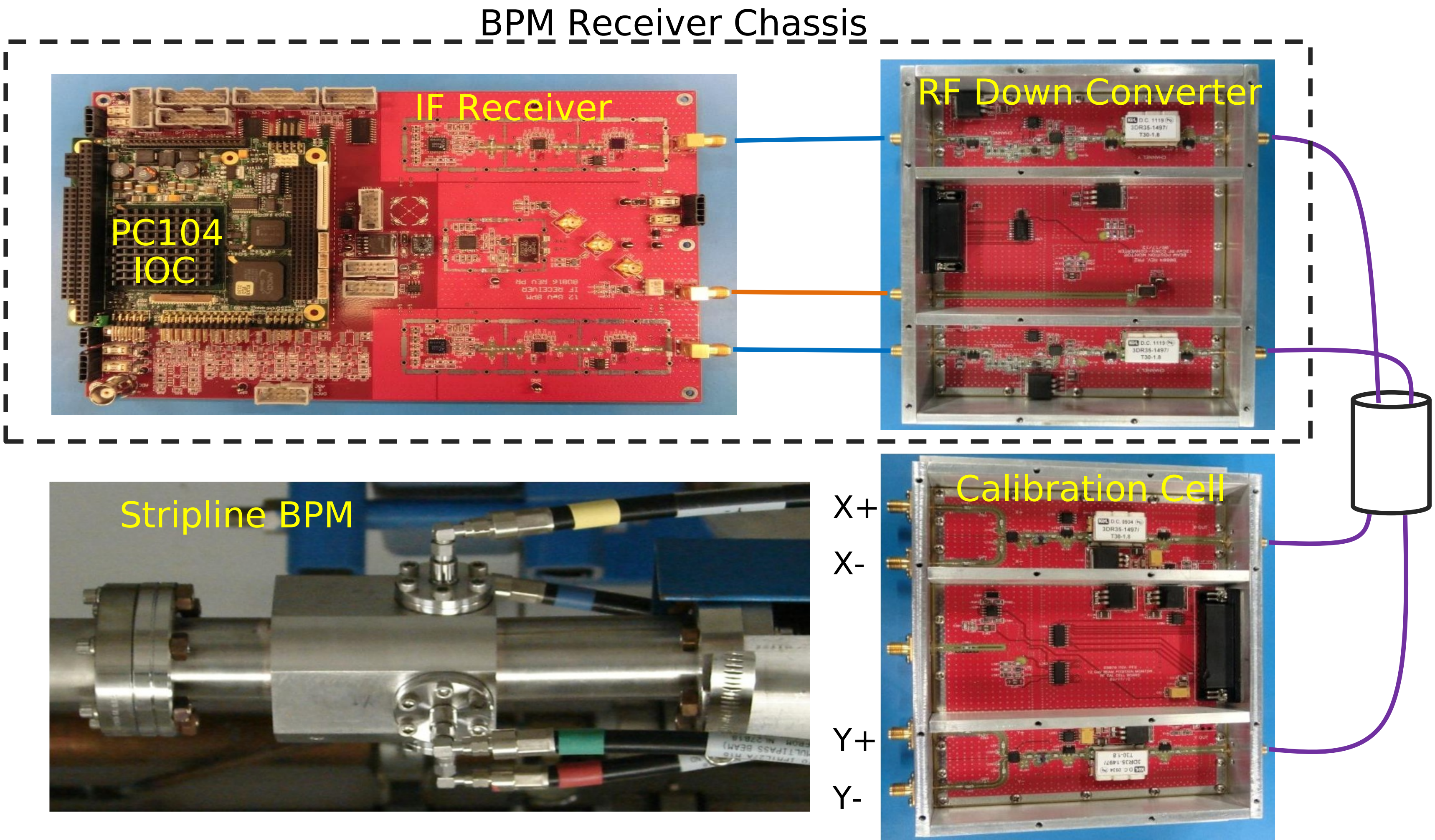




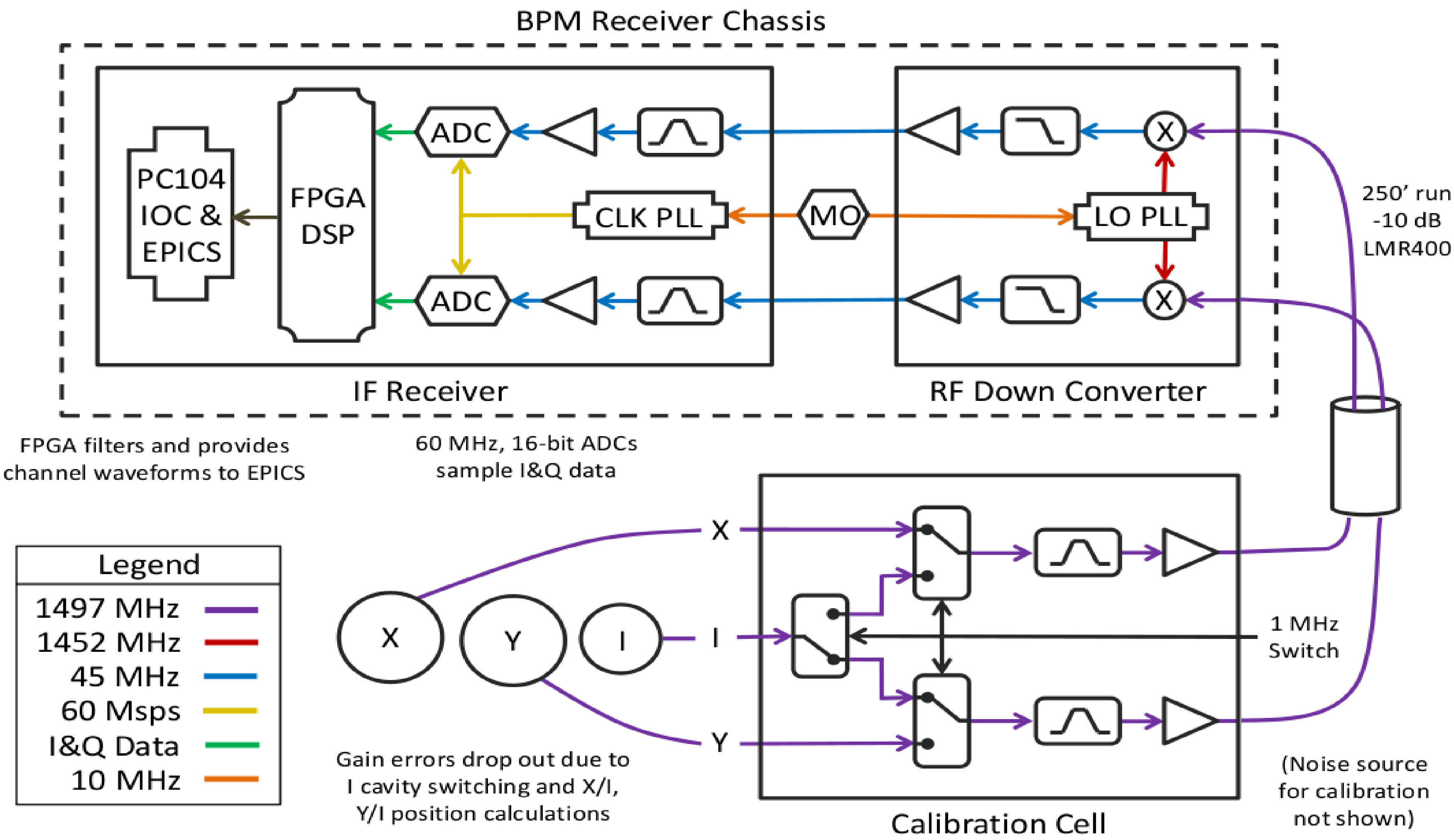
12 GeV BPM System Overview



12 GeV BPM System Components

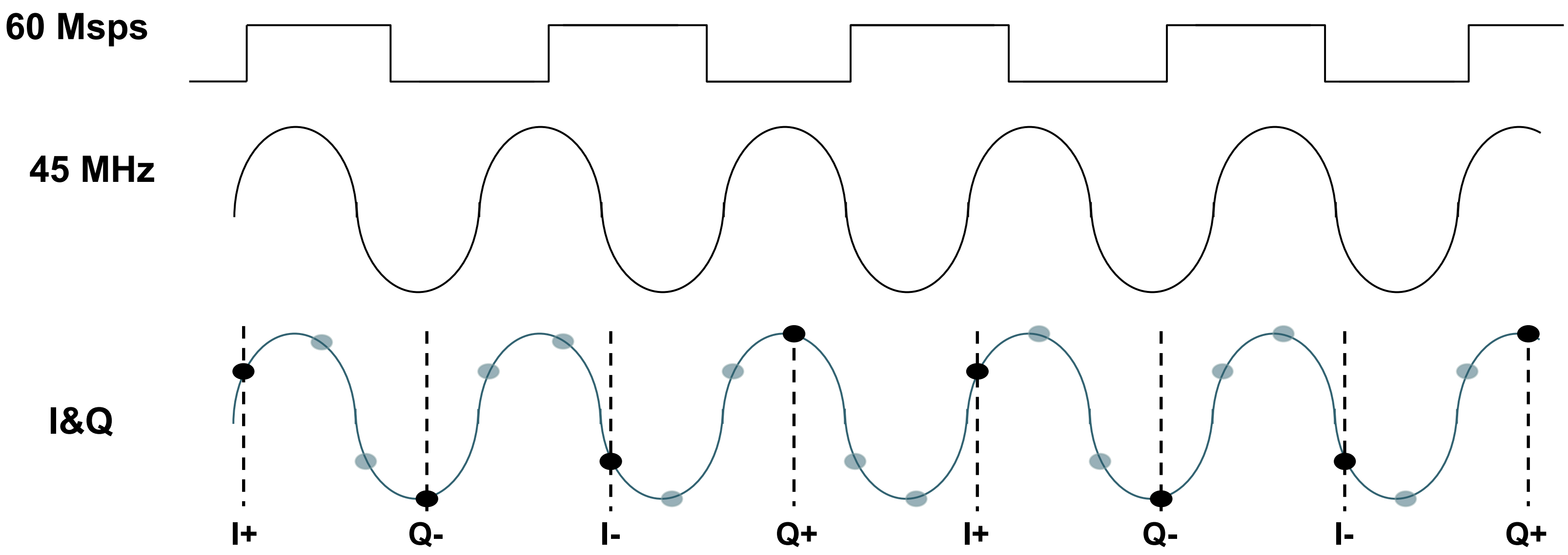


Cavity BPM Electronics



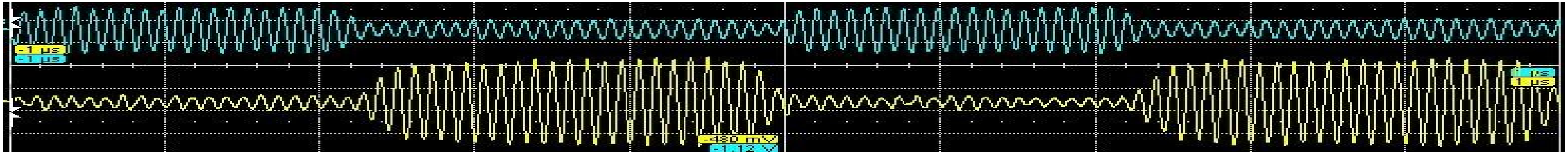
12 GeV BPM Firmware

Digital Down Conversion of 45 MHz IF at 60 Msps



- Any odd multiple yields I&Q
  - (4 * 45MHz) / (2n + 1)
  - 180, 60, 36, 25.7, … Msps
- Break into 30 Msps I&Q chains
  - I+, -(I-), I+, -(I-), …
  - -(Q-), Q+, -(Q-), Q+ …

12 GeV BPM Firmware



60 MS/s Data Stream with 1 MHz Plus/Minus Channel Switching

I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+

30 Plus Channel Samples at 60 MS/s

30 Minus Channel Samples at 60 MS/s

I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-, I-, Q+, I+, Q-

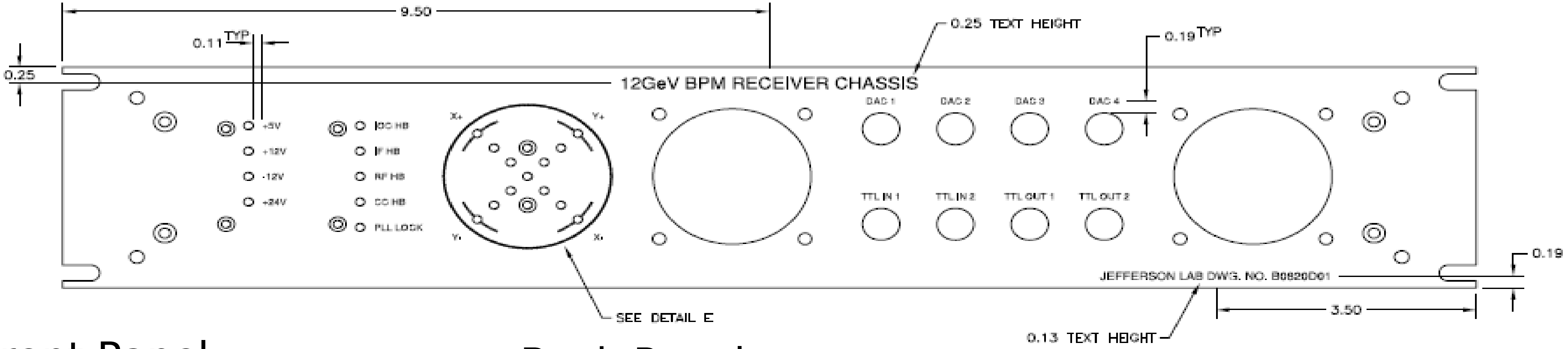
(I+) - (I-) + (I+) - (I-) + (I+) - (I-) + (I+) - (I-) + (I+) - (I-) + (I+) - (I-) + (I+) - (I-) + (I+) = I

-(Q-)+(Q+)-(Q-)+(Q+)-(Q-)+(Q+)-(Q-)+(Q+)-(Q-)+(Q+)-(Q-)+(Q+)-(Q-)+(Q+)-(Q-) = Q

at 1 MS/s

- De-multiplex both X and Y channels
- Skip first 4 data points (2 Is and 2 Qs) to ignore any filter related ringing issues
- Adjustable switch delay for cable lengths and filter delays delays
- Delayed in 16.67 nsec steps
- X and Y individually controllable

12 GeV BPM System Chassis

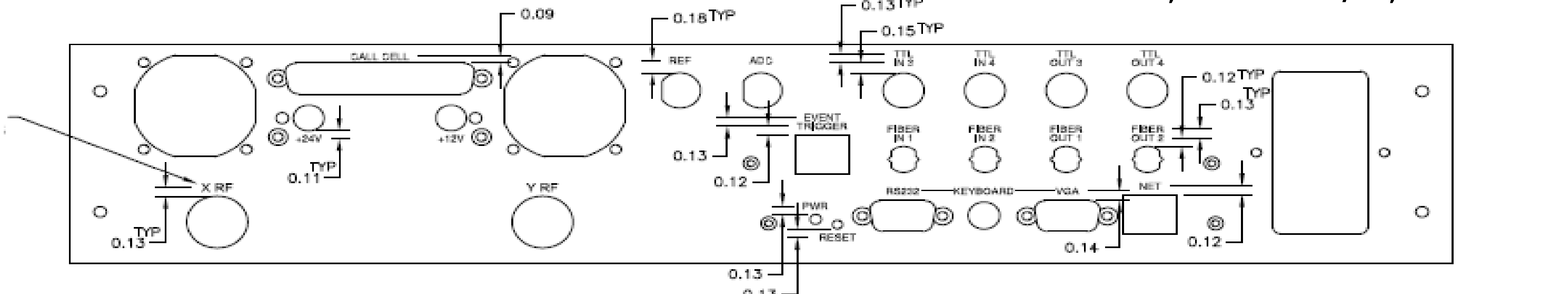


Front Panel

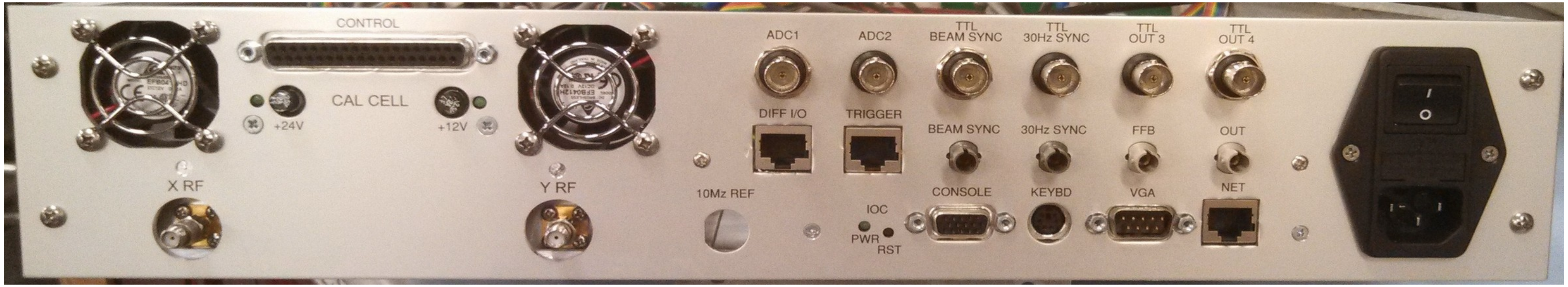
- Power & Status
- Diagnostic DACs
- TTL I/O
- Air intake/filters

Back Panel

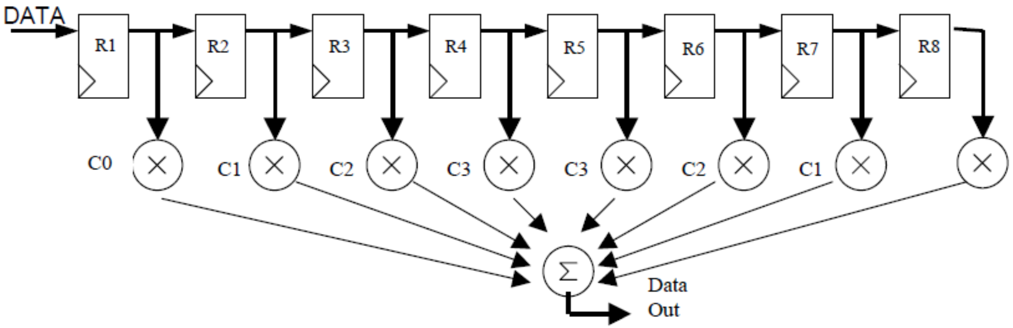
- Cal Cell Control
- RF DC Inputs
- 10MHz Reference
- Diagnostic ADC
- TTL I/O (BS, 30Hz)
- Fiber I/O (BS, 30Hz, FFB)
- Event Trigger
- Fans, PC104 I/O, Power




BPM RECEIVER CHASSIS
+5V
+12V
-12V
+24V
IOC HB
IF HB
DC HB
CC HB
30 Hz
B SYNC
REF LK
X+
Y+
Y-
X-
TTL IN 1
TTL IN 2
TTL OUT 1
TTL OUT 2
DAC 1
DAC 2
DAC 3
DAC 4
JTAG
AUDIO
JEFFERSON LAB DWG. NO. B0820D01

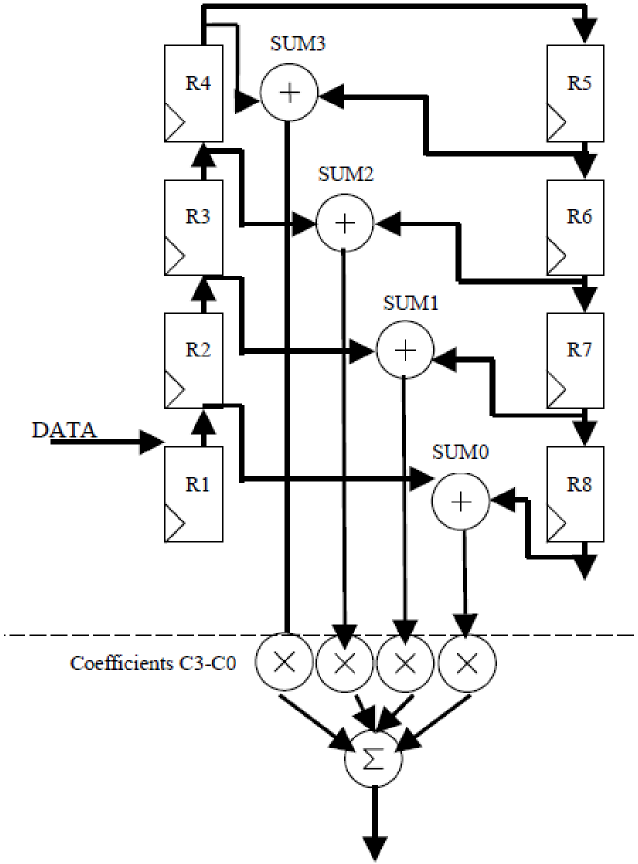

CONTROL
CAL CELL
+24V
+12V
X RF
Y RF
ADC1
ADC2
TTL BEAM SYNC
TTL 30Hz SYNC
TTL OUT 3
TTL OUT 4
DIFF I/O
TRIGGER
BEAM SYNC
30Hz SYNC
FFB
OUT
10Mz REF
IOC
PWR
RST
CONSOLE
KEYBD
VGA
NET

Digital Signal Processing Tools



FIR (Finite Impulse Response)

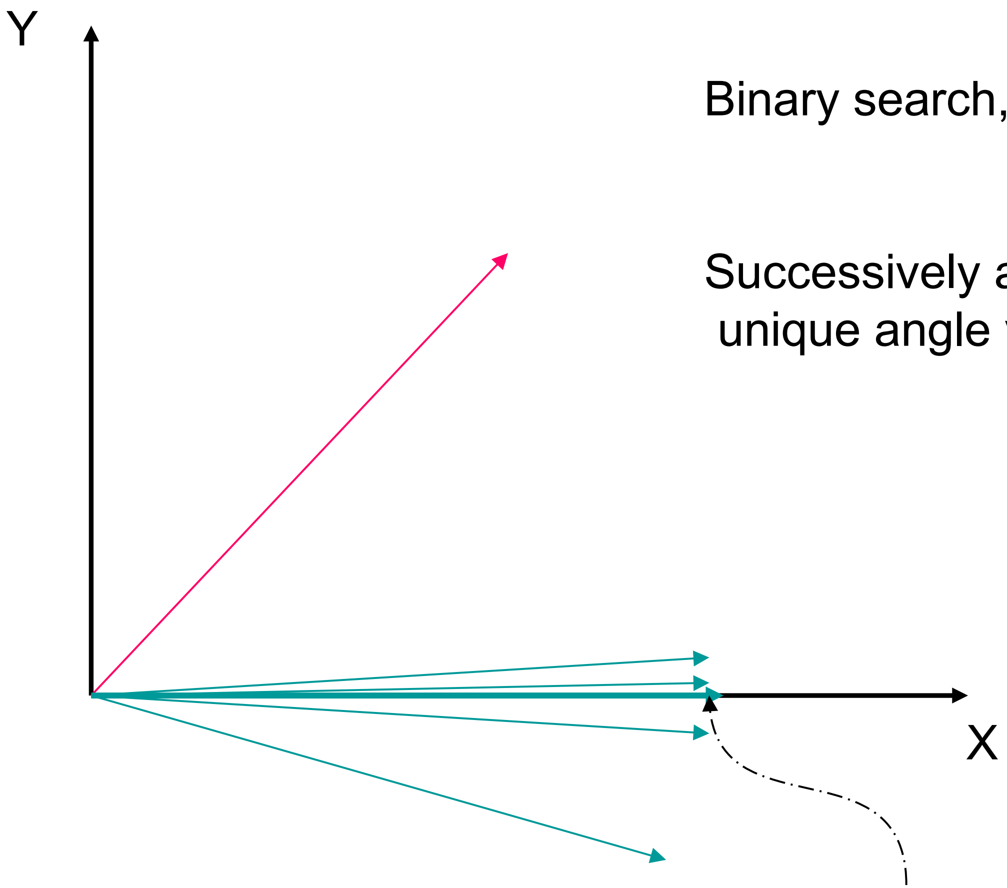
- Unconditional Stability and linear phase
- Symmetric coefficients allow for “folding”
  - Add two delayed samples together then multiply by common coefficient
  - Half as many multipliers



Digital Signal Processing Tools

- COordinate Rotation DIgital Computer
  - Jack E. Volder, *The CORDIC Trigonometric Computing Technique, IRE Transactions on Electronic Computers*, September 1959
  - Ray Andraka, *A Survey of CORDIC Algorithms for FPGA Based Computers,* FPGA '98. Proceedings of the 1998 ACM/SIGDA sixth international symposium on Field programmable gate arrays, Feb. 22-24, 1998, Monterey, CA. pp191-200.
- Iterative method for determining magnitude and phase angle
  - Avoids multiplication and division
- N_{bits}+1 clock cycles per sample
- Can also be used for vectoring and linear functions (eg. $y = mx + b$)

Functionally.....



Binary search, linked to sgn(Y)

$$d_i = \begin{cases} +1, & if\ y_i < 0 \\ -1, & if\ y_i \geq 0 \end{cases}$$

Successively add angles to produce unique angle vector

$$\phi = \sum_i d_i \cdot \arctan(2^{-i})$$

$$z_{i+1} = z_i - d_i \cdot \arctan(2^{-i})$$

Resultant lies on X (real) axis with a residual gain of 1.6

Concept

- Exploits the similarity between 45^o, 22.5^o, 11.125^o, etc. and Arctan of 0.5, 0.25, 0.125, etc.
- Multiplies are reduced to shift-and-add operations

Angle	Tan ( )	Nearest 2^{-N}	Atan ( )
45	1.0	1	45
22.5	0.414	0.5	26.6
11.25	0.199	0.25	14.04
5.625	0.095	0.125	7.13
2.8125	0.049	0.0625	3.58
1.406125	0.0246	0.03125	1.79
0.703125	0.0123	0.01563	0.90

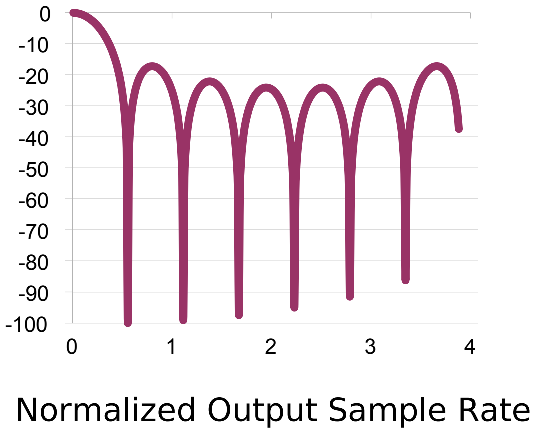
$$[x', y'] = [x, y] \cdot \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

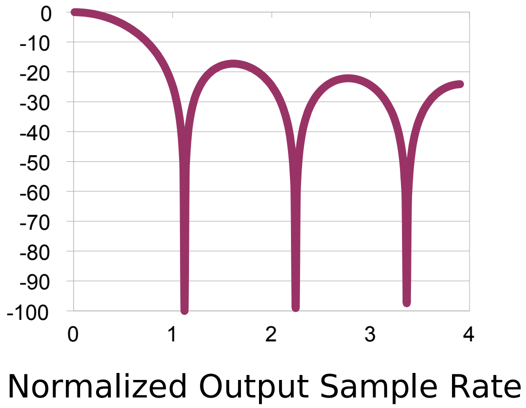
$$x_{i+1} = K_i \left[x_i - y_i \cdot d_i \cdot 2^{-i} \right]$$
$$y_{i+1} = K_i \left[y_i + x_i \cdot d_i \cdot 2^{-i} \right]$$

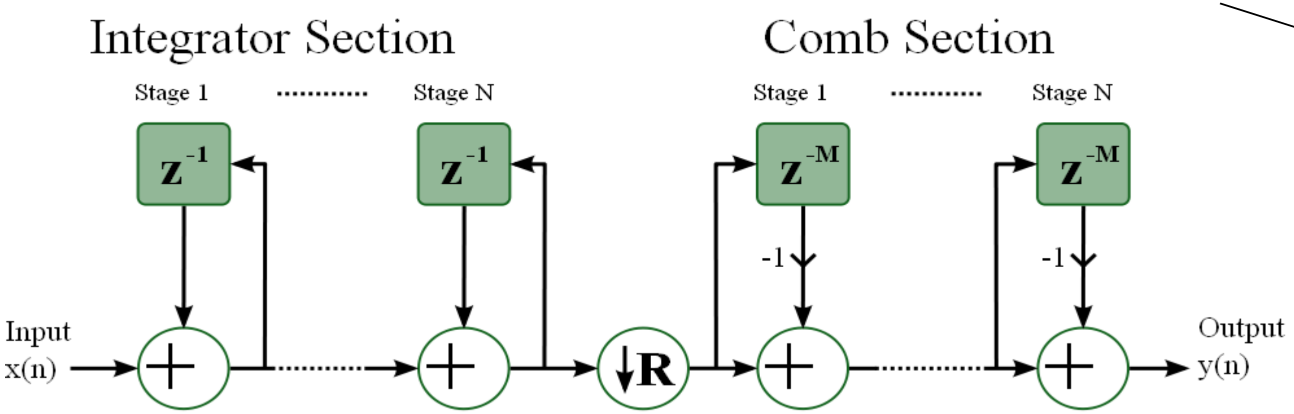
Digital Signal Processing Tools

CIC (Cascaded Integrated Comb)

- Good for decimation
- Sign extend for bit growth, G = (R * M) ^N
- Pick a combination that gives a factor of 2
  - R=4, M=2, N=3, G=512 (shift 9 bits)
  - R=8, M=1, N=2, G=64 (shift 6 bits)

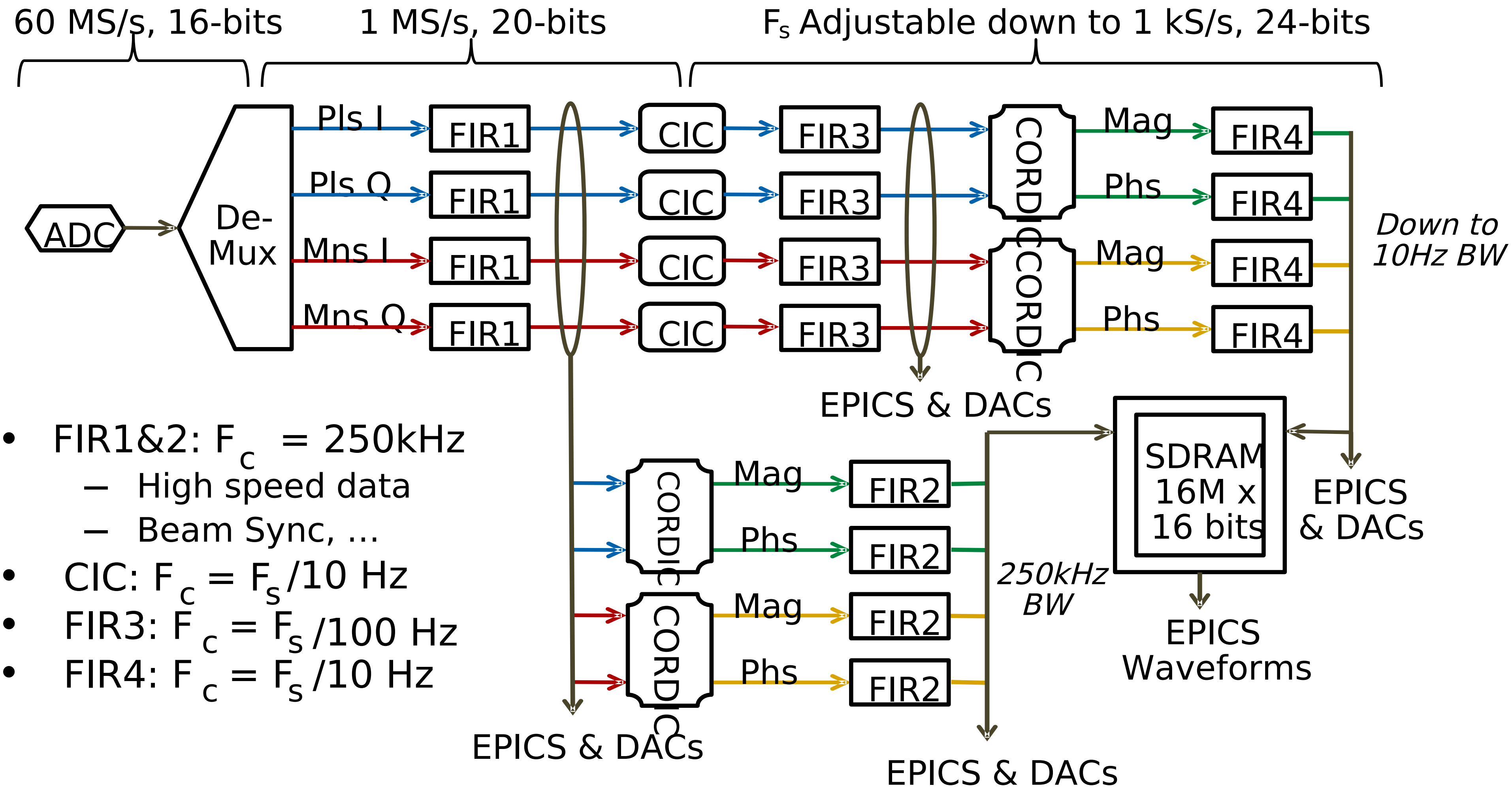






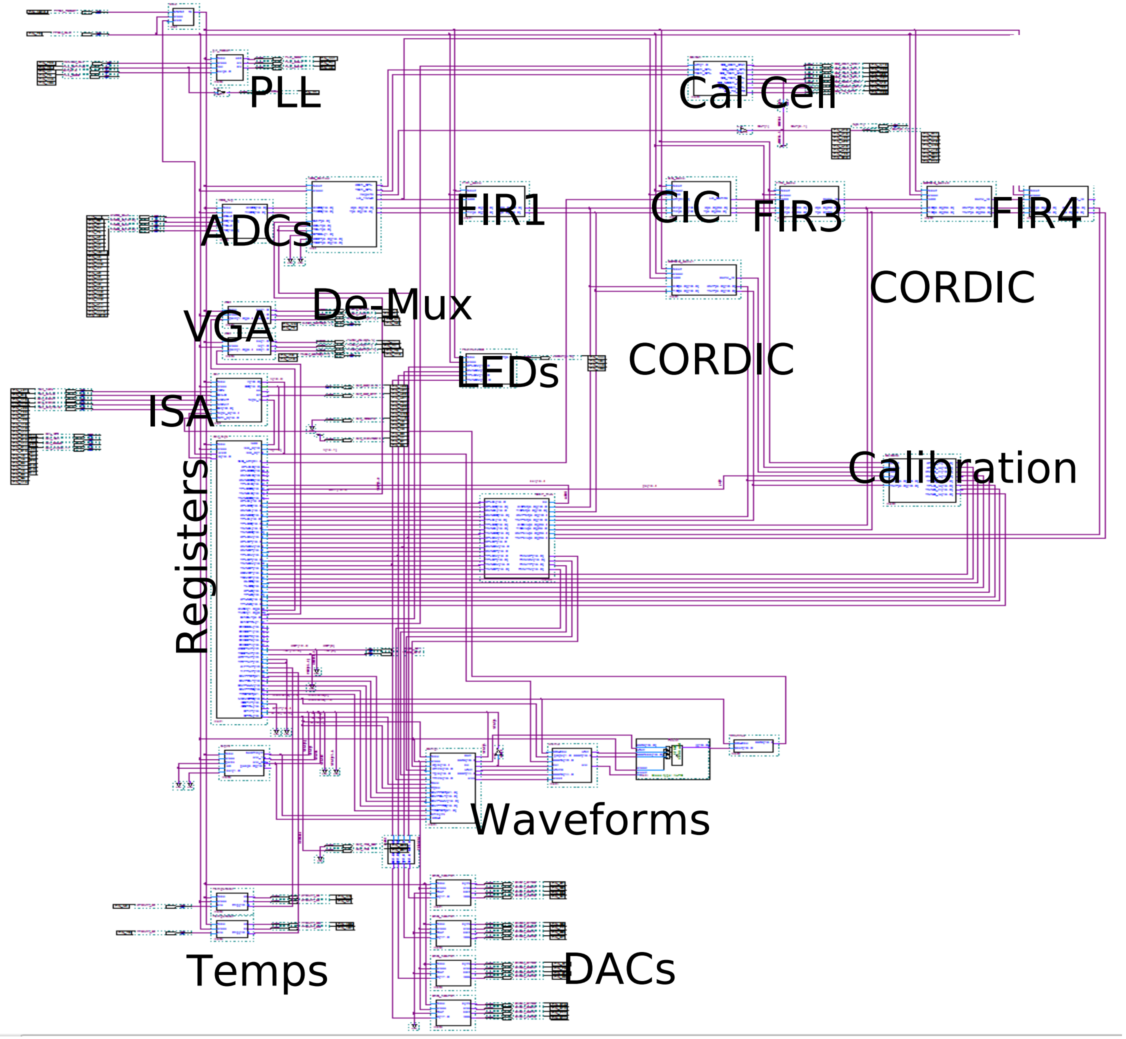
Decimating cascaded integrator-comb (CIC) filter; N stages, R decimation, M delays

12 GeV BPM Firmware (1 Channel)



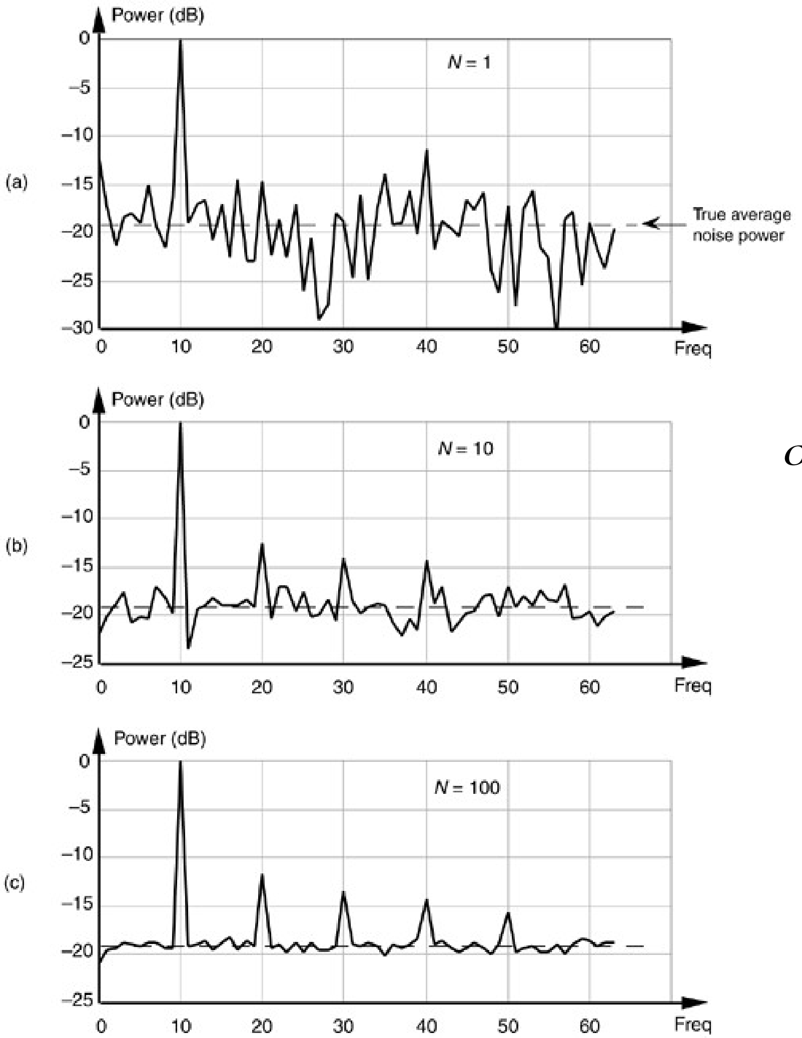
- FIR1&2: F_c = 250kHz
  - High speed data
  - Beam Sync, ...
- CIC: $F_c = F_s/10$ Hz
- FIR3: $F_c = F_s/100$ Hz
- FIR4: $F_c = F_s/10$ Hz

12 GeV BPM Firmware



- Waveforms
  - Fast and/or slow data
  - FSD circular buffer
  - "Beam gone" circular buffer
  - Adjustable size and rate
- Fast Feedback fiber output
- Diagnostic DACs for troubleshooting
- Flexibility
  - DSP algorithms can be changed to meet needs
  - Possible to implement other functionality (M56, MOMod lock-in, local position calculations..)

Filtering is basically integration...

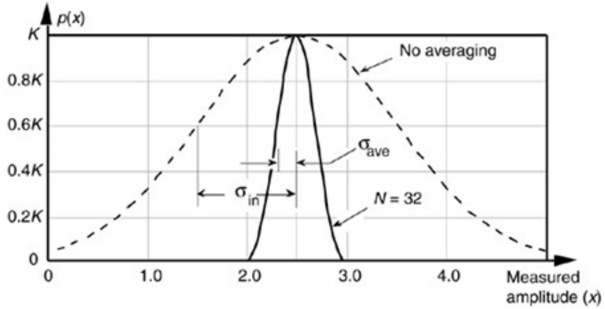


$$\sigma_{\overline{X}} = \frac{\sigma}{\sqrt{N}}$$

For amplitude measurement….

$$SNR_{\mathrm{incoh}}\ \mathrm{gain(dB)} = 10 \cdot \log_{10}(\sqrt{N})\ .$$

$$SNR_{\mathrm{coh}}\ \mathrm{gain(dB)} = 20 \cdot \log_{10}(SNR_{\mathrm{coh}}) = 20 \cdot \log_{10}(\sqrt{N}) = 10 \cdot \log_{10}(N)\ .$$



We generally express SNR in power ratios

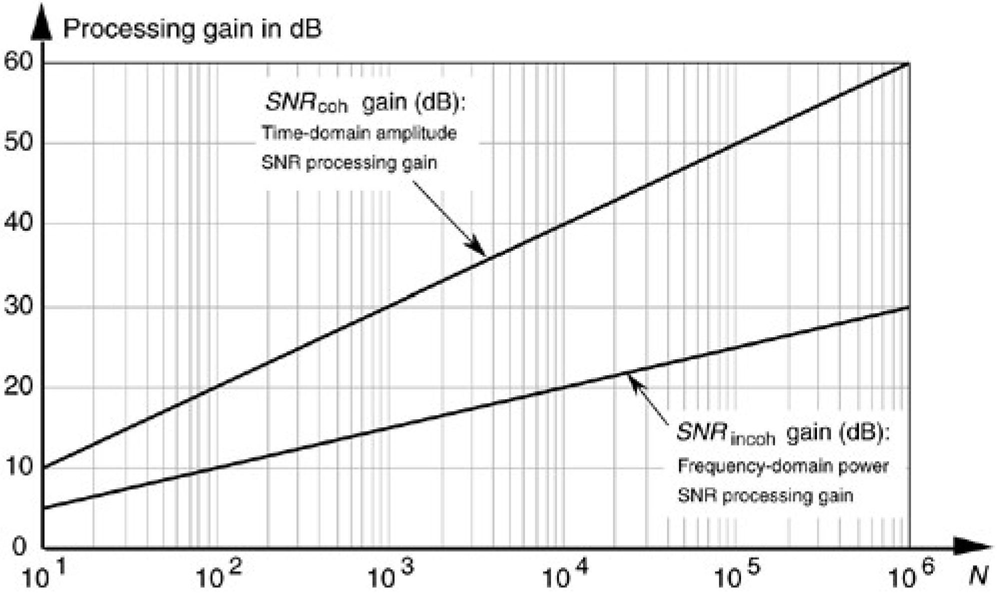
Let N be number of samples for a given bandwidth (>2x for Shannon/Nyquist compliance):

$$N = \frac{f_s}{2 * BW}$$

$$G_{processing} = 10 \cdot \log\left(\frac{f_s}{2 \cdot BW}\right)\ \text{dB}$$

Every factor of 6 dB improvement in SNR is an additional bit of significance…..

$$b_{excess} = \frac{G_{processing}}{6}$$

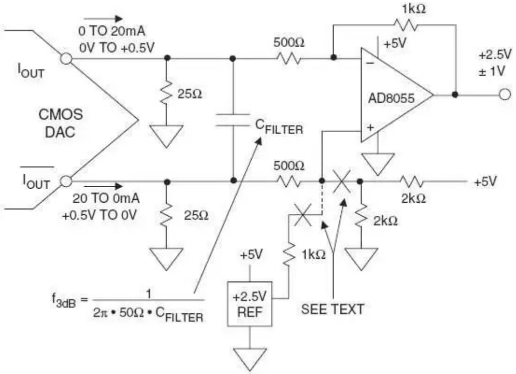


Example:
A 16-bit ADC, running at 60 MSPS (30 MSPS I/Q), with Signal-chain output BW of:

100 kHz	$16 + b_{excess} = 16 + 3 = 19\ b_{effective}$
1 kHz	$16 + b_{excess} = 16 + 7 = 23\ b_{effective}$
1 Hz	$16 + b_{excess} = 16 + 12 = 28\ b_{effective}$

An “ideal” 18-bit DAC can only faithfully represent an output bandwidth of ~1 MHz.

In reality, we usually lose 1-2 bits to noise, while analog output stages add additional noise (white *and* correlated).



12 GeV BPM Software

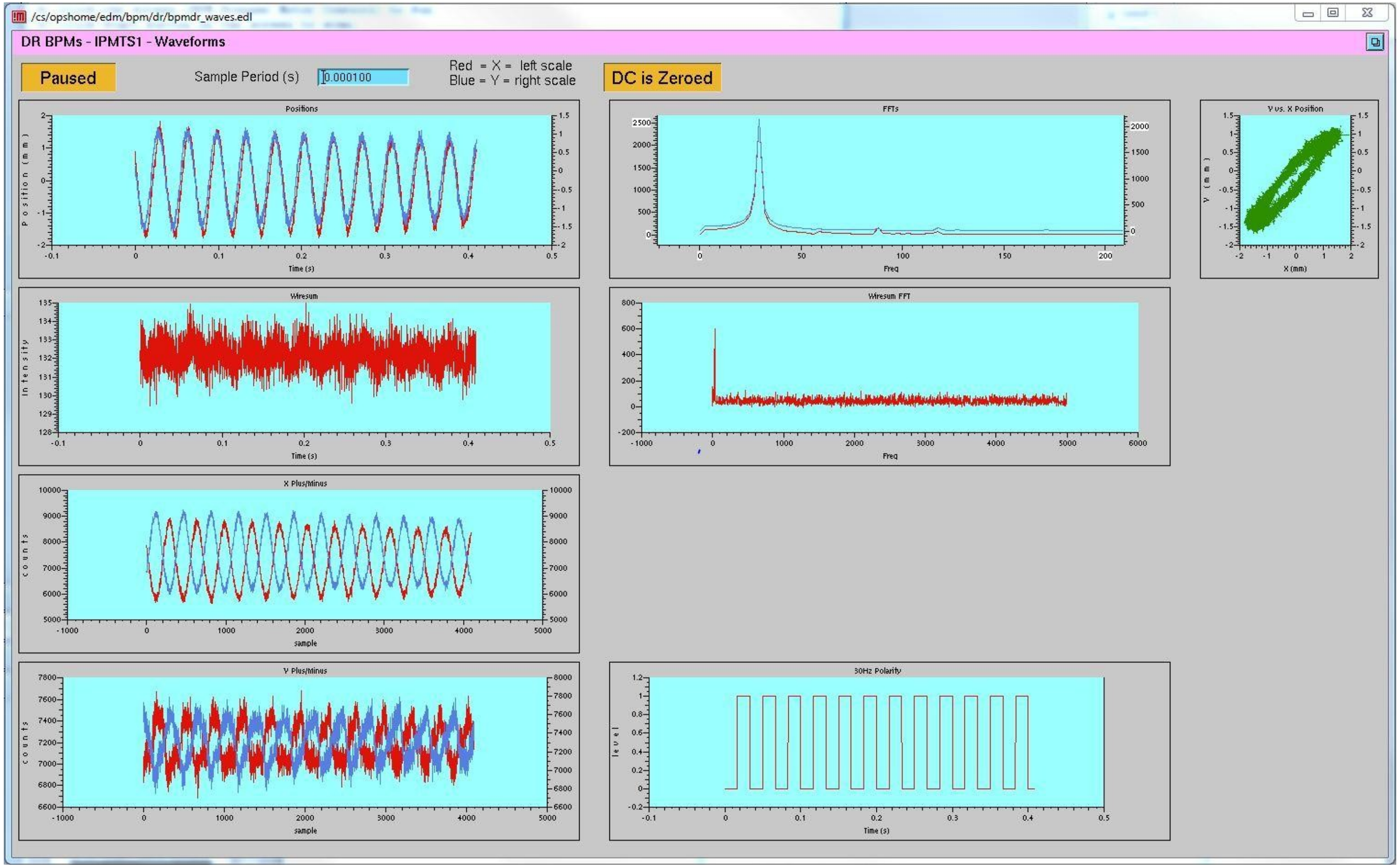
- One IOC per BPM
- PC104 inside chassis runs RTEMS and EPICS
- Data transfer is via paged memory map over the ISA bus
  - Interrupt driven
- Software design is based on SEE software
  - Buffered data from the FPGA has a similar format
  - Hardware control mimics SEE hardware functionality
  - Custom EPICS record based on bpmsee record
  - Calibration interface pending

12 GeV BPM Software

- "FastSEE" style data is always available
  - Sample period is user modifiable (1µs - ~35s)
  - At least twice an many samples available as FastSEE
- Position computations use the SEE algorithm
  - Timing mimics Linac Single Pass SEE
  - 1Hz position in **both** CW and Tune mode are based on sampling 32 times during the first 250 µs following each beam sync for 48 out of 60 beam syncs per second
  - Keeps positions steady when switching from Tune to CW

12 GeV BPM Software

Screen Shot of ~30Hz G-Line Pluck



On-Deck...New BCM

- Leaner, more specified version of 2-channel receiver
  - Version 1 Currently installed in UITF

- Simple protocol already written by Chad Seaton, and utilized in previous run.

- SFP Form-factor modules allow gigabit fiber/copper transmissions

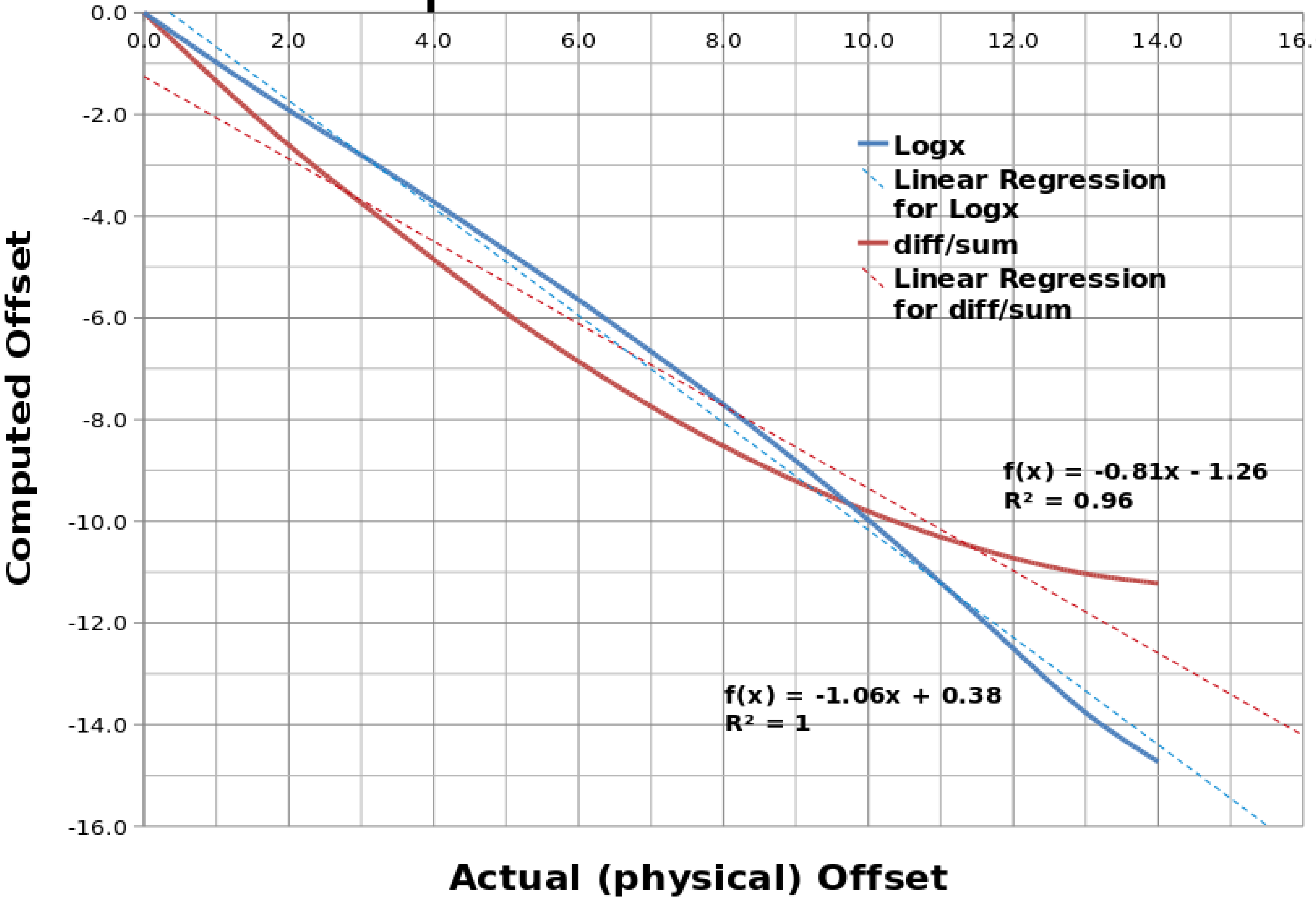
We can likely adopt timing and transmission requirements, if not too much overhead. We do feel more comfortable with Physics owning the DAC, signal conditioning, and DAQ-related activities…...

SPM Testing/Characterization

- Motivation
  - Verify manufacturability
  - Determine coeffs for each element/plane
  - Locate electrical center vs. physical center
  - Improve test methods
  - Provide precise data for CASA models

Position Calculation Algorithm Comparison

Agilent ENA5071
3-port N.A.



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

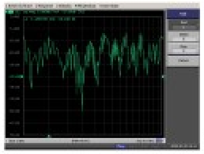
J. Musson, K. Cole, Thomas Jefferson National Accelerator Facility, Newport News, VA
S. Rubin, Rubytron, Port Chester, NY

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

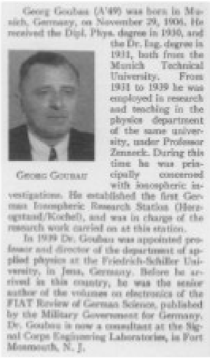


Return Loss (S11) plot of 1.6 mm diameter RadWire

Insertion Loss (S21) plot of 160 um diameter RadWire

Return Loss (S11) plot of 160 um diameter RadWire

Goubau



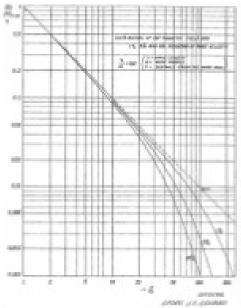
Georg Goubau (A'49) was born in Munich, Germany, on November 29, 1906. He received the Dipl. Phys. degree in 1930, and the Dr. Ing. degree in 1931, both from the Munich Technical University. From 1931 to 1939 he was employed in research and teaching in the physics department of the same university, under 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.

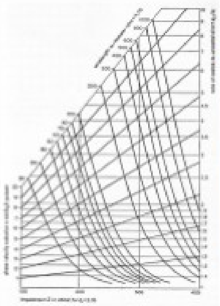
In 1939 Dr. Goubau was appointed professor and director of the department of applied physics at the Friedrich-Schiller University, in Jena, Germany. Before he arrived in this country, he was the senior author of the volumes on electronics of the FIAT Review of German Science, published by the Military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

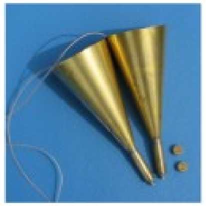
Georg Goubau

RUBYTRON

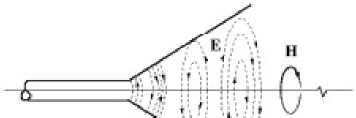
Development Of Surface Wave Lancher







.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.

Office of Science
U.S. DEPARTMENT OF ENERGY

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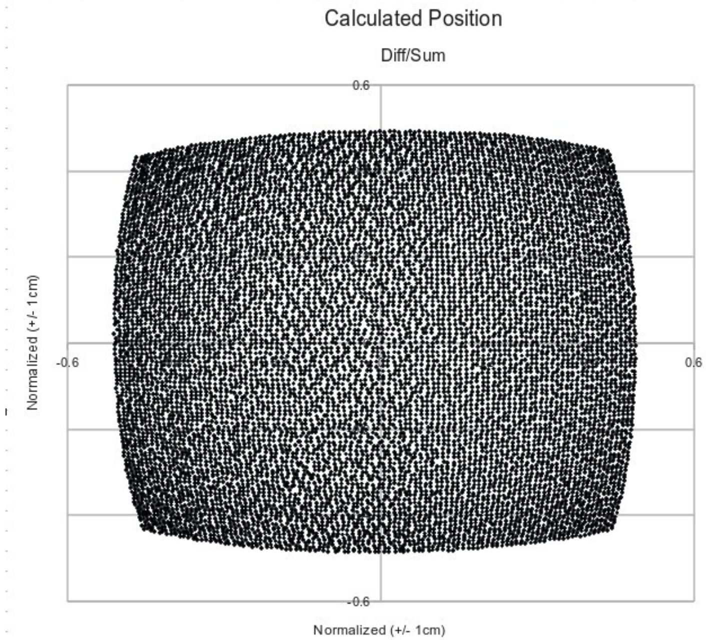
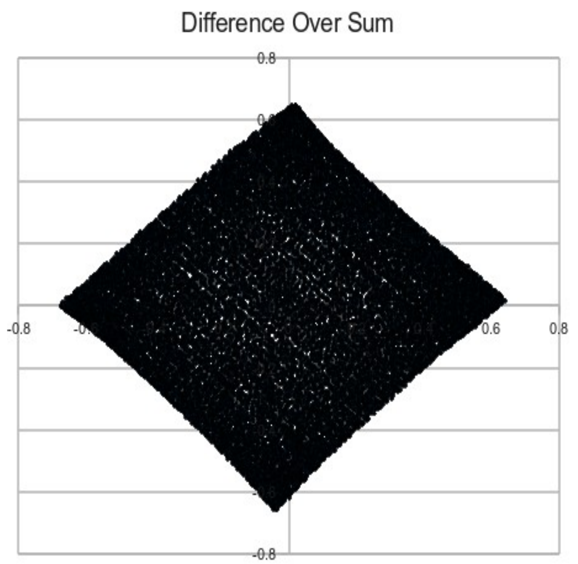
JSA Jefferson Science Associates, LLC
a SURA/CSC Company
Jefferson Lab

G-Line First-Fruits...

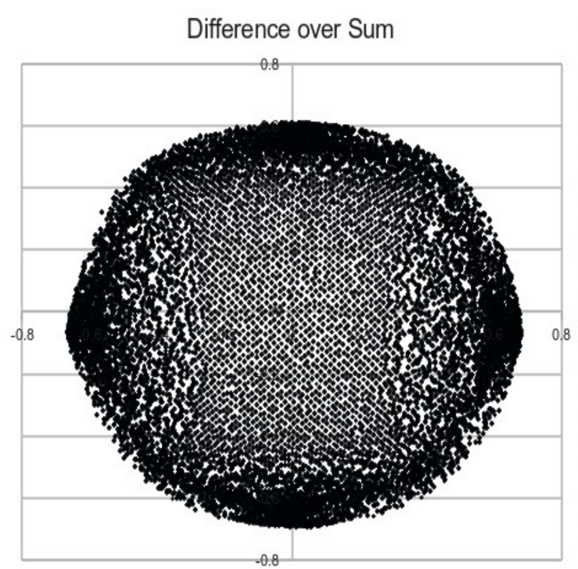
Step-size = 250 um



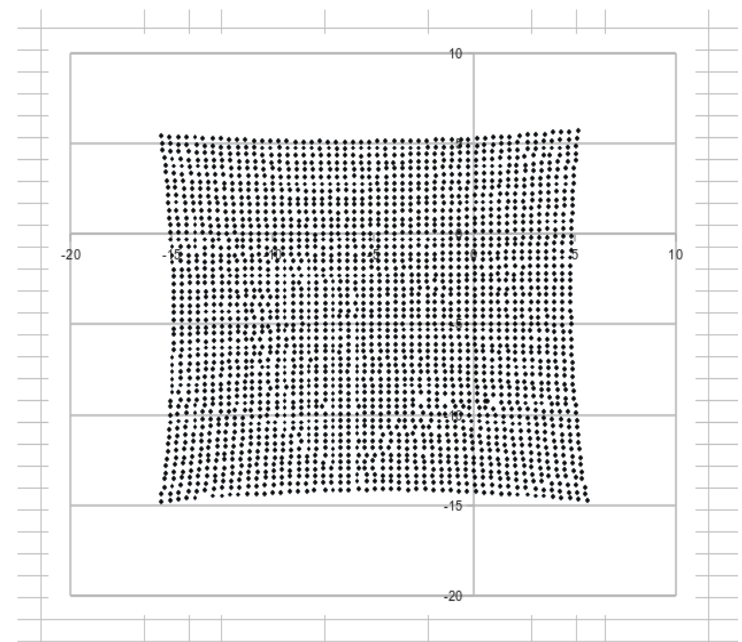
Sripline 1.5 cm^2 scan



M15 BPM



Stripline Prototype (full scan)



Stripline phase scan (interferometric)

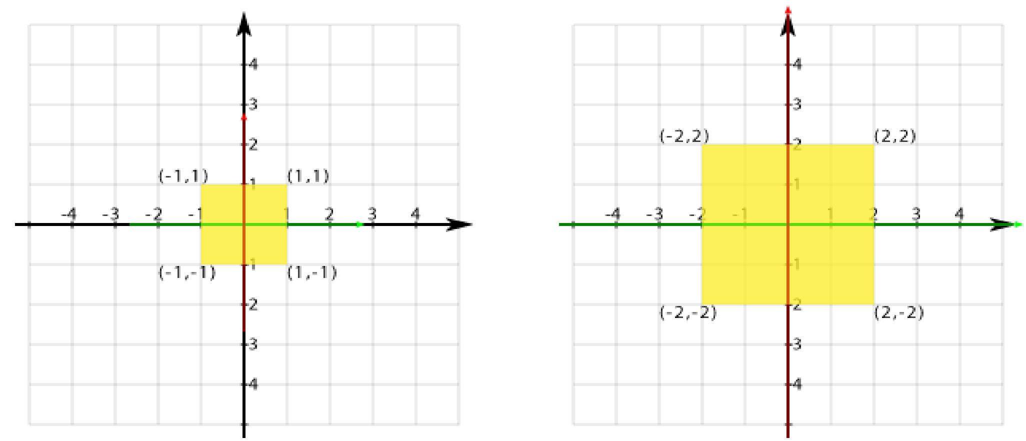
G-Line: 2-D Field Map Transformations

- Translation

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

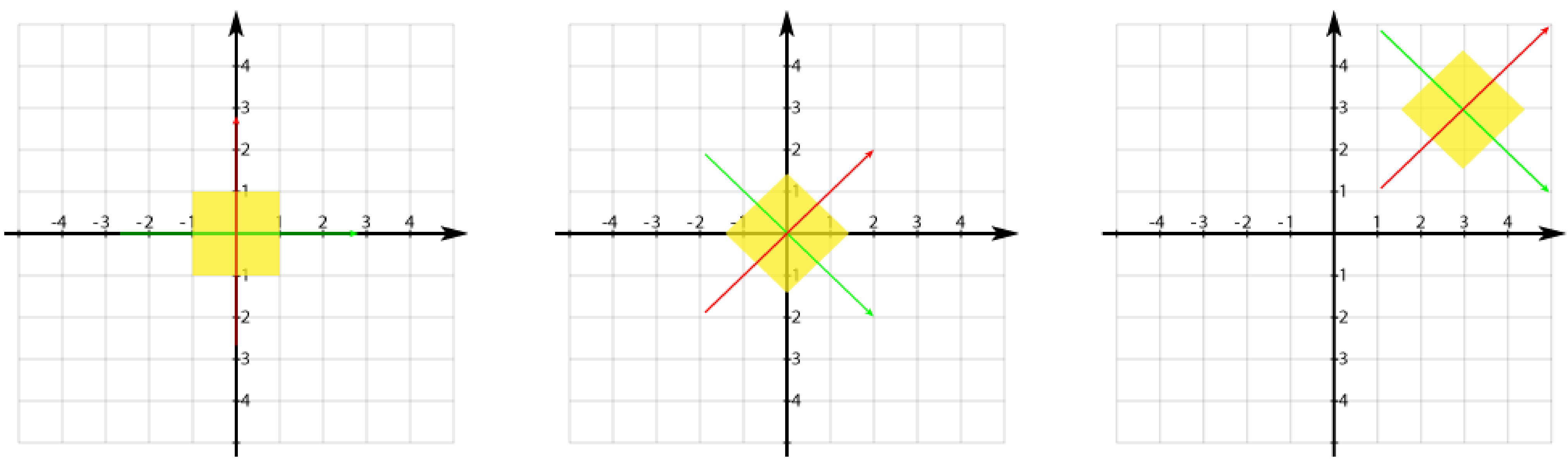
- Scaling

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

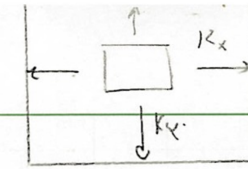


- Rotation

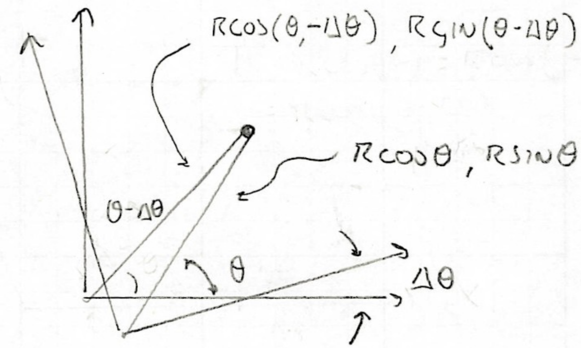
$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$



LMS Process, for Difference-over-Sum



$$X_{MEAS} = \frac{X_+ - X_-}{X_+ + X_-} = R\cos\theta$$



$$Y_{MEAS} = \frac{Y_+ - Y_-}{Y_+ + Y_-} = R\sin\theta$$

$$X_{PROPER} = K_x \cdot X_{MEAS} = K_x \cdot R\cos(\theta - \Delta\theta)$$

Combine rotation and scaling

$$Y_{PROPER} = K_y Y_{MEAS} = K_y R\sin(\theta - \Delta\theta)$$

(MARION, 1970)

EXTRACT $\Delta\theta$:

$$\cos(\alpha - \beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta$$

$$\sin(\alpha - \beta) = \sin\alpha\cos\beta - \cos\alpha\sin\beta$$

$$X_{PROPER} = K_x R\cos\theta\cos\Delta\theta + K_x R\sin\theta\sin\Delta\theta$$

$$= K_x\cos\Delta\theta \cdot X_{MEAS} + K_x\sin\Delta\theta \cdot X_{MEAS} = \alpha_x X_{MEAS} + \beta_x Y_{MEAS}$$

$$Y_{PROPER} = K_y R \sin\theta \cos\Delta\theta - K_y R \cos\theta \sin\Delta\theta$$

$$= K_y \cos\Delta\theta \; Y_{meas} - K_y \sin\Delta\theta \; X_{meas} = \alpha_y X_{meas} + \beta_y Y_{meas}$$

$$\alpha_x = K_x \cos\Delta\theta$$

$$\beta_x = K_x \sin\Delta\theta$$

$$\alpha_y = -K_y \sin\Delta\theta$$

$$\beta_y = K_y \cos\Delta\theta$$

NOW, ADD TRANSLATION:

$$X_{PROPER} = \alpha_x X_{meas} + \beta_x Y_{meas} + \Delta X$$

$$Y_{PROPER} = \alpha_y X_{meas} + \beta_y Y_{meas} + \Delta Y$$

LET $X = X_{PROPER}$

$Y = Y_{PROPER}$

$$X_1 = \alpha_x X_{meas_1} + \beta_x Y_{meas_1} + \Delta X$$
$$X_2 = \alpha_x X_{meas_2} + \beta_x Y_{meas_2} + \Delta X \quad , \quad \alpha_x = K_x \cos\Delta\theta$$
$$\vdots$$
$$X_n = \alpha_x X_{meas_n} + \beta_x Y_{meas_n} + \Delta X \quad \beta_x = K_x \sin\Delta\theta$$

$$Y_1 = \alpha_y X_{meas_1} + \beta_y Y_{meas_1} + \Delta Y$$
$$Y_2 = \alpha_y X_{meas_2} + \beta_y Y_{meas_2} + \Delta Y \quad , \quad \alpha_y = -K_y \sin\Delta\theta$$
$$\vdots$$
$$Y_n = \alpha_y X_{meas_n} + \beta_y Y_{meas_n} + \Delta Y \quad \alpha_y = K_y \cos\Delta\theta$$

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix} = \lambda \cdot \begin{bmatrix} \alpha_x \\ \beta_x \\ \Delta X \end{bmatrix} , \quad \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix} = \lambda \cdot \begin{bmatrix} \alpha_y \\ \beta_y \\ \Delta Y \end{bmatrix}$$

$$\lambda = \begin{bmatrix} X_{meas_1} & Y_{meas_1} & 1 \\ X_{meas_2} & Y_{meas_2} & 1 \\ \vdots & \vdots & \vdots \\ X_{meas_n} & Y_{meas_n} & 1 \end{bmatrix}$$

Finally,

$$\begin{bmatrix} \alpha_x \\ \beta_x \\ \Delta X \end{bmatrix} = \lambda^{-1} \cdot \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix}$$

$$\begin{bmatrix} \alpha_y \\ \beta_y \\ \Delta Y \end{bmatrix} = \lambda^{-1} \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix}$$

Use "Pseudo-Inverse": (Moore-Penrose, Rao, Mitra, 1971)

$$\lambda^{-1} = (\lambda^T \lambda)^{-1} \cdot \lambda^T$$

So,

$$\begin{bmatrix} \alpha_x \\ \beta_x \\ \Delta X \end{bmatrix} = (\lambda^T \lambda)^{-1} \lambda^T \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix}$$, Least MSE (Bishop, 2006)

$$\begin{bmatrix} \alpha_y \\ \beta_y \\ \Delta X \end{bmatrix} = (\lambda^T \lambda)^{-1} \lambda^T \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix}$$, Least MSE (Bishop, 2006)

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

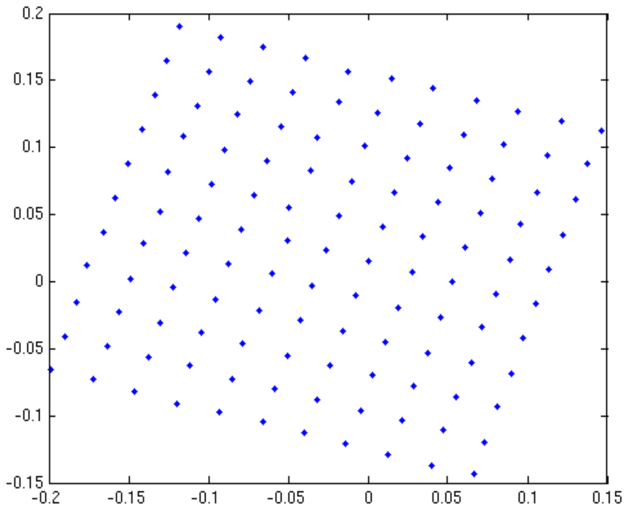
$$\Delta_x, \Delta_y$$

Arbitrary field offset;

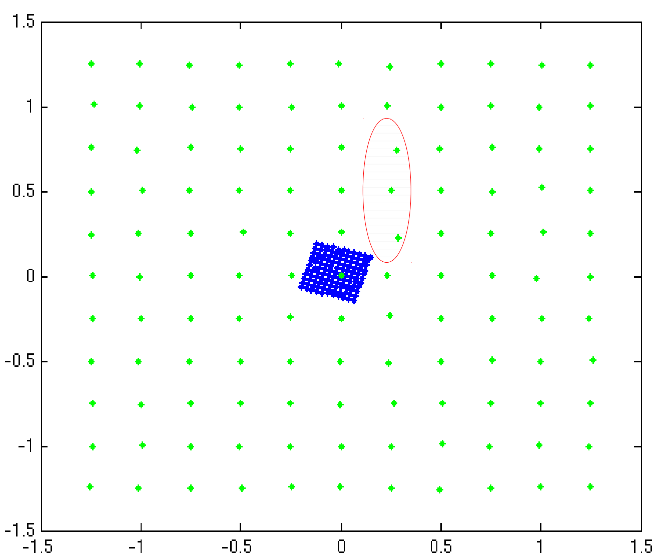
Merely tells us where we “should” have started the scan

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

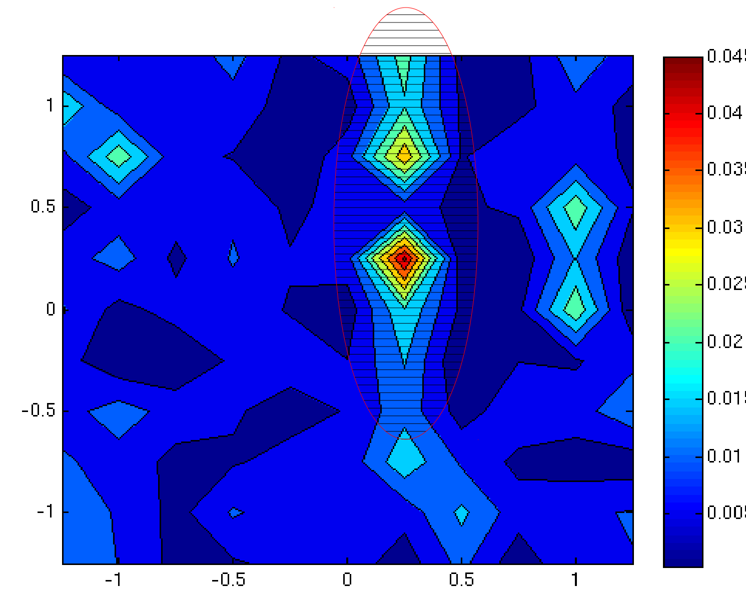
Algorithm Verification



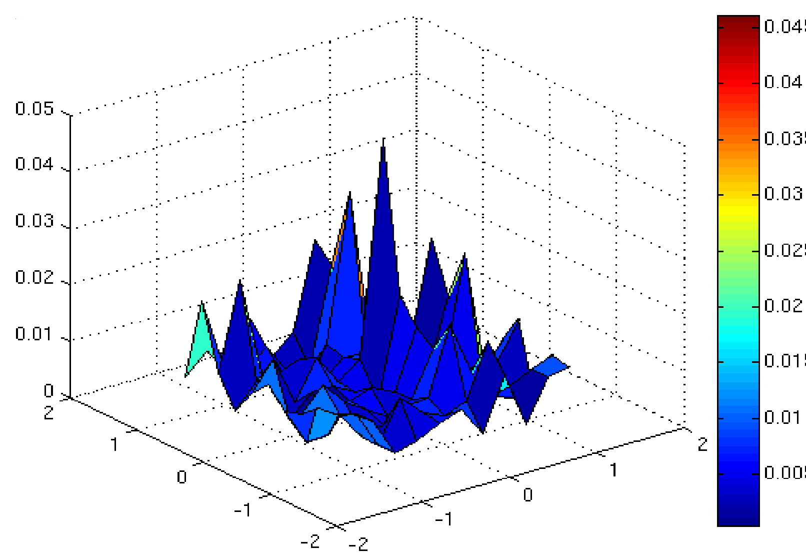
Raw Field Measurement



Scaled, Rotated, Translated....



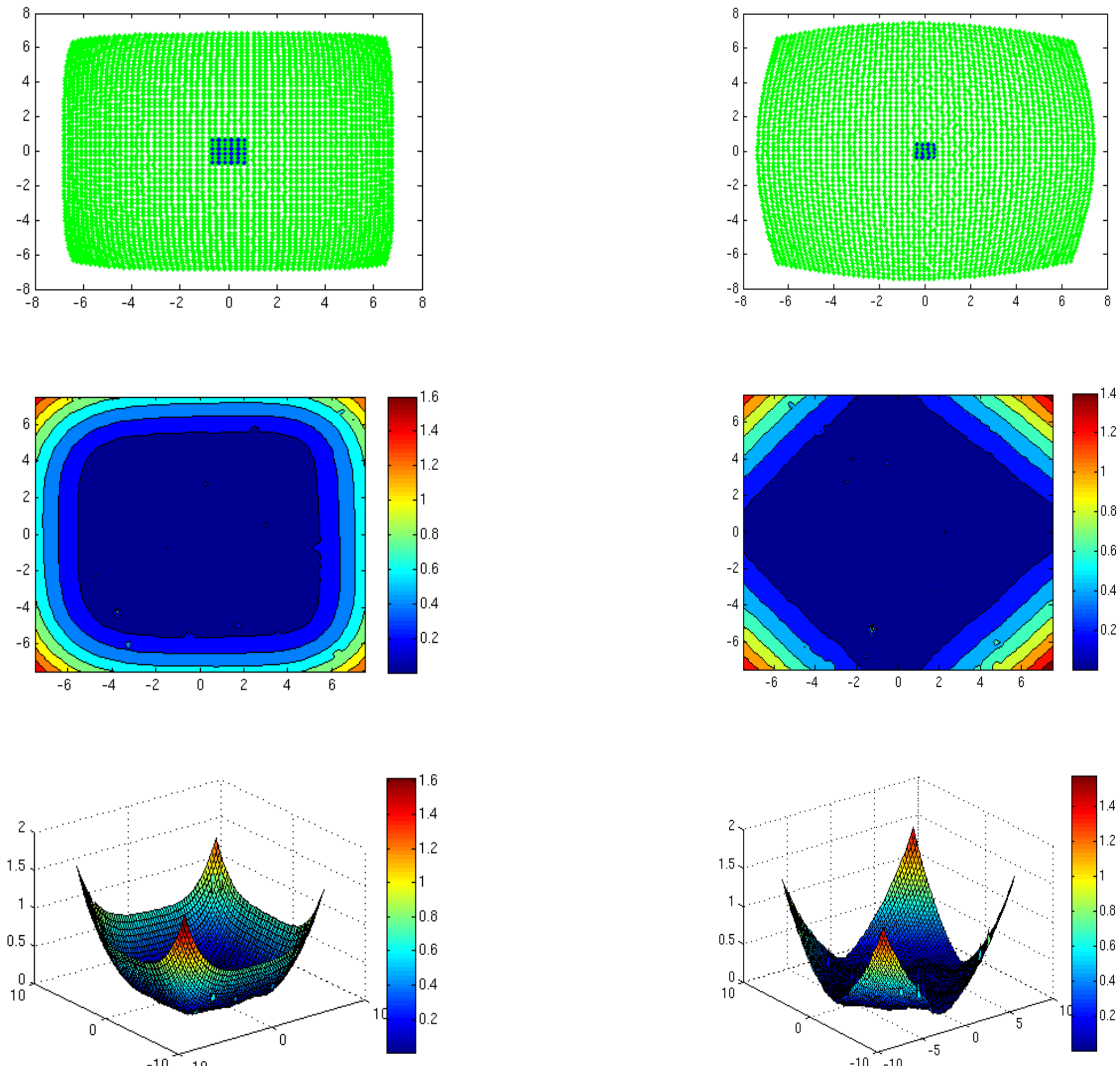
RMS Error Vector Magnitudes



Algorithm Applied to SPM Scan

LMS per 1cm x 1cm

Step-size = 250 um



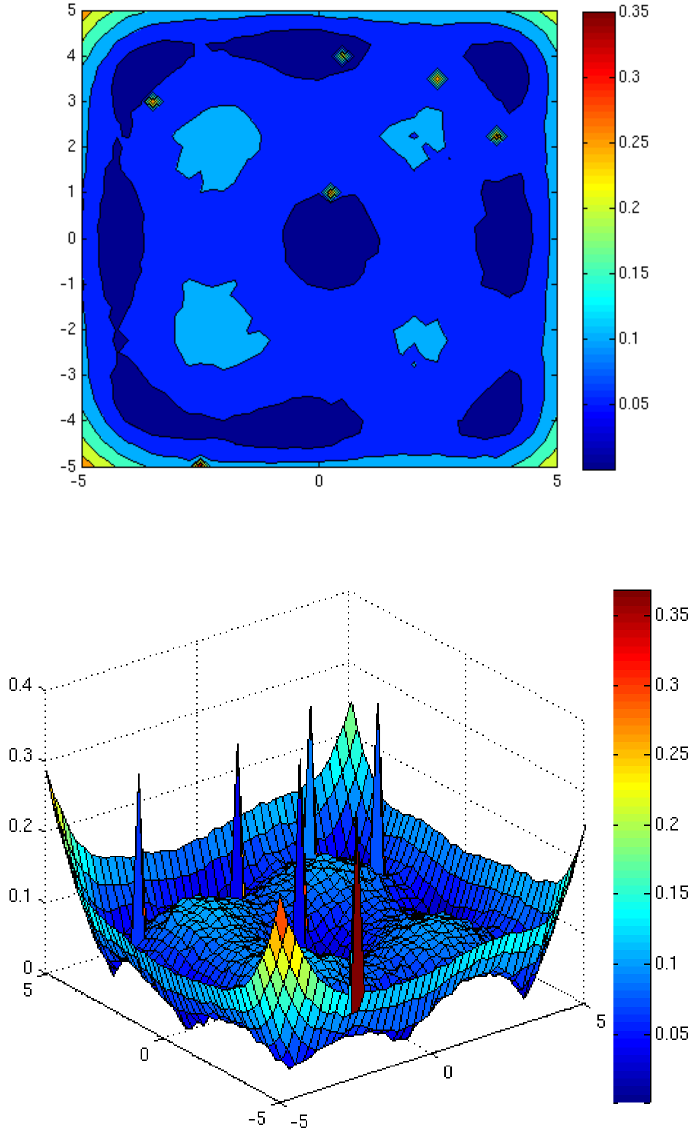
Units are in mm

SPM

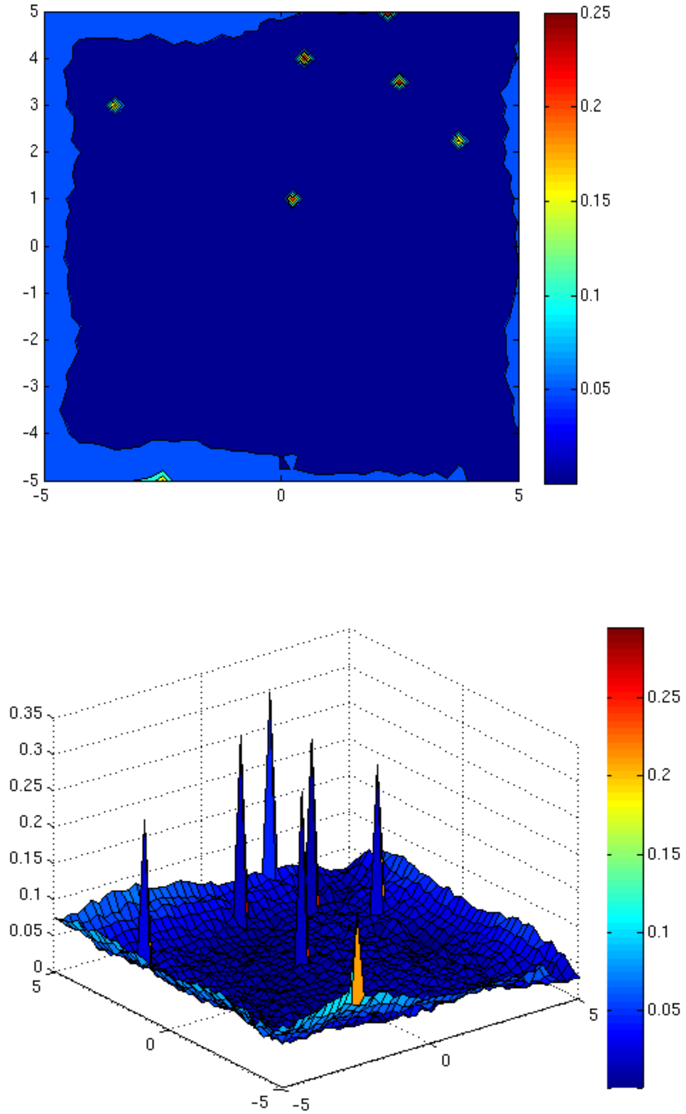
M15

LMS Fit: 1 cm^2 (SPM 26)

Linear Fit

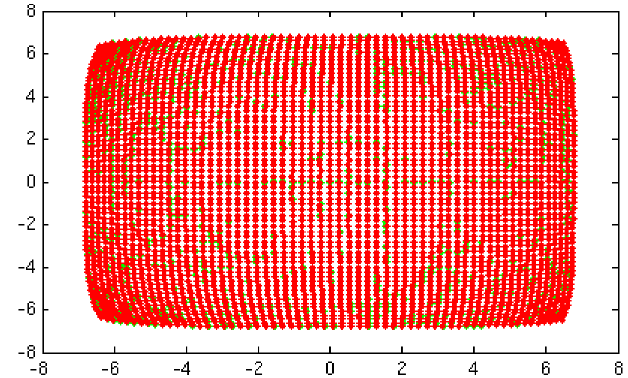


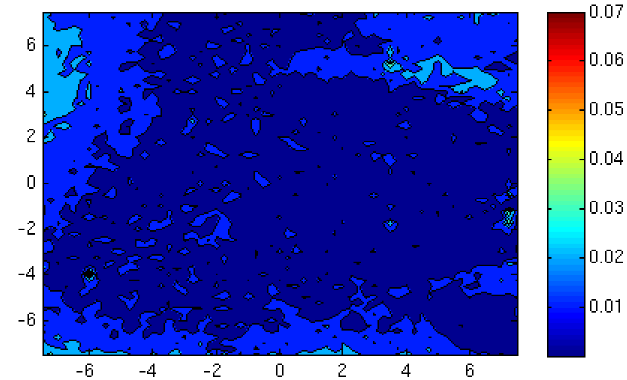
Log Fit



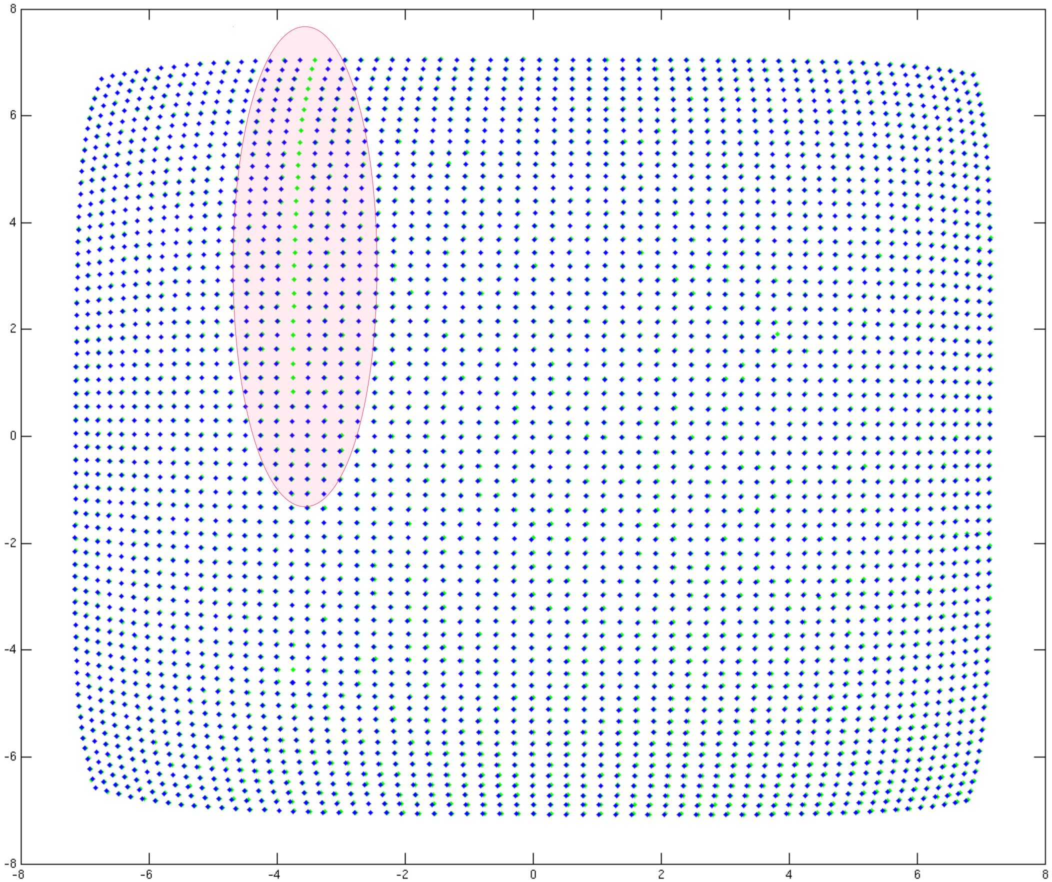
Scan Repeatability
(2 weeks...post-regression)

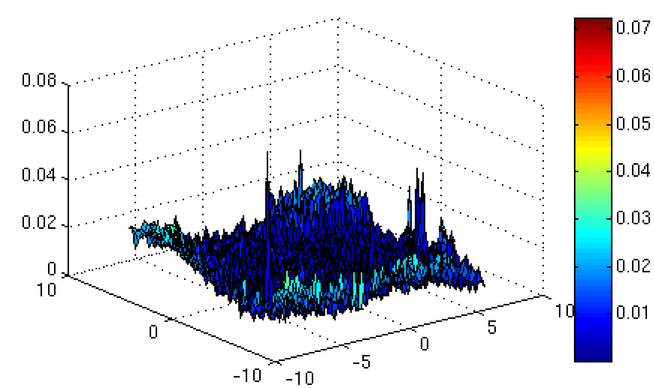
EVM





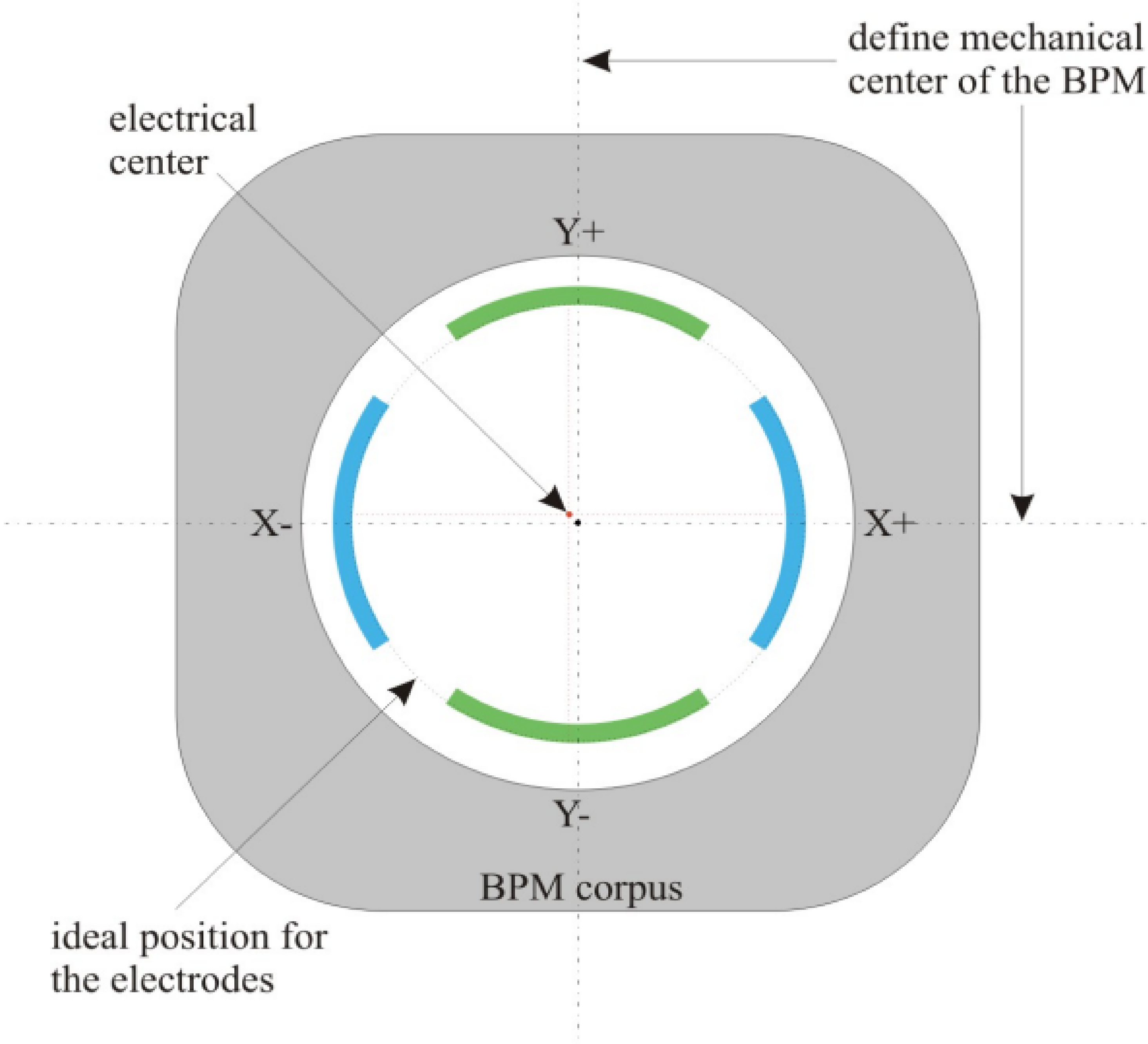
SPM 26





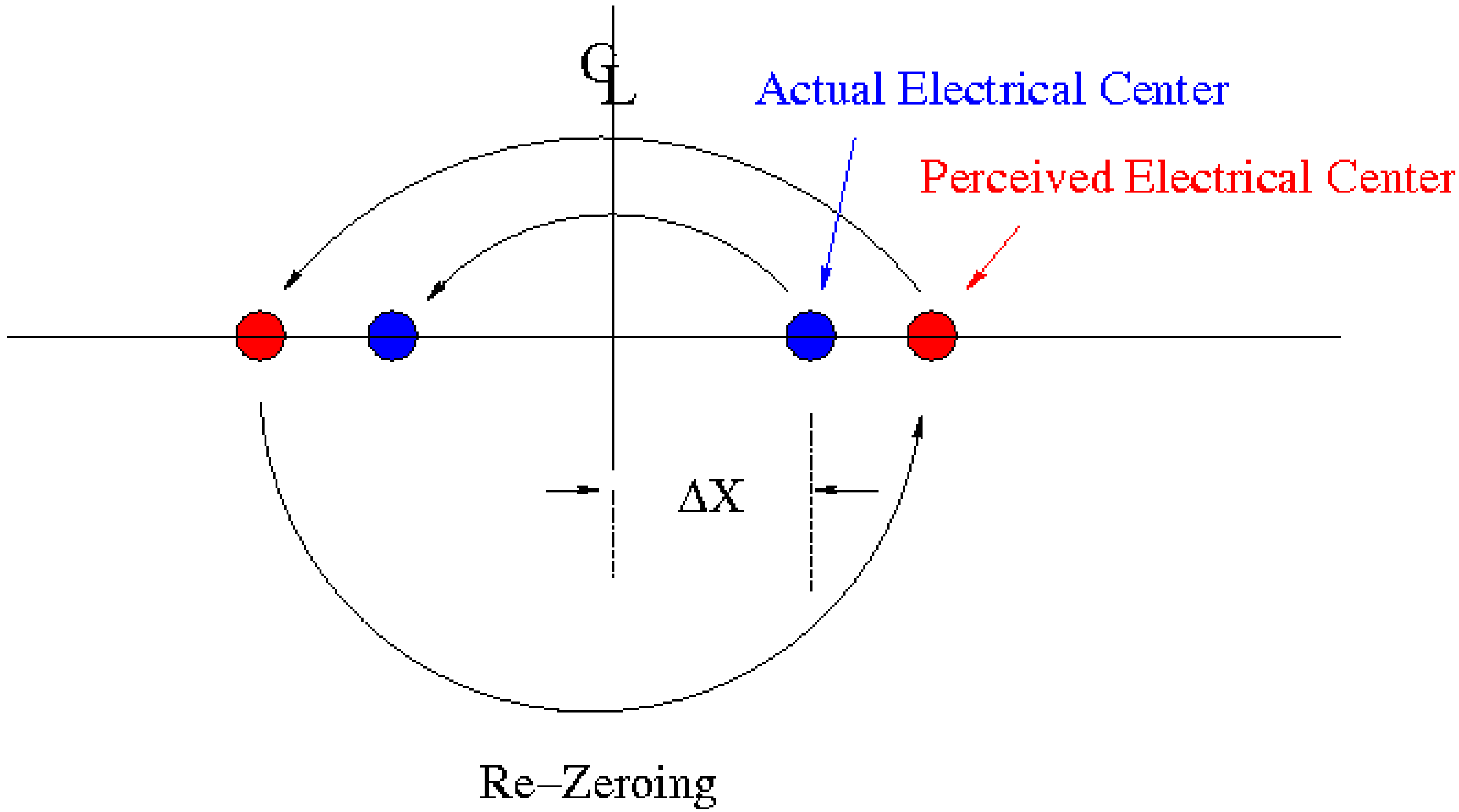
Missing data points reveal registration!!

Fiducialization



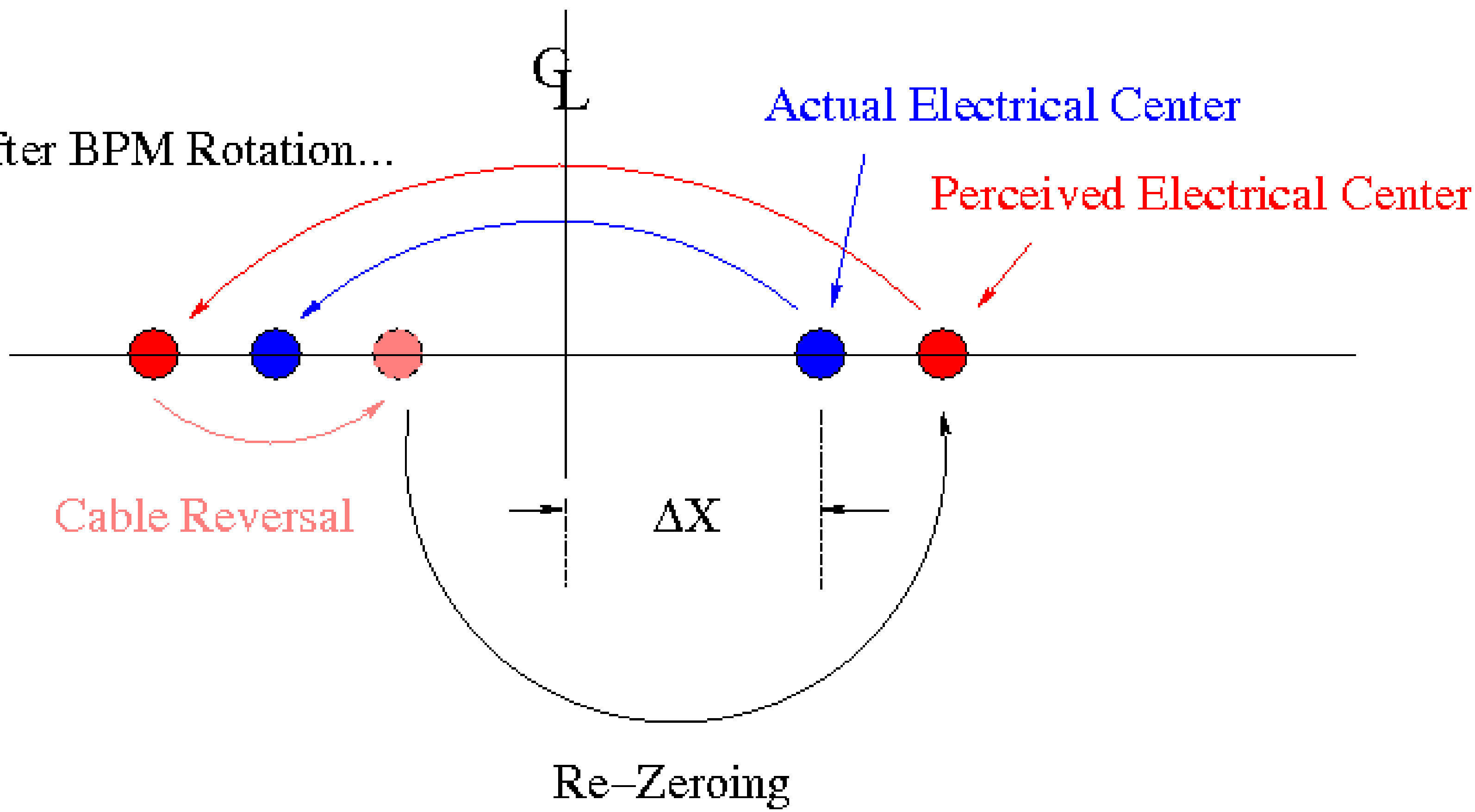
Effect of Test Cables / VVM Sensitivity

Case#1: No Cable Reversal



Effect of Test Cables, etc. (cont.)

Case#2: With Cable Reversal



Additional Sources of Error

- **Differential**
  - HP 8508A
    - +/- 0.2 dB
  - Cables
    - IL
      - -.467 dB
      - -.465 dB
      - -.463 dB
      - -.470 dB

      +/- 0.01 dB
  - Switch Imbalance

    +/- 0.05 dB

- **Non-Differential**
  - Geometry of Cradle
  - Mounts hold the pipe, not the body
  - An additional account code will likely fix....

BPM Summary

- SPM (n=33)
  - Kx, Ky = 9.91 mm

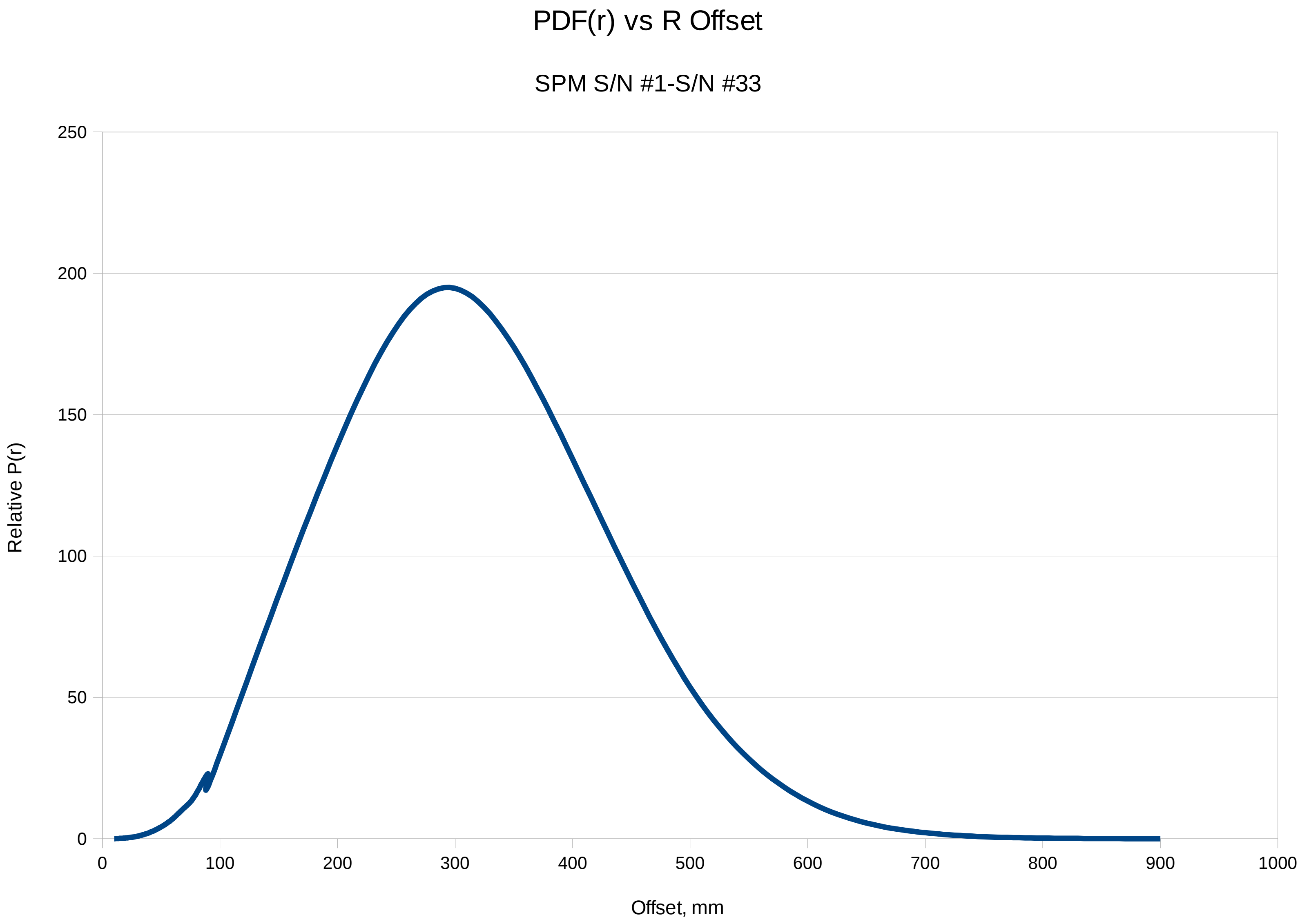
    +/- 0.19mm
  - Ax, Ay = 0.539 mm/dB

    +/- 0.01mm/dB
  - Coupling = 0.13 degrees
    +/- 0.12 degrees
  - Offset =211 um
- M15 (n=5)
  - Kx, Ky = 18.4 mm

    +/- 0.12mm
  - Ax, Ay = 1.05 mm/dB

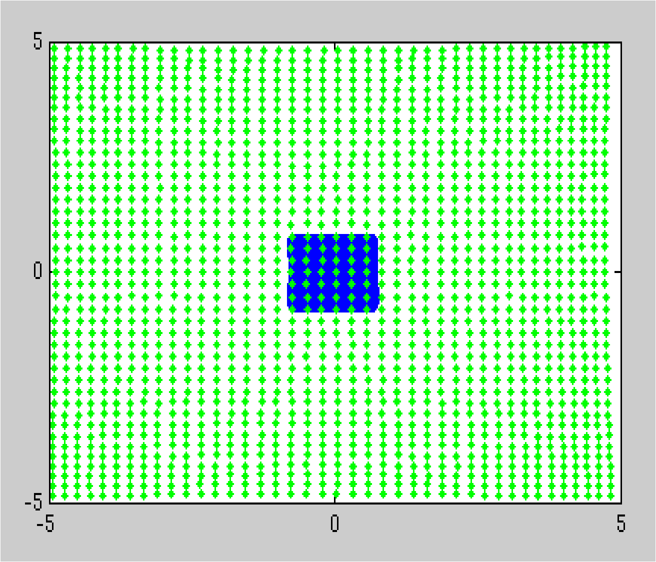
    +/- 0.01mm/dB
  - Coupling = 0.4 degrees
    +/- 0.2 degrees
  - Offset =235 um

Displacement Error Distribution



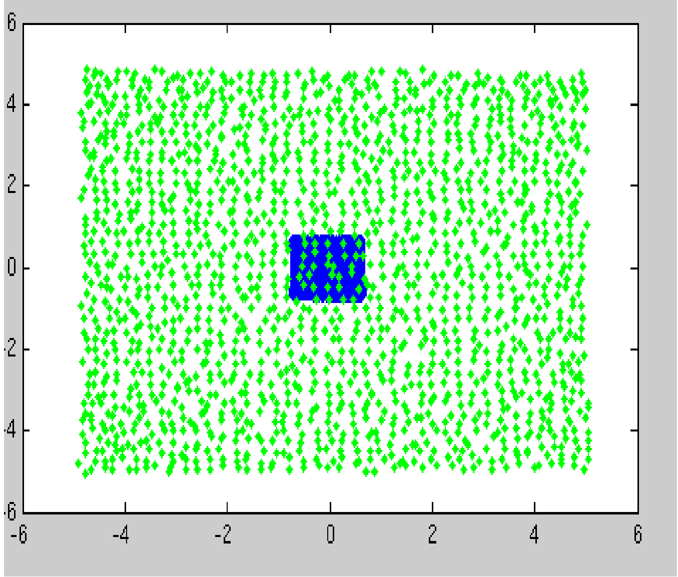
				TRUE (Position wrt Physical Center)					Linear Position Method			Log Position Method			Orthog
S/N	Delta-X counts	Delta_Y counts		X um	Y um	R um	Theta degrees		Kx mm	Ky mm	Ratio Kx/Ky dB	Ax mm/dB	Ay mm/dB	Delta dB	d_Theta degrees (mag)
M20															
M15_002	-1270	390		-158.75	-48.75	166.066628	17.0692993		18.49890	18.49230	0.00310	1.04840	1.04800	0.00040	0.38570
M15_015	1220	670		152.5	-83.75	173.983656	-28.7718221		18.41690	18.37540	0.01959	1.04350	1.04120	0.00230	0.12030
M15_013	880	-460		110	57.5	124.121916	27.5945121		18.51060	18.58960	-0.03699	1.04910	1.05360	-0.00450	0.67580
M15_028	700	2250		87.5	-281.25	294.546792	-72.7111664		18.25200	18.27410	-0.01051	1.03390	1.03520	-0.00130	0.51290
M15_023	2850	1700		356.25	-212.5	414.813588	-30.8125973		18.52400	18.51130	0.00596	1.04990	1.04910	0.00080	0.26720
Proto_#3	N/A	N/A		N/A	N/A	N/A	N/A		N/A	N/A	N/A	N/A	N/A	N/A	N/A
Proto_#2	1750	-1600		218.75	200	296.397643	42.4319492		9.73610	9.55280	0.16509	0.52840	0.51720	0.01120	0.07740
Proto_#1	-800	-1020		-100	127.5	162.037804	-51.8871887		9.65590	9.81810	-0.14469	0.52350	0.53340	-0.00990	0.11570
33	-440	1520		-55	-190	197.800404	73.8482113		9.94930	10.10060	-0.13109	0.54140	0.55050	-0.00910	0.05730
32	-2800	280		-350	-35	351.745647	5.7100171		10.08190	9.88850	0.16824	0.54940	0.53760	0.01180	0.16450
31	1120	2280		140	-285	317.529526	-63.8319941		9.81230	10.02380	-0.18523	0.53300	0.54590	-0.01290	0.07130
30	-40	180		-5	-22.5	23.0488611	77.4633777		9.99770	9.86770	0.11368	0.54430	0.53640	0.00790	0.14370
29	340	-300	'360, -380	42.5	37.5	56.6789202	41.4194872		9.70400	9.87230	-0.14935	0.52640	0.53670	-0.01030	0.00140
28	1400	-60		175	7.5	175.160641	2.45378413		9.74340	10.00000	-0.22579	0.52880	0.54450	-0.01570	0.01470
27	2180	-160		272.5	20	273.232959	4.19724493		9.67030	9.89490	-0.19943	0.52440	0.53810	-0.01370	0.04860
26	-440	340	-320, 300	-55	-42.5	69.5071939	-142.291405		9.88470	9.93940	-0.04793	0.53750	0.54080	-0.00330	0.16660
25	-1820	-1040		-227.5	130	262.023377	150.239962		10.01540	9.83030	0.16203	0.54540	0.53410	0.01130	0.11800
24	-940	-2100		-117.5	262.5	287.597809	114.102688		10.03080	10.08160	-0.04388	0.54630	0.54940	-0.00310	0.02150
23	1260	2420		157.5	-302.5	341.046185	-62.4894538		10.12520	10.11850	0.00575	0.55210	0.55160	0.00050	0.07110
22	2500	460		312.5	-57.5	317.745968	-10.4247569		10.02500	9.87360	0.13218	0.54600	0.53670	0.00930	0.20830
21	-1480	1300		-185	-162.5	246.234137	-138.690636		9.83330	9.88500	-0.04555	0.53430	0.53740	-0.00310	0.00038
20	1460	700		182.5	-87.5	202.391946	-25.6129004		10.00320	9.99990	0.00287	0.54460	0.54440	0.00020	0.12960
19	1100	-1440		137.5	180	226.50883	52.6188842		10.11580	10.05410	0.05314	0.55150	0.54770	0.00380	0.09710
18	-600	940		-75	-117.5	139.396019	-122.537642		9.89630	9.94060	-0.03879	0.53820	0.54080	-0.00260	0.21390
17	-440	740		-55	-92.5	107.616216	-120.723309		10.13830	10.22760	-0.07617	0.55290	0.55830	-0.00540	0.09560
16	-1160	540		-145	-67.5	159.941396	-155.021571		10.13760	10.03210	0.09087	0.55280	0.54640	0.00640	0.17030
15	260	900		32.5	-112.5	117.100384	-73.8791287		10.06170	10.16220	-0.08633	0.54820	0.55430	-0.00610	0.13210
14	-820	-500		-102.5	62.5	120.052072	148.612003		10.09280	10.09750	-0.00404	0.55010	0.55040	-0.00030	0.03180
13	1860	-580		232.5	72.5	243.541578	17.3171914		9.92440	9.98000	-0.04853	0.53990	0.54320	-0.00330	0.14700
12	-1780	520		-222.5	-65	231.800022	-163.698563		10.06970	9.96690	0.08913	0.54870	0.54240	0.00630	0.14380
11	-960	500		-120	-62.5	135.300591	-152.472616		9.99110	10.02370	-0.02830	0.54390	0.54580	-0.00190	0.11800
10	400	2100		50	-262.5	267.219479	-79.2077115		9.94410	9.61360	0.29359	0.54100	0.52090	0.02010	0.24360
9	1700	-900		212.5	112.5	240.442301	27.894457		9.75490	9.35270	0.36572	0.52940	0.50480	0.02460	0.07590
8	-1300	250		-162.5	-31.25	165.477529	-169.097414		9.69730	9.99420	-0.26194	0.52600	0.54410	-0.01810	0.00630
7	-1850	-2000		-231.25	250	340.553318	132.755433		9.94150	9.49930	0.39521	0.54090	0.51390	0.02700	0.06980
6	-3350	750		-418.75	-93.75	429.116097	-167.363794		9.70480	9.61900	0.07713	0.52640	0.52120	0.00520	0.71030
5	-750	-500		-93.75	62.5	112.673477	146.295174		9.45430	9.75720	-0.27392	0.51110	0.52960	-0.01850	0.13120
4	250	2550		31.25	-318.75	320.278199	-84.392147		10.08040	9.95220	0.11117	0.54930	0.54150	0.00780	0.19900
3	-500	-1900		-62.5	237.5	245.586034	104.732997		9.34500	9.79520	-0.40868	0.50440	0.53200	-0.02760	0.10130
2	-100	-200		-12.5	25	27.9508497	116.553293		9.78360	9.72050	0.05620	0.53120	0.52740	0.00380	0.13160
1	-300	-2500		-37.5	312.5	314.741958	96.8330047		10.00690	9.90490	0.08899	0.54490	0.53860	0.00630	0.16750
00									16.9245	16.9336	-0.00467	0.9562	0.9567	-0.00050	0.0794
			Average	-22.8788	-19.2803	211.014467	um	Average	9.9096	9.9112	-0.0015	0.5389	0.5390	-0.0001	0.1274
			St. Dev.	175.8352	160.8990	110.16869	um	St. Dev.	0.1942	0.1889	0.0023	0.0119	0.0115	0.0122	0.1232
				sigma	168.367084										
				r=	211	0.39343	P(r)								

Resolution

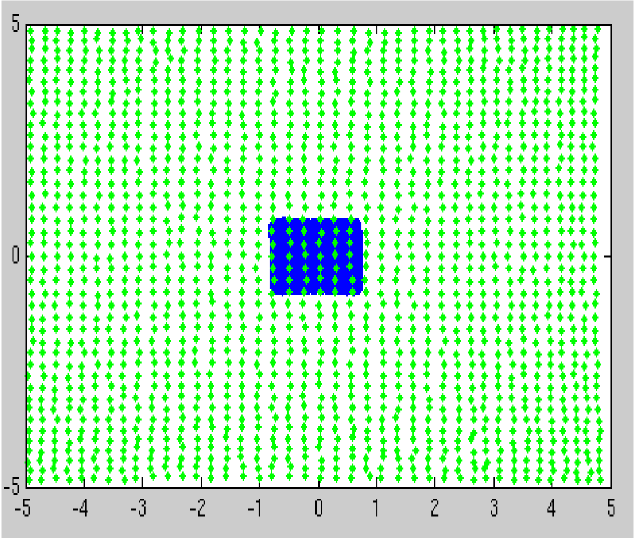


I ~ 800nA; B = 10 Hz

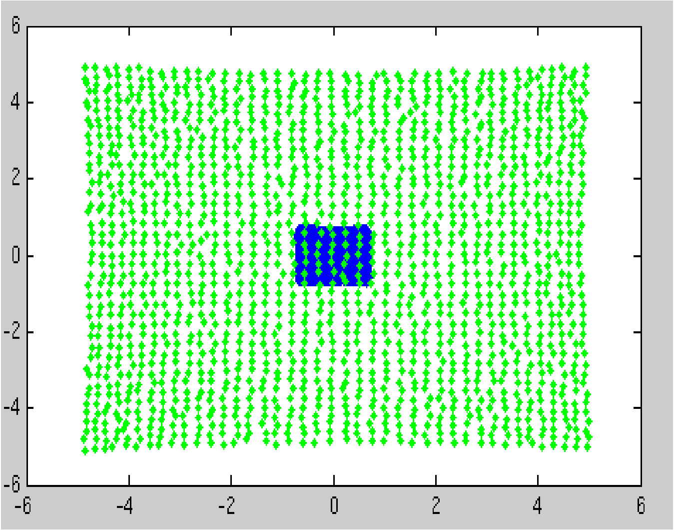
Step = 250 um



I ~ 100nA; B = 100 Hz



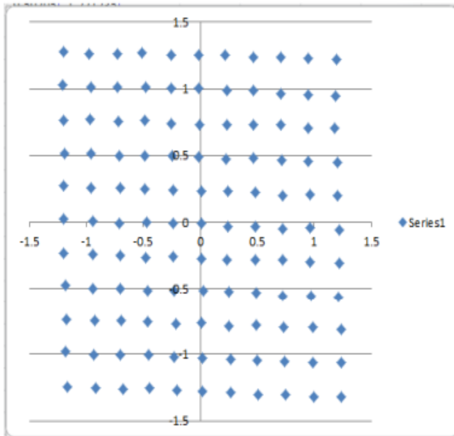
I ~ 100nA; B = 10 Hz



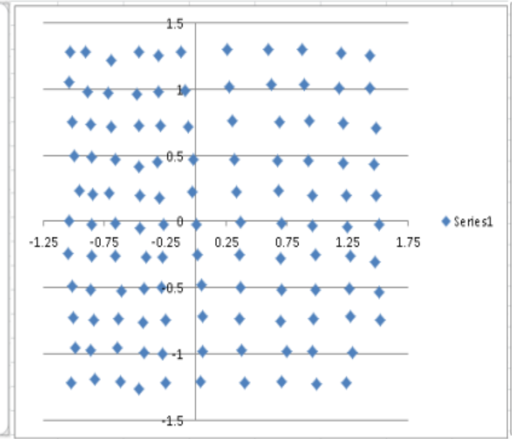
I ~ 70nA; B = 10 Hz

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

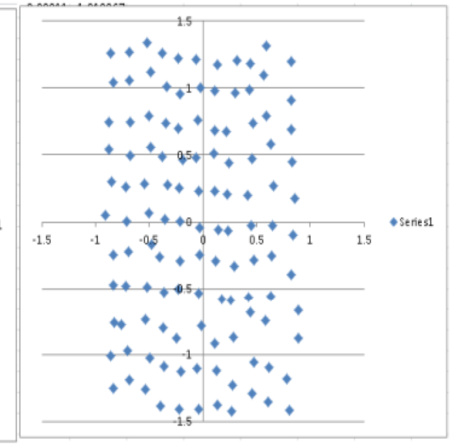
-65dBm = 400 nA



-71dBm = 200nA

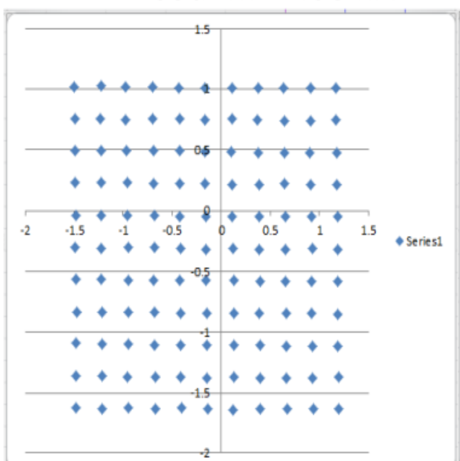


-77dBm = 100nA

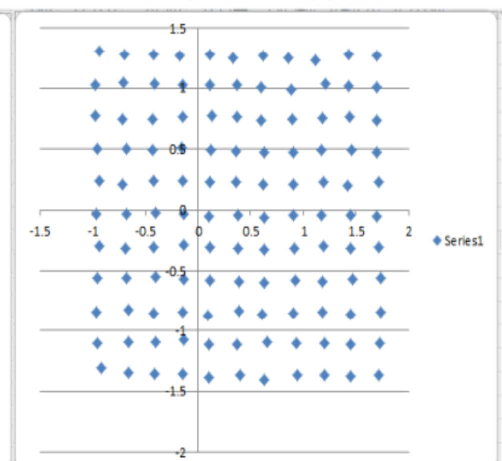


12 GeV Electronics with Stripline (10Hz)

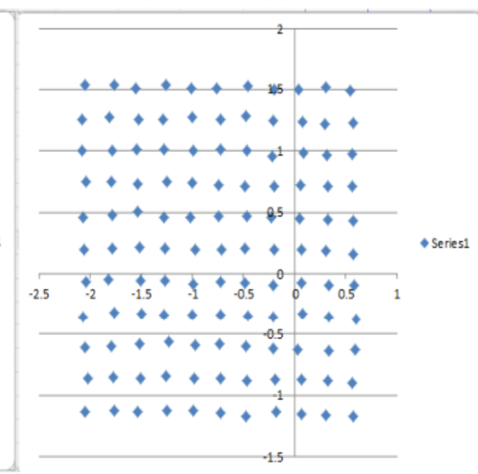
-65dBm = 400 nA



-71dBm = 200nA

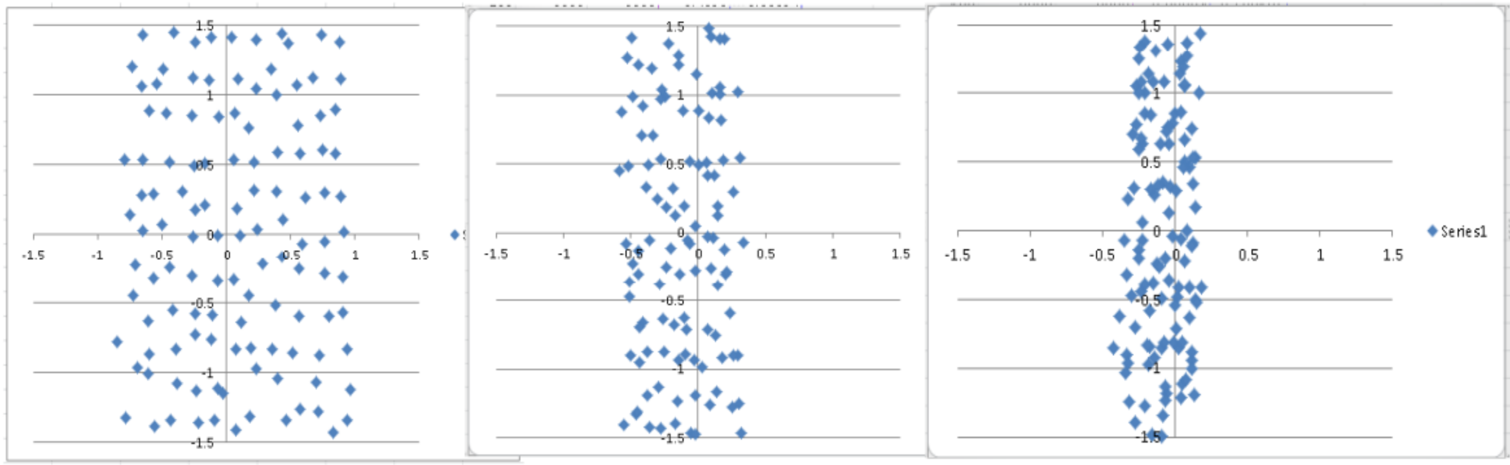


-77dBm = 100nA



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