Simulating the Space Environment for Hardware-in-the-Loop Testing of Space Particle Sensor Signal Chains

Dr. Chad Lindstrom

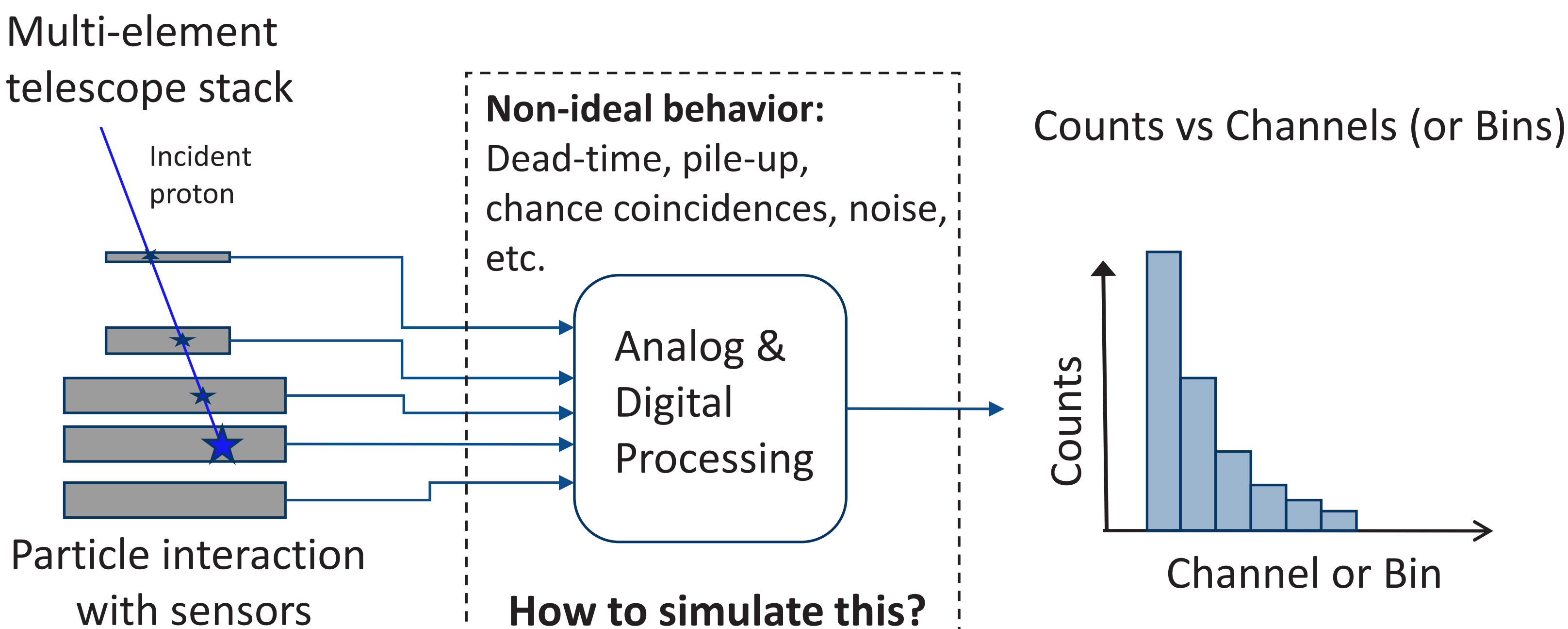
Space Vehicles Directorate **30 November 2018**

Motivation

Charged particle fluxes can vary greatly in magnetosphere

- Wide-dynamic range in particle flux due to location and time
- Relative ratio of charged particle-species (background contamination)
- Anisotropic angular dependence

Places significant demands on charged particle sensors to make measurements over wide range of conditions



Simulation Approach

1. Monte-Carlo Interaction of Environment with Sensitive Detectors (GEANT4)

2. Use event-by-event results to build sequences for input to signal chains

3. Program sequences into large-memory depth function generators to stimulate signal chain

Describe class that enables modeling of anisotropic fluxes

Bootstrap and exponential distributions to sample amplitudes & occurrence times

Requires proper calibration of function generator compared to typical detector response

Ultimately goal is to compare reported measurements from the signal chain against particle flux spectrum used to drive the simulation

Modeling of Anisotropic Particle Fluxes

From Sullivan (1971) for a single, time independent particle species for a detector:

$$C_i = \int_0^\infty dE \int_\Omega d\omega \int_S d\vec{\boldsymbol{\sigma}} \cdot \hat{\mathbf{r}} \varepsilon_i(E, \vec{\boldsymbol{\sigma}}, \omega)\, j(E,\omega)$$

- C_i: Average count rate in i'th channel
- $d\vec{\boldsymbol{\sigma}}$: Surface element
- $\hat{\mathbf{r}}$: Solid element dir.
- $j(E,\omega)$: Differential Flux
- Ω: Domain of integration in solid angle
- S: Domain over sensor surface
- ε_i: Chan. efficiency

Make approximation to separate flux into intervals with small variations in angle dist.

$$j(E,\omega) = J(E)F(\omega | E_k)$$

$J(E)$ – Energy dep. amplitude

$F(\omega | E_k)$ – Angular distribution

$\omega - (\theta, \phi)$ spherical polar angles

Can show for anisotropic flux with limited support (in energy) that:

Diff. omni. flux at center energy E_k and interval width ΔE_k

Count rate in i'th channel

$$C_i \approx \sum_{k=1}^{N} \int_{E_k}^{E_{k+1}} J_{omni}(E) \tilde{\Gamma}_{ik}(E)\, dE$$

Normalized gathering power ($\tilde{\Gamma}_{ik}$)

where:

$$\tilde{\Gamma}_{ik} = \frac{\int_\Omega d\omega \int_S d\vec{\boldsymbol{\sigma}} \cdot \hat{\mathbf{r}} \varepsilon_i(E, \vec{\boldsymbol{\sigma}}, \omega) F(\omega | E_k)}{\int_\Omega F(\omega | E_k)\, d\omega}$$

Inputs: Incident flux distribution in magnetic coordinates; Euler angles between magnetic and detector coordinates

Outputs: (1) Source gathering power (2) Integral of angular dist. (3) Initial momentum direction for each simulated event

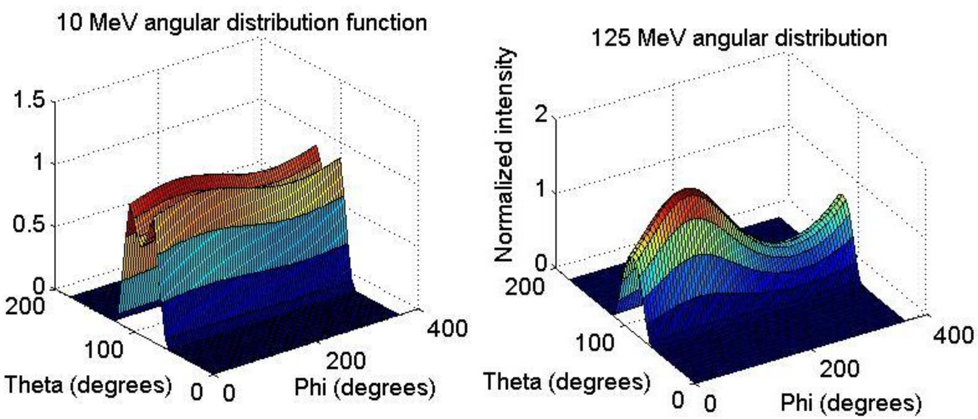
Constraints: Source is "flat" surface with constant surface normal

$$\Gamma_{ik} = \frac{N_{ik}}{N_{sim}} \Gamma_{source}$$

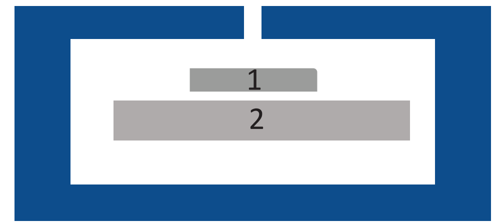
GEANT class allows calculation of normalized gathering power

Example: LEO Proton Response

Angular Distributions

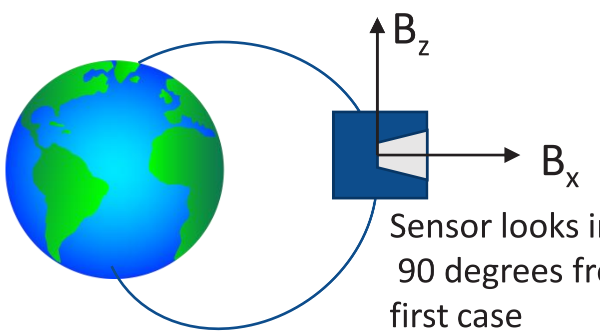


Pinhole type detector that only counts particles that deposit energy in detector 1 (rejects events that deposit 1 &2)

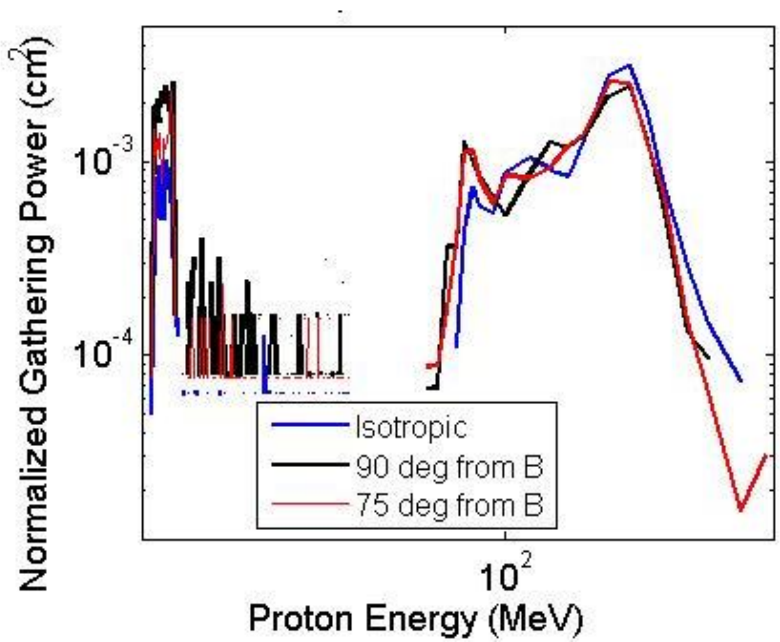


Lenchek & Singer type model[1] to include East-West effects in low-altitude trapped protons

- Pancake type pitch angle distribution
- Theta is pitch-angle relative to local mag. field; Phi is azimuthal angle
- Theta, phi are spherical polar angles in magnetic frame



Sensor looks in B_x at 90 degrees from B for first case



1. A.M. Lenchek, S.F. Singer, "Effects of the finite gyroradii of geomagnetically trapped protons", J. Geophys. Res. 67, 4073-4075 (1962).

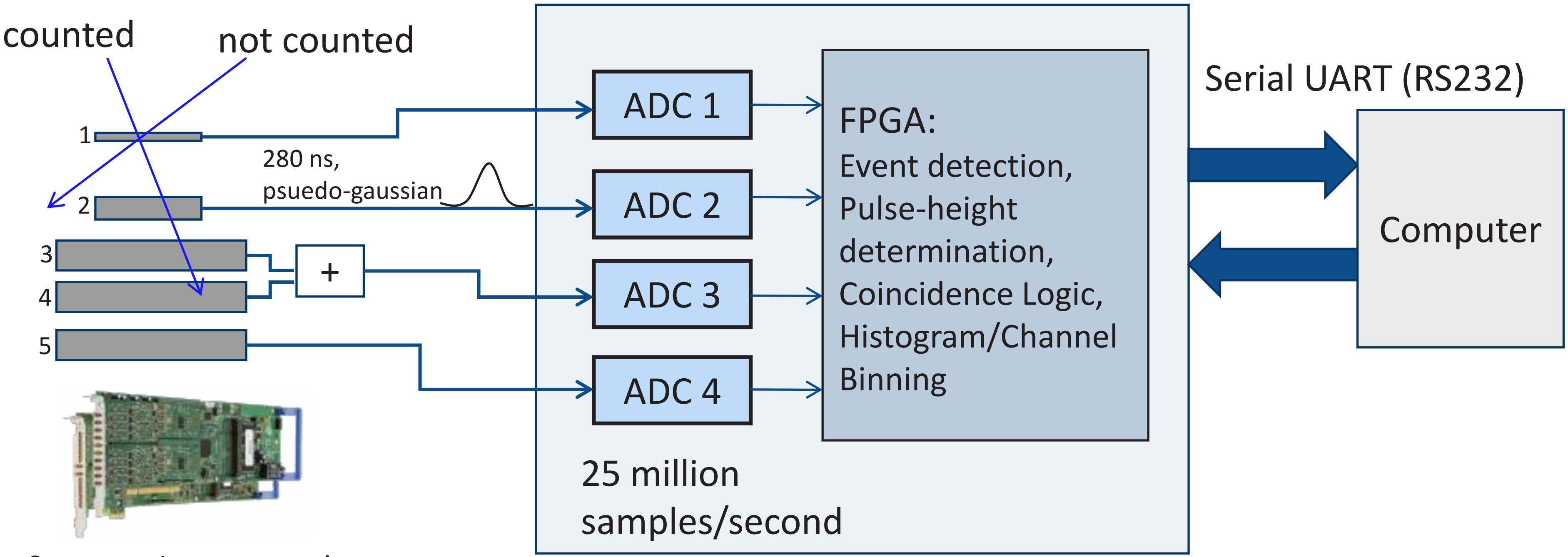
Simulated Detector & Hardware-in-Loop Test Setup

Simulated Detector

- 5 element detector (solid-state)
- Requires coincidence between 1 &2 for detection of event
- Pulse-height prop. to energy deposited

Analog to Digital Conversion

Event Processing

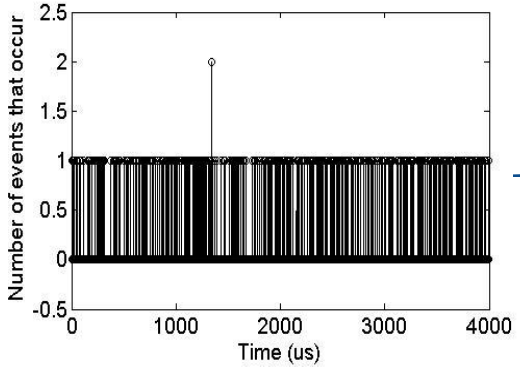


Spectrum-Instrumentation Corp. 4 output, 125 MSPS, 1 Gsample, 14-bit, D/A card used to simulate detector & analog chain

Events for electrons binned based on sum of energy deposited in detectors 1 through 4 (Energy deposited in Det. 2 < 1.8 MeV)

Test Sequence Creation

Step 1: Sample poisson distribution to determine when events occur



λ = (Sample Interval) x (Highest Detector Rate)

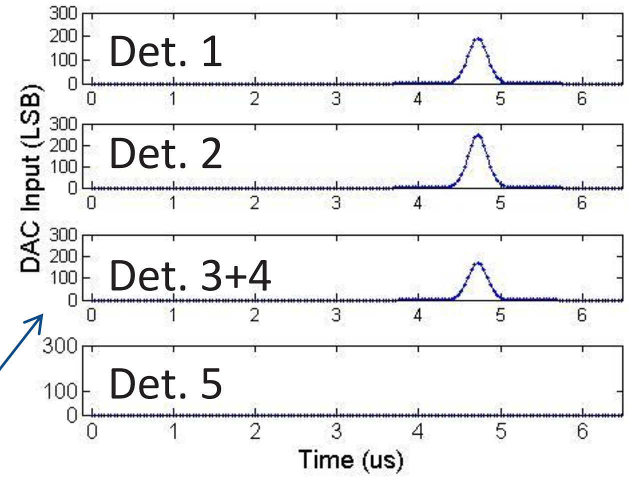
Currently implemented using Matlab functions

Step 2: For each non-zero time, sample the output of Monte Carlo simulation to get peak amplitudes

Event	Det. 1 Energy dep.	Det. 2 Energy dep.	Det. 3 Energy dep.	Det. 4 Energy dep.	Det. 5 Enegy dep.
1	0.61	0.00	0.00	0.00	0.00
2	0.17	0.00	0.00	0.00	0.00
3	0.18	0.00	0.00	0.00	0.00
4	0.17	0.00	0.00	0.00	0.00
5	0.16	0.22	0.85	0.00	0.00
6	0.55	0.00	0.00	0.00	0.00
7	0.14	0.00	0.00	0.00	0.00
8	0.15	0.65	1.03	0.00	0.00
9	0.14	0.00	0.00	0.00	0.00
10	0.43	0.67	0.46	0.00	0.00
11	0.35	0.72	0.00	0.00	0.00
12	0.17	0.00	0.00	0.00	0.00
13	0.45	0.00	0.00	0.00	0.00
14	0.17	0.00	0.00	0.00	0.00
15	0.24	0.00	0.00	0.00	0.00
16	0.14	0.64	0.00	0.00	0.00
17	0.16	0.54	0.00	0.00	0.00
18	0.00	0.70	0.33	0.00	0.00

Use uniform (or appropriate) distribution to select particular event with replacement (bootstrap method

Step 3: Create pulses for event and add to existing sequence



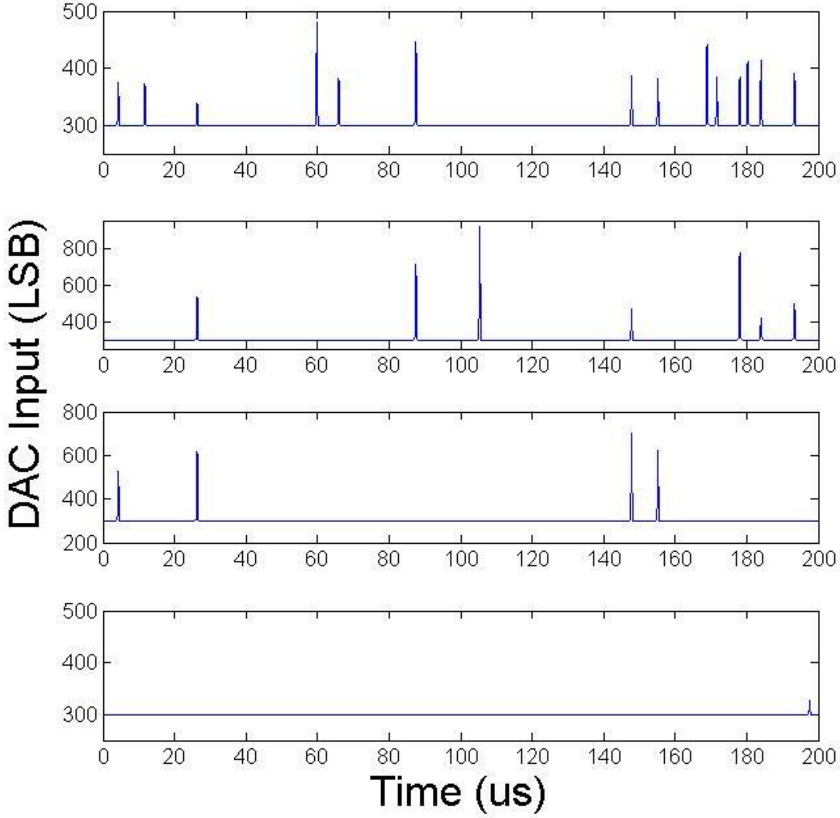
Requires that calibration exists to convert from MeV to DAC input

Process is repeated until all events have been created

Examples of Sequences

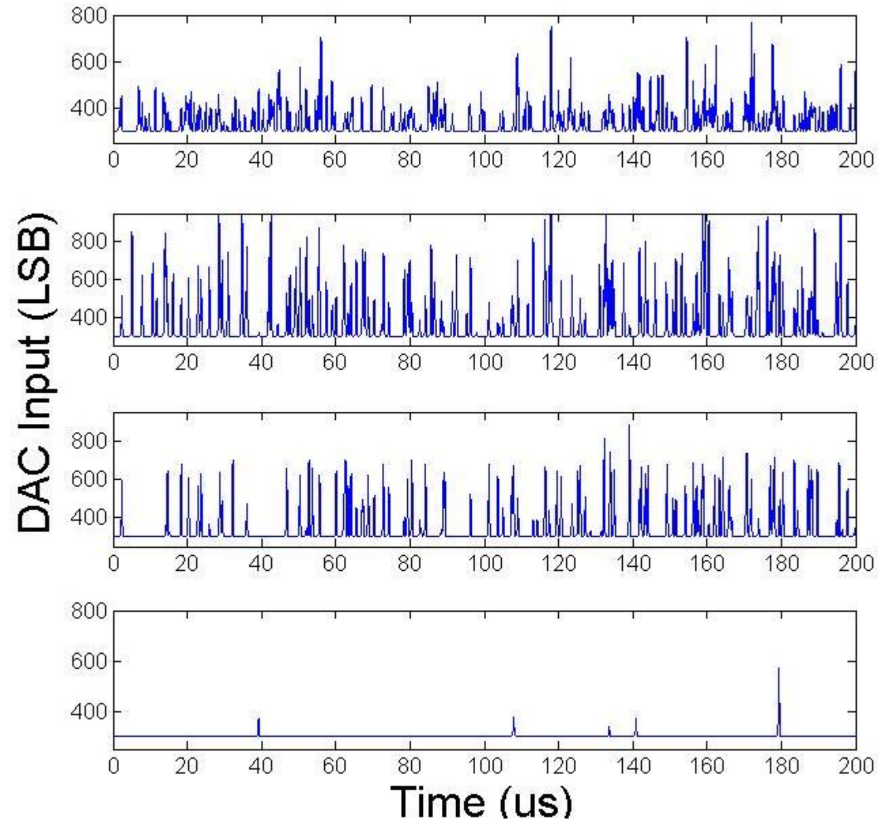
A 3 MeV electron beam was used to illuminate the sensor:

(~ 80 kHz)



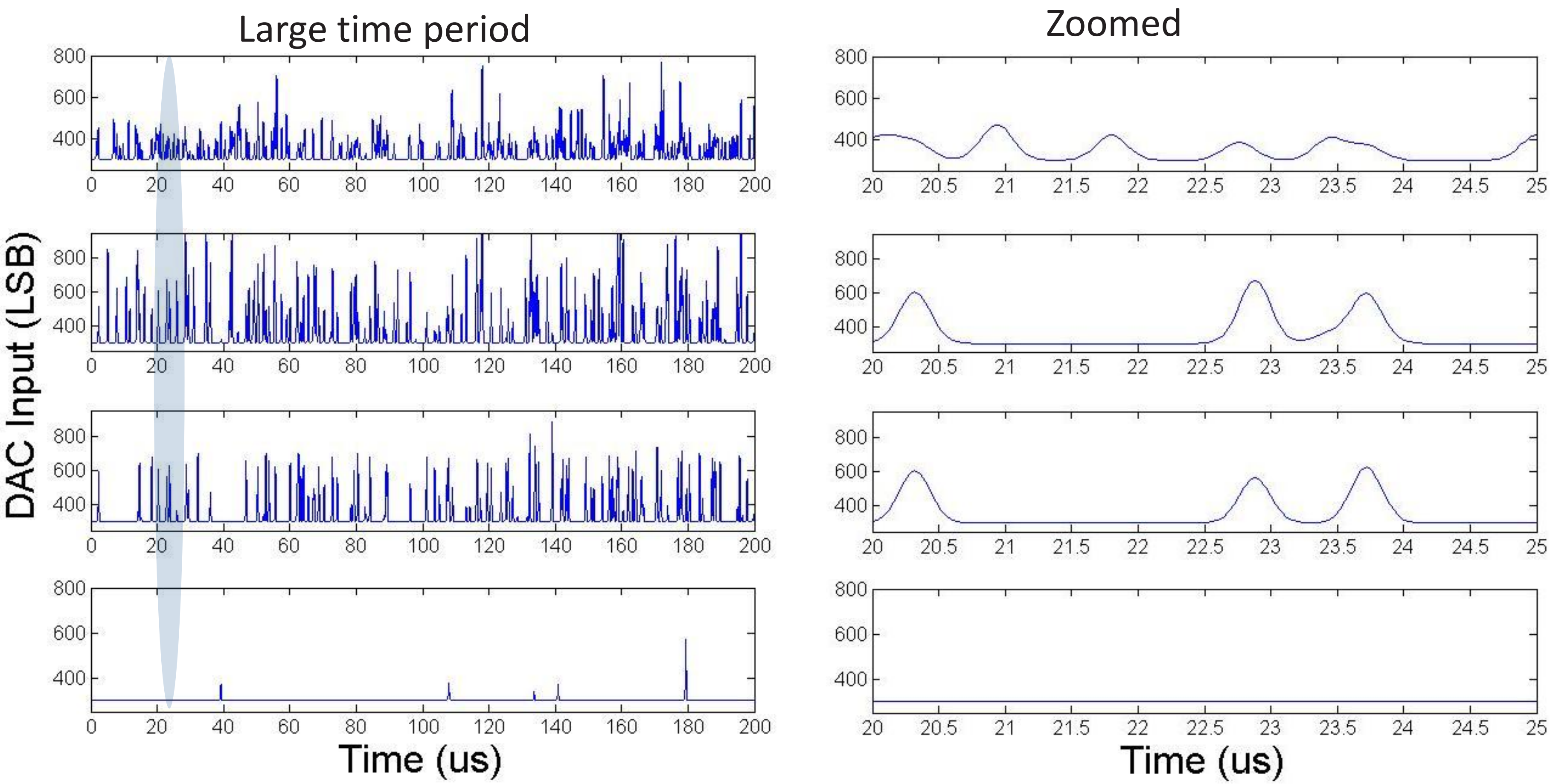
Full length of tested sequence = 0.101 s

(~ 1297 kHz)

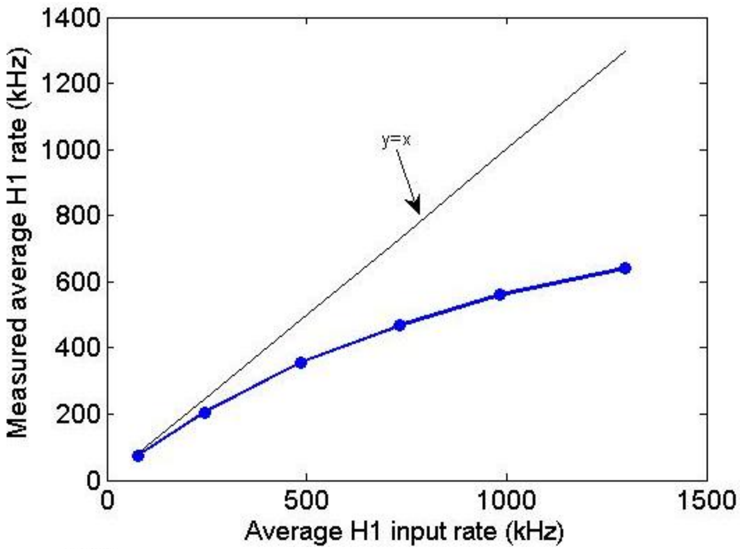


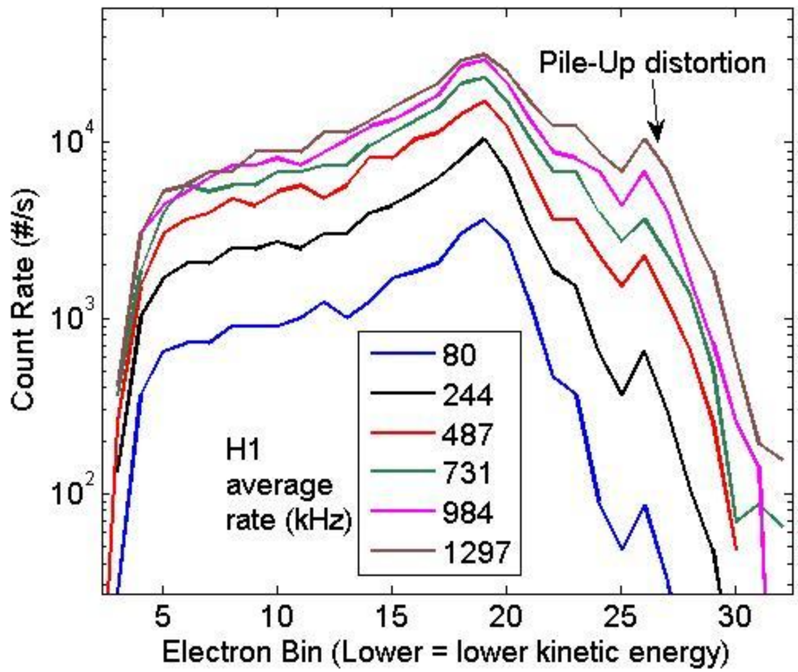
Full length of tested sequence = 0.021 s

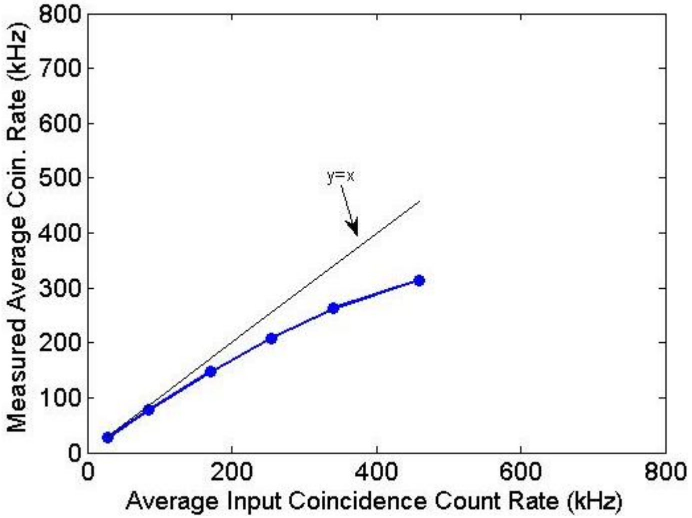
Multiple time-scales for 1400 kHz example



Initial Results







- Although approximately 50% of H1 events being dropped at 1.3 MHz more than 70% of coincidence events still being processed

- Note the build-up of the shoulder representative of pile-up in the count spectrum

Conclusions

Methods to investigate misbehavior of the sensor due to anisotropy & high count rates have been proposed

- Often hard to simulate using particle sources on the ground

- Simulating and modeling of anisotropic fluxes on response

- Creating simulated test sequences to investigate dead-time, pile-up, and signal processing artifacts for hardware-in-the loop testing

Questions?