Preliminary Studies on Digital Signal Processing of D0 L1 Calorimeter Trigger Pickoff Signals

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Plan

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**INTRODUCTION**

**CALORIMETER INFORMATION FOR D0 L1 TRIGGER**

32 phi x 40 eta Trigger Towers (0.2 x 0.2 segmentation)
Each Trigger Tower: 1 EM channel + 1 HAD channel
2560 channels in total for both EM and HAD

**SIGNAL OF EACH TRIGGER TOWER**

Differential analog signals delivered by Base Line Subtractor (BLS)
Digital conversion to be done
Estimation of the energy deposited in each tower for each Beam Crossing (132 ns)

**NEED OF (DIGITAL) SIGNAL PROCESSING**

Pulse duration larger than BC period
Long rising edge -> risk of premature triggering
Electronic noise and pileup noise rejection

**METHODOLOGY AND ANALYSIS TOOLS**

**MEASUREMENTS ON THE DETECTOR**

Collect samples of original signal on running experiment (BC = 396 ns)
Understand/quantify signal shape, time jitter, noise, etc...

**SIMULATED SIGNAL SAMPLES**

Based on pulses measured, generate train of pulses of variable amplitude, shape...
Physics simulation of detector @ F_{BC} = 132 ns -> noise, pileup studies (not done here)
Spice model of the electronic chain (not pursued in this study)

**SIGNAL PROCESSING ALGORITHM DEFINITION AND EVALUATION**

Define requirements, propose algorithms and criteria to compare them
Evaluate algorithms on simulated samples
Define procedure for parameter calibration and operation monitoring

**LATER PHASE: IMPLEMENTATION**

Feed hardware with simulated samples and check
Connect to detector in spy mode...
Signal Samples

Scope trace of one EM channel -- red trace: differential signal; purple: BC clock (396 ns)

Signal Samples (con’t)

Scope trace of one HAD channel -- note the shape

All traces and information provided by Dan Edmunds at:
http://www.pa.msu.edu/hep/d0/ftp/l1/cal_trig/pictures/trig_pickoff
**TOOLS AND SIMULATION CHAIN**

**Programs developed**
- Pattern generator: patg
- Sampling and Quantization: sampq
- Digital Filtering: filt

**Simulation chain**

```
Scope trace → filt → patg → filt → sampq → filt → display program
```

- Smooth
- Decimate
- Periodize
- Scale amplitude
- Add noise
- Add delay, jitter
- Simulate pileup

- Anti-aliasing
  - e.g. Butterworth
  - 2nd order cutoff @ 7.57 MHz

- Sample T
- Quantize N

- FIR
- IIR
- Algorithm X
- Floating point
- Fixed precision

All programs standalone; written in standard C; parameter file and command line options

I/O with data files or stdin/stdout (can use UNIX pipes between programs)

Your choice for post-processing and display program: Excel, xvgr, ...

**SIGNAL SPECTRUM**

- Most of the energy of the signal is in a band between 0 and ~8 MHz
- Some HF noise was picked by the scope in measurements
- A simulated 2nd order Butterworth lowpass filter with cutoff @ 7.57 MHz cleans up the signal

EM trace tek00101.csv -- 4096 point FFT
### Algorithm Evaluation Parameters

**Algorithm features**
- Dependent or not on trigger tower type and/or trigger tower number
- Number of parameters to adjust, individually or not, procedure for parameter calculation
- Algorithm intrinsic latency
- Input sampling frequency and precision
- Baseline correction, behavior under saturation

**Algorithm quality**
- Precision on amplitude for the BC concerned and residual error on adjacent BCs
- Time/amplitude resolution - separation of adjacent pulses
- Probability on undetected pulse (e.g. small amplitude)
- Probability of pulse assignment to the wrong BC

**Sensitivity of the algorithm**
- Electronic noise, pileup noise
- Signal phase and jitter compared to sampling clock
- Dependence on signal shape
- Limited precision arithmetic, coefficient truncation, input quantization

**Implementation**
- Hardware resources
- Operating frequency of each part
- Effective algorithm latency

### Proposed Algorithms

**Finite Impulse Response Filter (FIR) deconvolution**
- Pros: optimal for pileup rejection - linear (detection of small and large pulses in same way)
- Cons: sensitivity to signal shape, phase, jitter,... - per trigger tower parameter set

**Peak detector + weighted average around peak**
- Pros: less sensitive to signal phase and jitter - few parameters to adjust
- Cons: no pileup rejection - risk of double detection for 2 peaks shaped signals (HAD calo.)

**Matched filter + peak detector**
- Pros: optimal for white noise rejection
- Cons: not optimal for pileup correction, but coeff can be tuned - per tower parameter set

**Simplified correlator + weighted average around peak**
- Pros: simple peak localization - little sensitivity to signal shape, phase and jitter
- Cons: no pileup rejection - risk of no detection for small signals

**Other ideas?**
**FIR DECONVOLUTION**

**Principle**

\[
\text{Error} = \begin{bmatrix}
a_4 & a_5 & 0 & 0 & 0 & 0 \\
a_2 & a_3 & a_4 & a_5 & 0 & 0 \\
a_0 & a_1 & a_2 & a_3 & a_4 & a_5 \\
0 & 0 & a_0 & a_1 & a_2 & a_3 \\
0 & 0 & 0 & 0 & a_0 & a_1 \\
\end{bmatrix}
\begin{bmatrix}
E_0 \\
E_1 \\
E_2 \\
E_3 \\
P \\
0
\end{bmatrix}
\]

Sample signal at \( T = \frac{T_{BC}}{N} \)  
\( T_{BC} : 132 \text{ ns} \); \( N_{\text{min}} = 2 \) (Shannon's sampling theorem); \( N_{\text{max}} \sim 3-4 \)

Evaluate convolution for \( t = k \cdot T_{BC} \)

Adjust coefficients \( a_i \) so that \( \text{Error} \cdot \text{Error}^T \) is minimum (iterate over input vectors)

**Features**

- Set of coefficients determined on a per tower basis
- Training vector set can include shape distortion, time jitter, noise...
- If \( N \) even, number of coefficients should also be even
- Coefficients count must be sufficient to keep output at 0 after pulse
- Time position of peak adjustable: low intrinsic latency (can be 0 or even <0)
- Optimum linear solution; separation of adjacent pulses (pileup rejection)
- Signed coefficients and arithmetic

**FIR DECONVOLUTION - EXAMPLE**

Conditions: input: EM trace tek00101.csv -- signal sampling \( @F_{BC} \times 2 \) -- 8 bit samples  
FIR 12 Coefficients -- 32 bit floating point arithmetic -- algorithm intrinsic latency: 0
**FIR DECONVOLUTION - IMPLEMENTATION**

**Multiplier Accumulator**

- K coefficients: K word SRAMs (single port or separate I/O) or parallel shift registers
- On some FPGA's: dedicated 18 x 18 bit Multiplier blocks (32 on Xilinx 500K gates Virtex 2)

**Distributed Arithmetic**

- K shift registers; 2^K word SRAM Look Up Table
- input running at M * sampling rate; SRAM and adder running at M * beam crossing clock

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**PEAK DETECTOR + AVERAGING**

**Principle**

- Sample signal at T = T_{BC} / N
- T_{BC} = 132 ns; N_{typ} = 2; N_{max} = 3-4

Apply series of conditions to determine presence of peak; e.g.:

peak at (k-1)T IF

1. \[ E(kT) < E((k-1)T) \]
2. \[ E((k-1)T) >= E((k-2)T) \]
3. \[ E((k-2)T) >= E((k-3)T) \]

Assign value to output:

IF (!peak) R(kT)=0; ELSE R(kT) = A \cdot (\text{Sum of M samples around peak})

**Features**

- Presence of peak found by dE/dt \(\rightarrow\) oversampling degrades performance; sensitive to noise
- No rule to determine optimal set of conditions for peak detection: “try and see”
- Some separation of pulses close in time but no pileup rejection
- Output=0 for BC not concerned - but risk of missing pulses or assignment to wrong BC
- For white noise; signal almost flat around peak: noise reduction by \(\sqrt{M}\)
- Simple hardware; few parameters; low intrinsic latency (1 sampling period in the example)
- Tolerant to pulse time jitter, pulse shape distortion, sampling clock phase
**PEAK DETECTOR + AVERAGING (CON’T)**

**Example**

![Graph showing simulated and estimated peaks](image)

- Output = 0 outside BC of interest; errors for small peaks (wrong BC or no detection)

**Implementation**

Channel #N

-MUX
-Reg
-Cmp
-A>B peak
-Logic
-Sequencer
-Adder
-LUT
-Output #N
-Control bus

**Matched Filter + Peak Detector**

**Principle**

- Matched filter: best detection \( E(kT) \) in white noise: filter impulse response \( h(kT) = E(T_0 - kT) \)
- Sample signal at \( T = \frac{T_{BC}}{N} \): \( T_{BC} = 132 \text{ ns}; N_{typ} = 2; N_{max} \approx 3-4 \)
- Use FIR for convolution of input by impulse response
- Output of filter \( ! = 0 \) for BCs around that of interest: use peak detector after filter
  - IF \( S(kT) < S((k-1) T) \) AND \( S((k-2) T) < S((k-1) T) \)
  - THEN \( R(kT) = S((k-1) T) \)
  - ELSE \( R(kT) = 0 \)

**Features**

- Optimum SNR (if white noise)
- Some separation of pulses close in time (depends on signal shape)
- Coefficient tuning for best trade-off between electronic noise and pileup noise rejection
- Output = 0 for BC not concerned - few risks of missing pulses or assignment to wrong BC
- Matching intrinsic latency = \( T_0 - T_{peak} \) i.e. several sampling periods (+1 for peak detection)
- One parameter set per channel
- Tolerance to pulse time jitter, pulse shape distortion (double peak), sampling clock phase
**Example**

Matched filter + peak detector (con’t)

![Graph showing amplitude vs BC index with simulated and estimated peaks]

Conditions:
- HAD trace tek00401.csv
- Sampling @F_{BC} x 2
- 8 bit samples
- 6 coefficients 6 bit
- Latency: 2 T_{BC}

**Implementation**

Channel #N

![Diagram of simplified correlator + peak detector]

SIMPLIFIED CORRELATOR + PEAK DETECTOR

**Principle**

Matched filter on non-linear transformation of signal + peak detector + local averaging

Make non linear transformation of input:
- IF \[ E(kT) < E((k-1) T) \] THEN \( C(kT) = -1 \)
- ELSE IF \[ E(kT) > E((k-1) T) \] THEN \( C(kT) = +1 \)
- ELSE \( C(kT) = 0 \)

Convolve \( C(kT) \) with \( h(kT) \) — If local maximum found: peak is present

Assign value to output:
- IF \(!\text{peak}\) \( R(kT) = 0 \); ELSE \( R(kT) = A \times (\text{Sum of M samples around peak}) \)

**Features**

- Improved variant of peak detector + averaging around peak
- Output = 0 for BC not concerned - few risks of missing pulses or assignment to wrong BC
- Intrinsic latency = differentiate + matching + find peak = 1 + (T_0 - T_{peak}) + 1
- Few parameters specific to each channel
- Tolerance to pulse time jitter, pulse shape distortion (double peak), sampling clock phase
SIMPLIFIED CORRELATOR + PEAK DETECTOR (con’t)

Example

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>BC Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>128</td>
</tr>
<tr>
<td>16</td>
<td>256</td>
</tr>
</tbody>
</table>

Errors for small peaks: no detection

Conditions:
- EM trace tek00101.csv
- Sampling @F_{BC} x 2
- 8 bit samples
- Matching: 8 ternary coefficients
- Averaging: 4 samples
- 8 bit arithmetic
- Latency: 3 T_{BC}

Implementation

- Channel #N
-MUX
-Registers
-Comparators
-Shift register
-Matching logic
-Peak detector
-Encoder
-Sequencer
-Adder
-LUT

Output #N
-Control bus

ALGORITHM COMPARATIVE STUDIES

DIGITIZATION

- Sampling at F_{BC} x 2, F_{BC} x 3 or F_{BC} x 4
- Use 8 bit of 8 or 10 bit ADC

PARAMETERS TO BE STUDIED

- Signal peak amplitude over full range
- Signal phase wrt sampling clock over [-1/2 T_{BC}, +1/2 T_{BC}]
- Simulated electronic noise level
- Simulated pileup noise
- Pulses close in time
- Generic set of parameters for all TT in EM or HAD
- Number of samples/coefficients
- Finite precision arithmetic
- Behavior under saturation...
- Study each parameter individually then combined
**Sampling Rate**

**Various rates to consider**

ADC conversion rate: \( F_{\text{ADC}} = N \cdot F_{\text{BC}} \quad N \in [1, \sim 7] \)  
\( F_{\text{BC}}: 7.57 \text{ MHz} ; 132 \text{ ns period} \)

Digital signal processing: input rate: \( F_{\text{in}} = F_{\text{ADC}} / M \quad M=1 \text{ or } 2, 3 \)  
output rate: \( F_{\text{out}} = F_{\text{BC}} \)

**Practical limits**

- Peak detector or simple correlation + averaging: peak detection runs @ \( F_{\text{in}} \) -- made by conditions on \( \frac{dV}{dt} \): limits \( F_{\text{in}} \leq \sim 3.F_{\text{BC}} \); averaging @ \( F_{\text{out}} \)
- Deconvolution FIR: multiply accumulate @ \( F_{\text{out}} \) but impulse response must cover duration of complete pulse: \( F_{\text{in}} = 2 \cdot F_{\text{BC}} \) to avoid too many coefficients
- Matched filter + peak detector: all logic runs @ \( F_{\text{in}} \): limits number of coefficients/input rate. Typical value with 100 MHz logic: 10 coeff. with \( F_{\text{in}} = F_{\text{BC}} \) or 5 coeff. with \( F_{\text{in}} = 2 \cdot F_{\text{BC}} \)

**Analog to digital conversion latency**

Pipeline ADCs of interest have a typical latency of 3 sampling clock for 8 bit models and 5 sampling clock for 10 bit models

\( F_{\text{ADC}} = 4 \cdot F_{\text{BC}} \) could be good choice (ADC latency = 99-165 ns) with decimation by 2 before digital signal processing -- selecting which samples to take can be used to make coarse phase adjustment of signal with respect to sampling clock

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**Amplitude Scaling**

Input: series of pulses (EM tek00101.csv) with peak amplitude from 0 to 255

Small estimation errors on BC concerned for all algorithms

Non null estimation on adjacent BCs for deconvolution FIR
**BASELINE VARIATION**

Input: series of pulses (EM tek00101.csv) Peak=128 -- baseline shifted by -8 to +8 LSB
Linear (~) estimation error for correct BC with all algorithms but FIR which is better
On adjacent BCs matching algorithms output 0; errors with deconvolution FIR

**SIGNAL PHASE wrt BC REFERENCE CLOCK**

Conditions:
- EM trace tek00101.csv
- Sampling @F_{BC} x 2
- 8 bit samples
- Pulse peak amplitude: 128

Simplified correlator:
- 8 ternary coefficients
- Averaging: 4 samples
- 8 bit arithmetic
- Latency: 3 T_{BC}

Matching filter:
- 8 coefficients 6 bits
- Latency: 2 T_{BC}

Phase difference = 0 when peak of signal phase aligned with BC clock (and sampling clock)
Simplified correlator: error of +/-5% on -64, +20 ns range -- wrong assignment if phase > 32 ns
Matched filter: ~2% error on -30, +20 ns range -- peak finder misses pulse if too much shift
Algorithms robust against phase jitter and may not need compensation for static phase shift
**Signal Phase wrt BC Reference Clock (con’t)**

**Conditions:**
- EM trace tek00101.csv
- Sampling \( @F_{BC} \times 3 \)
- 8 bit samples
- Pulse peak amplitude: 128

**Peak detection:**
- 3 conditions
- Averaging: 4 samples
- 8 bit arithmetic
- Latency: 1 \( T_{BC} \)

Signal sampling at \( F_{BC} \times 3 \) for improved peak detection and flatter signal around peak

\(~2\%\) error on estimated peak on phase range from -20 to +60 ns

peak is assigned to previous BC if phase shift in -20, -66 ns

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**Signal Phase wrt BC Reference Clock (con’t)**

**Conditions:**
- EM trace tek00101.csv
- Sampling \( @F_{BC} \times 2 \)
- 8 bit samples
- Pulse peak amplitude: 128

**Deconvolution FIR:**
- 12 coefficients
- 32 bit floating point arithmetic
- Latency: 0

FIR coefficient calculations made for only one pulse at phase = 0

\(-5.0\) \(-2.5\) \(0.0\) \(2.5\) \(5.0\)

Phase difference (ns)

Large errors (~50\%) on phase drift by +/-30 ns; non null amplitude for non relevant BCs

Coefficient tuning to correct phase of each channel -- but algorithm remains sensitive to jitter
**Separation of Pulses Close in Time**

- **Input**: series of pulses (EM tek00101.csv) Peak=128 -- time interval between peaks 1-10 BCs
- Only deconvolution FIR gives correct results in this case

**Behavior Under Saturation**

- **Input**: series of pulses (EM tek00101.csv) Peak from 256 to 512 -- ADC saturation at 255
- Best results with matched filter -- acceptable output for others if saturation <~320
- For any algorithm, take care of overflow in finite precision arithmetic to avoid roll-over
**Fixed-Point Arithmetic - FIR**

- **Absolute Error for BC Concerned (LSB)**
- **Conditions:** EM trace tek00101.csv
  - Pulse peak amplitude: 1 to 63

- **Absolute Error for Other BCs (LSB)**

  - **FIR 12 coefficients**
  - **8 bit samples**
  - **Sampling @**$F_{BC}$ x 2

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**Not too much influence seen for estimation error on BC concerned**

- Residual error on adjacent BCs unacceptable if coarse coefficient quantization
- Algorithm sensitive to precision of arithmetic -- signed coeff: 1 bit consumed for sign

**Try to take into account number representation when coeff are calculated?**

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**Number of Coefficients - Matched Filter**

- **Absolute Error for BC Concerned (LSB)**

  - **8 coeff 6 bit**
  - **5 coeff 6 bit**

- **Conditions:** EM trace tek00101.csv
  - Pulse peak amplitude: 1 to 255
  - **Sampling @**$F_{BC}$ x 2

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**Limited precision, small number of coefficients OK -- unsigned coeff: all bits used for mantissa**

- Residual error on adjacent BCs null in this test

**More tests needed to conclude, but very good properties seen so far**
**Adding White Noise to Signal**

Conditions:
- EM trace: tek00101.csv
- Pulse peak amplitude: 128
- Sampling: $T_{BC} \times 3$
- Peak Detector + averaging
- Wide-band uniform dist noise added before anti-aliasing filter

**Peak detector:** worst – undetected pulses and assignment to wrong BC occur
**Matched filter:** ~2 LSB error max on BC; 0 on adjacent BCs
**Simple correl + averaging:** ~3 LSB error max on BC; 0 on adjacent BCs
**Deconvolution FIR (32 FP arithm.):** <=8 LSB if noise less than [-16, +16]

Noise model unrealistic; this test is for demo only
Good model of noise needed; more work to be done in this area

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**Demo Test With All Effects Combined**

Conditions:
- EM trace: tek00101.csv
- Peak amplitude: uniform in [8, 255]
- Noise: uniform in [-8, +8] LSB
- Pulse inter-delay: fixed 8 $T_{BC}$
- Pulse time jitter: uniform in [-10, +10] ns

A set of “good” input parameters was picked-up to show a working demo...
but parameters need to be set to realistic values; e.g. time distribution of pulse
inter-arrival is unrealistic and results depend critically on pileup
Model of noise, signal jitter, pileup and tower occupancy needed
**Comparison of Algorithms**

- Low effective latency
- Hardware simplicity
- Quality
- Noise immunity
- Pileup rejection
- Tolerant to limited precision
- Tolerant to time phase / jitter
- Behavior under saturation

- **Peak detector**
- **Matched filter**
- **Deconvolution FIR**
- **Simple correl.**

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**Matched filter + Peak detector best choice -- (like theory says and other experiments do...)**

**Coefficient tuning for optimal pileup/noise rejection**

**Deconvolution FIR: no satisfactory results obtained -- independent study needed**

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**Summary**

**Simulation chain developed**

- Sample generation from scope trace measurements, filtering and sampling
- Allows to study algorithms off-line on a standalone PC or workstation

**4 algorithms described**

- Linear: deconvolution with FIR
- Non linear: Peak detection (2 methods) + local averaging or Matched filter + peak detection

**Performance evaluation of algorithms**

- Large set of parameters to play with
- So far matched filter + peak detection shows best results

**Future work on simulation**

- Need to quantify incoherent noise, pileup noise, ...
- Refined simulations with realistic input parameters

**Still a lot to understand and do...**