Numerical Method for High Count-Rate Dead-Time Correction in Neutron Multiplicity Counting using Multi-Channel List-Mode Recorders

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Introduction:

- A neutron detector in safeguards has a body of polyethylene with a cavity for the sample. Around it, gas proportional counters, often $^3\text{He}$ tubes, are embedded in the polyethylene body.
- Traditional neutron counters/detectors sum up the signals from different preamplifiers.
- Recording signals from preamplifiers individually using multi-channel list-mode recorders provide additional possibilities for data analysis and other advantages.
Introduction:

The list mode recorder provides with exact times and channels of arrival of a pulse.

One of the additional possibility of data analysis is an improved method for dead-time correction especially developed for high count-rates.

Schematic setup of neutron multiplicity counting using a multi-channel list-mode recorder:
Assumptions and notations:

**TIC:** Time is broken up in time-intervals, either one bearing a pulse (1) or not (0).

- $t$ ... global time of the detector

- $\tau_i$ ... time at certain channels from a specific event (leading pulse)

- $P_i(t)$ pulse on channel $i$ at time $t$, observed or lost.

- $C_i(t)$ count is a observed pulse accounted for at channel $i$ and time $t$.

- $L_i(t)$ lost pulse. Of course $P_i(t) = C_i(t) + L_i(t)$.

- $e_i$ relative efficiency of channel $i$ where of course $\sum_i e_i = 1$.

- $p_i(\tau_i)$ probability for losing a pulse at channel $i$ has as timeline $\tau_i$, time from the last recorded pulse on channel $i$. Assuming, dead-time follows such a "dead-time pattern" or function $0 \leq p_i(\tau_i) \leq 1$.

$$L_i(t) \approx p_i(\tau_i)P_i(t) \quad \text{or} \quad \frac{L_i(t)}{p_i(\tau_i)} \approx P_i(t). \quad \text{(eqn.3)}$$
Estimating lost pulses – Some Math:

By definition of relative efficiency:

\[ \int_{t_1}^{t_2} P_i(t) \, dt \approx e_i \int_{t_1}^{t_2} \sum_j P_j(t) \, dt \]

Subtracting \( e_i \int_{t_1}^{t_2} P_i(t) \, dt \) from both sides, dividing both sides by \( 1 - e_i \) and using \( P_i(t) = C_i(t) + L_i(t) \) yields:

\[ \int_{t_1}^{t_2} P_i(t) \, dt \approx \frac{e_i}{1 - e_i} \int_{t_1}^{t_2} \sum_{j \neq i} P_j(t) \, dt = \frac{e_i}{1 - e_i} \int_{t_1}^{t_2} \sum_{j \neq i} (C_j(t) + L_j(t)) \, dt \quad \text{(eqn. 2)} \]

Using eqn. 3 from before we get:

\[ \int_{t_1}^{t_2} \frac{L_i(t)}{p_i(\tau_i)} \, dt \approx \frac{e_i}{1 - e_i} \int_{t_1}^{t_2} \sum_{j \neq i} (C_j(t) + L_j(t)) \, dt \]
Estimating lost pulses – Some Math:

By reducing the interval \([t_1, t_2]\) to one TIC, the minimum time period our electronic can resolve, and multiplying both sides with \(p_i(\tau_i)\) yields:

\[
L_i(t) \approx p_i(\tau_i) \frac{e_i}{1 - e_i} \sum_{j \neq i} (C_j(t) + L_j(t))
\]

However, we have one such equation for each channel! Bringing all lost pulses to the left side and the counts to the right side for all channels we get a system of equations \((k \ldots \text{max. no of channels})\)

\[
\left( L_i(t) - p_i(\tau_i) \frac{e_i}{1 - e_i} \sum_{j \neq i} L_j(t) \approx p_i(\tau_i) \frac{e_i}{1 - e_i} \sum_{j \neq i} C_j(t) \right)_{i=1,\ldots,k}
\]
Estimating lost pulses – Some Math:

Replace the unknown lost pulses $L_i(t)$ by our estimations $l_i(t)$ to be calculated (in order to avoid confusion), results in the following matrix equation:

$$
\begin{bmatrix}
1 & -\frac{p_1(\tau_1)e_1}{1-e_1} & -\frac{p_1(\tau_1)e_1}{1-e_1} & \cdots & -\frac{p_1(\tau_1)e_1}{1-e_1} \\
-\frac{p_2(\tau_2)e_2}{1-e_2} & 1 & -\frac{p_2(\tau_2)e_2}{1-e_2} & \cdots & -\frac{p_2(\tau_2)e_2}{1-e_2} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
-\frac{p_k(\tau_k)e_k}{1-e_k} & -\frac{p_k(\tau_k)e_k}{1-e_k} & \cdots & 1 & -\frac{p_k(\tau_k)e_k}{1-e_k} \\
\end{bmatrix}
\begin{bmatrix}
l_1(t) \\
l_2(t) \\
\vdots \\
l_k(t) \\
\end{bmatrix}
=
\begin{bmatrix}
\frac{p_1(\tau_1)e_1}{1-e_1} & \sum_{j\neq 1} C_j(t) \\
\frac{p_2(\tau_2)e_2}{1-e_2} & \sum_{j\neq 2} C_j(t) \\
\vdots & \vdots \\
\frac{p_k(\tau_k)e_k}{1-e_k} & \sum_{j\neq k} C_j(t) \\
\end{bmatrix}
$$

Doing so repeatedly for every $t$ from our timeline and for every meaningful (means non-zero) right hand side we obtain a second, estimated pulse train.

Attention: The $l_i(t)$ are not probabilities, but estimations (may occasionally become larger than 1)
Calibrating the system – determining \( p_i(\tau_i) \):

In general the dead-time pattern \( p_i(\tau_i) \) is not known in advance: The system must be calibrated!

For doing so we take advantage of the Rossi-Alpha distribution: The Rossi-Alpha distribution is the distribution in time of events that follow after an arbitrary starting event. Repeatedly fix an pulse from the pulse train as the starting pulse and record each subsequent pulse in a bin corresponding to the time-distance from the starting pulse.

Use eqn. 2 with \( P_i(t) = C_i(t) + L_i(t) \): Provided a non-dead-timed pulse train, the fraction of pulses received and lost on one channel follows statistically the equation:

\[
C_i(t) + L_i(t) \approx \frac{e_i}{1 - e_i} \sum_{j \neq i} (C_j(t) + L_j(t))
\]

If we calculated the lost pulses \( l_i(t) \) correctly, this shall also hold for the calculated \( l_i(t) \):

\[
C_i(t) + l_i(t) \approx \frac{e_i}{1 - e_i} \sum_{j \neq i} (C_j(t) + l_j(t)) \quad \text{(eqn. 9)}
\]
Calibrating the system – determining $p_i(\tau_i)$:

Idea is to use eqn. 9 and apply it to a Rossi-Alpha distribution with accounted $C_i(t)$ and estimated lost pulses $l_i(t)$. Eqn. 9 shall also hold on a Rossi-Alpha because a Rossi-Alpha is just a superposition (or "sum") of many pulse streams.

Trigger at the accounted pulses $C_i(t)$ only; discriminate both between recorded $C_i(t)$ and estimated $l_i(t)$ pulses and between pulses on channel $i$ and pulses on other channels.

$RA_{i}^{C-O}(\tau)$ the Rossi-Alpha part with accounted pulses $C_j \neq i(t)$ on channel $j$ other than trigger channel $i$.

$RA_{i}^{C-S}(\tau)$ the Rossi-Alpha part with accounted pulses $C_i(t)$ on channel $i$ when triggered on channel $i$.

$RA_{i}^{l-O}(\tau)$ the Rossi-Alpha part with estimated pulses $l_j \neq i(t)$ on channel $j$ other than trigger channel $i$.

$RA_{i}^{l-S}(\tau)$ the Rossi-Alpha part with estimated pulses $l_i(t)$ on channel $i$ when triggered on channel $i$.

$RA_{i}^{l-caus}(\tau)$: The later one contains a fraction of pulses, from which the loss was caused by a leading pulse. These can be got directly from eqn. 7 during/after having solved this eqn. 7 using the corresponding $\tau_i$ for each channel of this equation. Discriminate this from $RA_{i}^{l-S}(\tau)$ by subtracting!
Calibrating the system – determining $p_i(\tau_i)$:

$$\begin{bmatrix}
\frac{1}{1-e_2} & -\frac{p_1(\tau_1)e_1}{1-e_1} & \cdots & -\frac{p_1(\tau_1)e_1}{1-e_1} \\
-\frac{p_2(\tau_2)e_2}{1-e_2} & \frac{1}{1-e_1} & \cdots & -\frac{p_2(\tau_2)e_2}{1-e_2} \\
\vdots & \vdots & & \vdots \\
-\frac{p_k(\tau_k)e_k}{1-e_k} & -\frac{p_k(\tau_k)e_k}{1-e_k} & \cdots & 1 
\end{bmatrix} \begin{bmatrix}
l_1(t) \\
l_2(t) \\
\vdots \\
l_k(t) 
\end{bmatrix} = \begin{bmatrix}
\frac{p_1(\tau_1)e_1}{1-e_1} \sum_{j \neq 1} C_j(t) \\
\frac{p_2(\tau_2)e_2}{1-e_2} \sum_{j \neq 2} C_j(t) \\
\vdots \\
\frac{p_k(\tau_k)e_k}{1-e_k} \sum_{j \neq k} C_j(t) 
\end{bmatrix} \quad \text{(eqn.7)}$$

If the probabilities $p_i(\tau_i)$ were accurate, the following equation should hold:

$$\frac{e_i}{1-e_i} \left( RA_i^{c-o}(\tau) + RA_i^{l-o}(\tau) \right) - \left( RA_i^{c-s}(\tau) + RA_i^{l-s}(\tau) \right) \approx 0$$
Calibrating the system – determining $p_i(\tau_i)$:

$R_{i-caus}(\tau)$ from eqn. 7

If the probabilities $p_i(\tau_i)$ were accurate, the following equation should hold:

$$\frac{e_i}{1 - e_i} \left( R_{i-c}^0(\tau) + R_{i-l}^0(\tau) \right) - \left( R_{i-c}^S(\tau) + R_{i-l}^S(\tau) \right) \approx 0$$

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Calibrating the system – determining $p_i(\tau_i)$:

Take $RA_i^{L-O}(\tau) + RA_i^{C-O}(\tau)$
Calibrating the system – determining $p_i(\tau_i)$:

**Scale** $RA_i^{l-O}(\tau) + RA_i^{c-O}(\tau)$ with $\frac{e_i}{1-e_i}$

**Subtract** $RA_i^{c-S}(\tau) + RA_i^{l-S}(\tau) - RA_i^{l-caus}(\tau)$

Get:
Calibrating the system – determining $p_i(\tau_i)$:

Normalize it to 1 by dividing by (itself + $RA_i^{c-S}(\tau)$)

This will be the new guess of $p_i(\tau_i)$

Repeat this procedure (by repeatedly calculating a new estimated pulse stream $l_i(t)$) until the difference between $p_i(\tau_i)$ and its previous version is small enough.

Then this will fulfil the equation from before:

$$\frac{e_i}{1-e_i} \left( RA_i^{c-o}(\tau) + RA_i^{l-o}(\tau) \right) - \left( RA_i^{c-S}(\tau) + RA_i^{l-S}(\tau) \right) \approx 0$$

(Of course one could also repeat this procedure until this equation is sufficiently fulfilled)!
Calibrating the system – determining $p_i(\tau_i)$:

**Flow chart:**

1. **Input:** Portion of dead-timed pulse train, rel. channel efficiencies $e_{\ell}$.

2. Build $RA_i^{C-S}(\tau)$ and $RA_i^{C-O}(\tau)$.

3. Start with some arbitrary $p_i(\tau_i)$.

4. Estimate lost pulses using eqn. 7 and $p_i(\tau_i)$.
   At the same time build $RA_i^{l-Caus}(\tau)$ using this estimated lost pulses and $\tau_i$.

5. Build $RA_i^{l-S}(\tau)$ and $RA_i^{l-O}(\tau)$ from estimated pulse train.

6. Scale $RA_i^{C-O}(\tau) + RA_i^{l-O}(\tau)$ with $\frac{e_{L}}{1 - e_{\ell}}$.
   From this subtract $RA_i^{C-S}(\tau)$ and $RA_i^{l-S}(\tau) - RA_i^{l-Caus}(\tau)$.
   Normalize the result to 1 by dividing by (itself + $RA_i^{C-S}(\tau)$) to get new $p_i(\tau_i)$.

7. **Stopping criterion reached?**

   - **No**
   - **Yes**

8. **Output:** $p_i(\tau_i)$. 

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Reconstructing multiplicity histograms:

During multiplicity counting one collects a multiplicity histogram \((m_0, m_1, m_2, \ldots)\):

- Trigger at time \(t_0\) and sum up pulses during \([t_0 + \tau_1, t_0 + \tau_2]\), means \(M = \sum_{t_0+\tau_1}^{t_0+\tau_2} \sum_i C_i (t)\)
- Increase \(m_M\) by the number of triggers \(\sum_i C_i (t_0)\).
- Do so for every time \(t_0\) where you find a pulse.

The multiplicity histogram \((m_0, m_1, m_2, \ldots)\) tells you, how often there had been 0, 1, 2, 3, \ldots pulses accounted for within such a gate.

This multiplicity histogram is affected by pulse loss due to dead-time in 2 ways:

1. If a pulse is lost no gate is triggered and the entry in the histogram \((m_0, m_1, m_2, \ldots)\) is lost.
2. The number of pulses \(M = \sum_{t_0+\tau_1}^{t_0+\tau_2} \sum_i C_i (t)\) is calculated wrongfully due to missing pulses within the gate, so the wrong \(m_M\) may be increased in the histogram \((m_0, m_1, m_2, \ldots)\).
Reconstructing multiplicity histograms:

Some more theoretical considerations (some more math):

- Assume a number $g$ of gates with same multiplicity $M$; in total $p$ pulses lost within all gates.
- In average were $x = p/g$ pulses missing in each gate.
- As long as the measurement conditions stay the same $p/g$ shall be constant.
- Neutrons collide within detector-moderator and are reflected sufficiently often → position/channel of neutron detection are independent from event to event → probability whether there was DT-loss caused by leading neutron on that channel is independent from case to case.

Mathematically $M$ such success/failure experiments are described by the Binomial distribution $B_{M,p/Mg}$ (expectation $p/g$).

In principle there are infinitely many gates, we just can measure finitely many. Therefore we need to let $g \to \infty$ (and $p \to \infty$) with $p/g$ stays constant.

It is well known that in such a case the Binomial distribution $B_{M,p/Mg}$ converges to the Poisson distribution $P_{p/g}$ (with expectation $p/g$).
Reconstructing multiplicity histograms:

So our distribution in question is some Poisson distribution $P_{p/g}$ (with expectation $p/g$).

Let’s come back for a moment to eqn. 7:

$$
\begin{pmatrix}
\frac{1}{1 - e_2} & -\frac{p_1(\tau_1)e_1}{1 - e_1} & \cdots & -\frac{p_1(\tau_1)e_1}{1 - e_1} \\
-\frac{p_2(\tau_2)e_2}{1 - e_2} & \frac{1}{1 - e_1} & \cdots & -\frac{p_2(\tau_2)e_2}{1 - e_2} \\
\vdots & \ddots & \ddots & \ddots \\
-\frac{p_k(\tau_k)e_k}{1 - e_k} & -\frac{p_k(\tau_k)e_k}{1 - e_k} & \cdots & \frac{1}{1 - e_k}
\end{pmatrix}
\begin{pmatrix}
l_1(t) \\
l_2(t) \\
\vdots \\
l_k(t)
\end{pmatrix}
= 
\begin{pmatrix}
\frac{p_1(\tau_1)e_1}{1 - e_1} \sum_{j \neq 1} C_j(t) \\
\frac{p_2(\tau_2)e_2}{1 - e_2} \sum_{j \neq 2} C_j(t) \\
\vdots \\
\frac{p_k(\tau_k)e_k}{1 - e_k} \sum_{j \neq k} C_j(t)
\end{pmatrix}
$$

(eqn.7)

The lost pulsed $l_i(t)$ are calculated from accounted ones $C_j(t)$ as reference, under the assumption that pulses are randomly distributed to channels.

Means that a pulse $C_j(t)$ could have been at $l_i(t)$ depending on loss probability $p_i(\tau_i)$ and efficiency $e_i$. However, in this case $C_j(t)$ had not been there.

Therefore we apply the Poisson distribution $P_{p/g}$ to gates with one multiplicity less: $M - 1$!

However this assumption is still imprecise, but for the moment it’s the best we have!
Reconstructing multiplicity histograms:

Procedure: Apply multiplicity counting on both pulse trains \( (C_1(t), C_2(t), \cdots, C_k(t)) \) and \( (l_1(t), l_2(t), \cdots, l_k(t)) \) collecting 4 histograms \( (m_0, m_1, m_2, \cdots), (m_0, m_1, m_2, \cdots), (n_0, n_1, n_2, \cdots), \) and \( (n_0, n_1, n_2, \cdots) \):

1. Trigger on dead-timed pulse train \( (C_i(t))_{i=1,\cdots,k} \) counting pulses \( C_i(t) \) in gate: Calculate \( M = \sum_{t_0}^{t_0+\tau_1} \sum_i C_i(t) \) and increase \( m_M \) by \( \sum_i C_i(t_0) \). \( \rightarrow \) Normal dead-timed mult. histogram \( (m_0, m_1, m_2, \cdots) \).

   1.1 Trigger on the dead-timed pulse train \( (C_i(t))_{i=1,\cdots,k} \) and count the pulses \( l_i(t) \) in the gate:
   \[ x = \sum_{t_0}^{t_0+\tau_1} \sum_i l_i(t) \]
   and increase \( m_M \) by \( x \sum_i C_i(t_0) \). \( \rightarrow \) Histogram \( (m_0, m_1, m_2, \cdots) \) containing the estimated sum of lost pulses in gate of a specific multiplicity.

2. Trigger on the estimated lost pulse train \( (l_i(t))_{i=1,\cdots,k} \) and count the pulses \( C_i(t) \) in gate. Increase \( n_M \) by the sum of triggers on the estimated pulse train \( \sum_i l_i(t_0) \rightarrow \) dead-timed mult. histogram \( (n_0, n_1, n_2, \cdots) \) for lost triggers/gates (can simply be added to the original histogram).

   2.1 Trigger on the on the estimated lost pulse train \( (l_i(t))_{i=1,\cdots,k} \) and count the pulses \( l_i(t) \) in the gate \( x = \sum_{t_0}^{t_0+\tau_1} \sum_i l_i(t) \): Weight this with sum of estimated lost triggers \( \sum_i l_i(t_0) \): calculate \( x \sum_i l_i(t_0) \). Then increase \( n_M \) by \( x \sum_i l_i(t_0) \) \( \rightarrow \) Histogram \( (n_0, n_1, n_2, \cdots) \) containing the average number of lost pulses in lost gates.
Reconstructing multiplicity histograms:

- **Trigger position** $t_0$
- **Observed pulse train** $\sum_i C_i(t)$
- **Estimated lost pulse train** $\sum_i l_i(t)$
- **Normal Trigger**
- **Estimated lost Trigger**
- **Gate** $t_0 + \tau_1$
- **Gate** $t_0 + \tau_2$
- **Multiplicity in gate**: 9
- **Estimated average no. of pulses lost inside this gate**: 3.7

**Legend:**
- **Observed pulse**
- **Estimated pulse lost**, height and value indicating average no. of estim. lost pulses at this position

0.3 0.5 0.8
0.5 0.7 0.9
0.5 0.7 0.9
Reconstructing multiplicity histograms:

3. Create new histogram \((m_0^{new}, m_1^{new}, m_2^{new}, \ldots)\): redistribute histograms \((m_0, m_1, m_2, \ldots)\) and \((n_0, n_1, n_2, \ldots)\) like that:

\[
m_{i+j}^{new} = m_{i+j}^{new} + m_i \text{Pois}\left[\frac{m_{i+1}}{m_{i+1}}\right](j) \quad \text{for } j=0,1,2,\ldots
\]

\[
m_{i+j}^{new} = m_{i+j}^{new} + n_i \text{Pois}\left[\frac{n_{i+1}}{n_{i+1}}\right](j) \quad \text{for } j=0,1,2,\ldots
\]

New multiplicity histogram \((m_0^{new}, m_1^{new}, m_2^{new}, \ldots)\) now corrected for dead-time loss.

Use this procedure on both the histograms for "R+A gate" (\(\tau_1\) small) and "A gate" (\(\tau_1\) large but same difference \(\tau_2 - \tau_1\))

From these improved mult. histogr. calculate Singles, Doubles, Triples \(\rightarrow\) improved results.
Results from simulations:

Simulation of pulse train:

- Minimum time-slot (TIC) 100ns were used;
- 10 s simulation time (100 Mega-TICs);
- A Poisson-process was simulated, each event producing 10 neutrons.
- About 10 M-neutrons produced in these 10 seconds, (1 million/s).
- Neutrons delayed in time with exponentially distributed die-away of 10 microseconds (expected)
- Randomly distributed to 5 channels.

Simulation of dead-time: 3 different patterns
Results from simulations:

Rossi-Alpha: Comparison of deleted to reconstr. pulses

Square DT: Originally deleted and reconstructed lost pulses

Reconstructed lost pulses  Original deleted pulses

Square DT upd.: Originally deleted and reconstructed lost pulses

Reconstructed lost pulses  Orig. deleted pulses

Slope DT: Originally deleted and reconstructed lost pulses

Reconstructed lost pulses  Orig. deleted pulses

Loss:

• Square DT: 12.04% (true) – 12.05% (est.);
• Square DT upd.: 13.12% (true) – 12.98% (est.);
  → 1.07% underest. (from deleted pulses)
• Slope DT: 15.9% (true) – 15.9% (est.).
Results from simulations:

Rossi-Alpha on original pulse stream

Rossi-Alpha of reconstruction:

Rossi-Alpha reconstr.: Square DT
Results from simulations:

Rossi-Alpha reconstr: Square DT upd.

Rossi-Alpha of reconstruction:

Rossi-Alpha reconstr.: Slope DT
Results from simulations:

Square Dead-Time: Multiplicity histograms

Multiplicity Histograms and reconstruction:

Square Dead-Time updating: Mult. histograms

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Results from simulations:

Slope Dead-Time: Multiplicity histograms

Multiplicity Histograms and reconstruction:

Results from simulations:  

Squares DT: Singles, Doubles, Triples Rates

Square DT upd.: Singles, Doubles, Triples Rates

Slope DT: Singles, Doubles, Triples Rates

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<th>Slope dead time</th>
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Conclusion:

A new method for dead-time correction for high and very high count-rates using a comparison of the signals of different preamplifiers has been developed:

- The estimation of lost pulses and the calibration had been demonstrated to work very well;
- Correction of Singles, Doubles and Triples are reasonably good, however some improvement is desirable.

Several advantages:

- It works for high and very high count rates;
- It does not need any prior calibration, can use measurement data for calibration (provided the count-rate is sufficiently high);
- Works for any gate-with, delay, pre-delay and even fast accidentals;
- Works for higher moments like Quadruples, however high statistical uncertainty limits its use;
- Reasonable computing time (30 sec for the simulation of 10 sec with 100 Mpulses).
- Potential for further development (e.g. for estimating double pulsing, etc.)
Thank you!

Questions?

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