PMT Pulse Digitization Simulations for Hall D

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Abstract

Typical photomultiplier tube (PMT) signal pulses were created and digitized in simulation. In particular the pulses were simulated to be typical of those of FEU-115 and FEU-84-3 PMTs. The parameters of the digitization were varied to simulate a broad range of analog to digital conversion (ADC) module specifics. The goal is to understand how resolution of the pulse integral measurement changes with ADC sampling frequency and bit depth.

1, Pulse Modeling

Anode pulses from an FEU 115 powered with a supply voltage of 1900V were collected by optically coupling an Americium source embedded in a small piece of inorganic scintillater (approx. 1cm^3) to the photocathode with a small amount of optical grease. The pulses were digitized using a digital oscilloscope at a sampling frequency of 2.5 GHz and 16 bits of depth. The trigger level of the oscilloscope was adjusted to capture 2500 pulses ranging in amplitude from 0.015V to 1.5V. The pulses were each fitted to a function of the form:

$$V(t)= \begin{array}{ll} t \le P_4 & -P_1 * \mathrm{Exp}[\,-((t-P_4)\,/\,(0.838339*P_2))^2\,] \\ t \ge P_4 & -P_1 * \mathrm{Exp}[\,-((t-P_4)\,/\,(0.838339*P_3))^2\,] \end{array} \qquad (1)$$

Table I: Arbitrary Parameters of Pulse Model

Parameter (P)	Physical Interpretation
1	Pulse Amplitude
2	10% to 90% Rise Time
3	10% to 90% Fall Time
4	Peak Time Offset

The advantages of this functional form over most others are that the parameters have direct physical interpretations and that it is analytically integrable. The FEU-115 pulse data when fitted showed a linear relationship between amplitude and charge integral (see Fig. I). The rise and fall times were found to vary by only a small amount (see Figs. II and III). These relationships are as follows:

Table II: Relationships of Pulse Parameters

Amplitude vs. Integral	$\mathrm{Amp}(-V) = 0.054593(\mathrm{ns}^{-1}) * \mathrm{Int}(-V*\mathrm{ns})$
Rise Time vs. Integral	$T_R(\mathrm{ns}) = 0.049892(V^{-1}) * \mathrm{Int}(-V*\mathrm{ns}) + 2.7638(\mathrm{ns})$
Fall Time vs. Integral	$T_F(\mathrm{ns}) = 0.0027652(V^{-1}) * \mathrm{Int}(-V*\mathrm{ns}) + 8.5304(\mathrm{ns})$

For the purposes of simulating FEU-115 pulses, a fixed rise and fall time was used since the variation of rise and fall times was so little over a wide range of amplitude. Pulses were also collected from the FEU-84-3 to determine a characteristic rise and fall time for it as well. These rise and fall time parameters were used in all simulations:

Table III: Characteristic Pulse Widths of PMTs

Photomultiplier Tube	Rise Time	Fall Time
FEU-115	3.25ns	8.56ns
FEU-84-3	8.18ns	15.09ns

2, Digitization Simulation

PMT pulses are digitized using ADC circuitry which measures the pulse voltage at regular intervals determined by the sampling frequency. The time period between sampling is inversely proportional to the sampling frequency. A 250MHz ADC frequency would produce a data point every 4ns, a 500MHz frequency would produce a data point every 2ns. At each sample point the ADC truncates the voltage to discrete values determined by the bit depth and maximum scale setting. A bit depth of 8 results in 2^8 possible discrete values including 0. Thus the voltage is recorded in discrete increments of 1 / (2^8-1) of the maximum scale. The digitized pulse must then be integrated and the result of this integral is stored as data.

Pulses were simulated by using equation 1 with the above mentioned rise and fall time parameters. The time offset varied randomly between 0 inclusive and 1 sampling period exclusive. The amplitude parameter varied randomly within a defined interval for each simulation. This was to prevent certain sample bit depth's from appearing artificially superior or inferior depending on how closely they could fit the pea amplitude. ADC digitization was simulated using a looping procedure which filled a histogram with the value of the function starting at t=–250 sampling periods through t=250 sampling periods. The resulting values were then truncated by multiplying all entries to (2^n-1)/ maxscale(V) to convert the data to bits, rounding down to the nearest integer, and then multiplying by maxscale/(2^n-1) to return the data to voltage levels.

Once a simulated digitized pulse was produced, three methods were used to integrate it. The first was standard Simpson's rule numeric integration computed by summing the voltage of all the samples for a given pulse and multiplying this value by the sample interval. The second method utilized the linear relationship between amplitude and integral. The amplitude of the pulse was simply determined by finding the greatest (most negative) sample voltage for a given pulse under the assumption that this information can be used to extrapolate the value of the integral. The third method involved fitting a function of the form of equation 1 to the digitized data using the CERN hbook MINUIT fitting routine and analytically integrating this function (a simple formula). The fitting routine is always given the following values for parameter guesses:

Table IV: Fitting Parameter Initial Guesses

P_1 -Amplitude (V)	.45
P_2 -Rise Time (ns)	6
P_3 - Fall Time (ns)	11
P_4 -Peak Time Offset (ns)	0

All three of the integration techniques were performed for each pulse and the result was compared to an analytical integration of the original pre-digitized pulse to produce a relative error. The relative errors of each of the three methods are recorded for a large sample of pulses each digitized with the same frequency and bit depth. The standard deviation of the errors for each of the three methods is then computed for the entire sample. This process is repeated for each combination of frequency and bit depth which results in a map of resolution as a function of frequency and bit depth.

3, Resolution vs. ADC sampling frequency and bit depth.

For convenience the maximum scale of the ADC is set to 1 V. in all the simulations. The ADC is considered optimized for a given pulse if it's maximum scale setting is very near the peak amplitude of the pulse. This allows the ADC to give the most precise measurements of the pulse voltage without truncating the pulse due to overflow. The simulation was run to produce a resolution value at each bit depth between 4 and 13 and at every 100 MHZ between 100MHz and 1GHz.

In the first set of simulations the pulse amplitude varies randomly from 0.70 V inclusive to 0.80 V exclusive (see Fig. IV). This is close to optimal for the ADC maximum scale setting. Each resolution value is derived from 1,000 pulse digitizations. As expected, resolution improves with increased data in either bits or sampling frequency. The FEU-115 resolution is more dependent on the sampling frequency, while the FEU 84-3 is more dependent on bit depth. Simpson's rule appears to be the best method of integration.

In the second set of simulations the pulse amplitude varies randomly between 0.10 V inclusive and 0.20 V exclusive (see Fig. V). This is not at all optimal for the ADC max scale setting. Each resolution value is derived from 1,000 pulse digitizations. Sample bit depth dependency appears to increase in all cases from corresponding simulations in the previous set. The CERN hbook MINUIT fitting routine appears to break down except for the highest sampling frequencies and bit depths.

The final set of simulations varies the amplitude randomly from 0.10 V and 0.90 V. This is most of the range of the ADC (see Fig. VI). The FEU-84-3 simulation was run with 10,000 pulses per point, the FEU-115 simulation was run with 5,000 pulses per point. The results in all cases are very similar to the results for the low amplitude pulses suggesting that it is these pulses which dominate the resolution.

Remaining questions:

Can the fit routine be improved to produce better results?

Can a better scheme for estimating peak amplitude be created to improve this technique?

Can an improved fit routine extrapolate overflow data to improve the dynamic range of the ADC?

Figure I: Amplitude vs. Integral for FEU-115

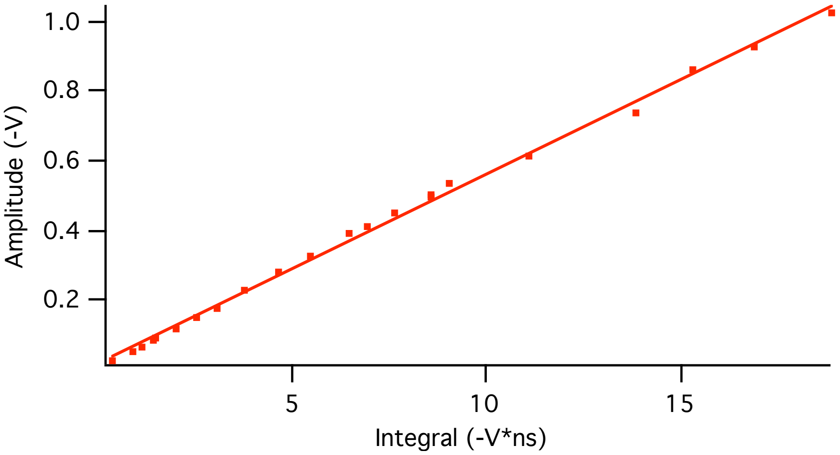


Figure II: Rise Time vs. Integral for FEU-115

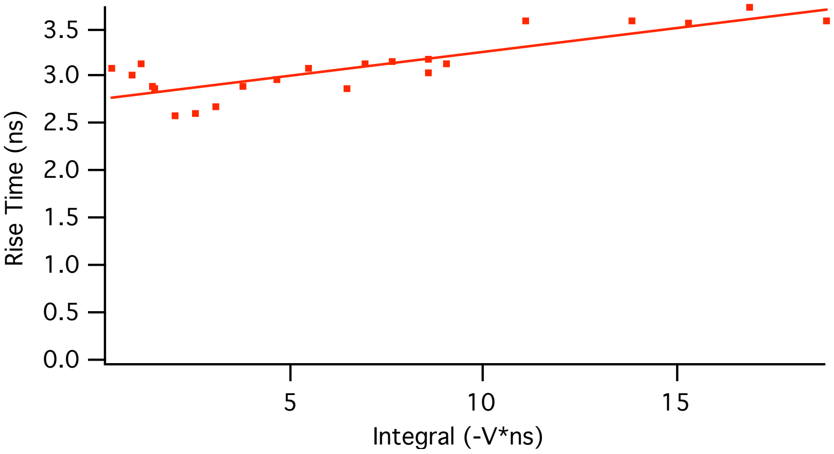


Figure III: Fall Time vs. Integral for FEU-115

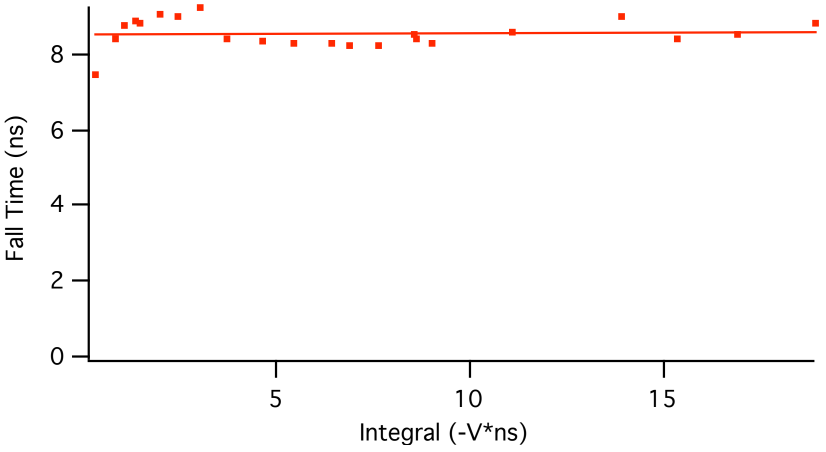
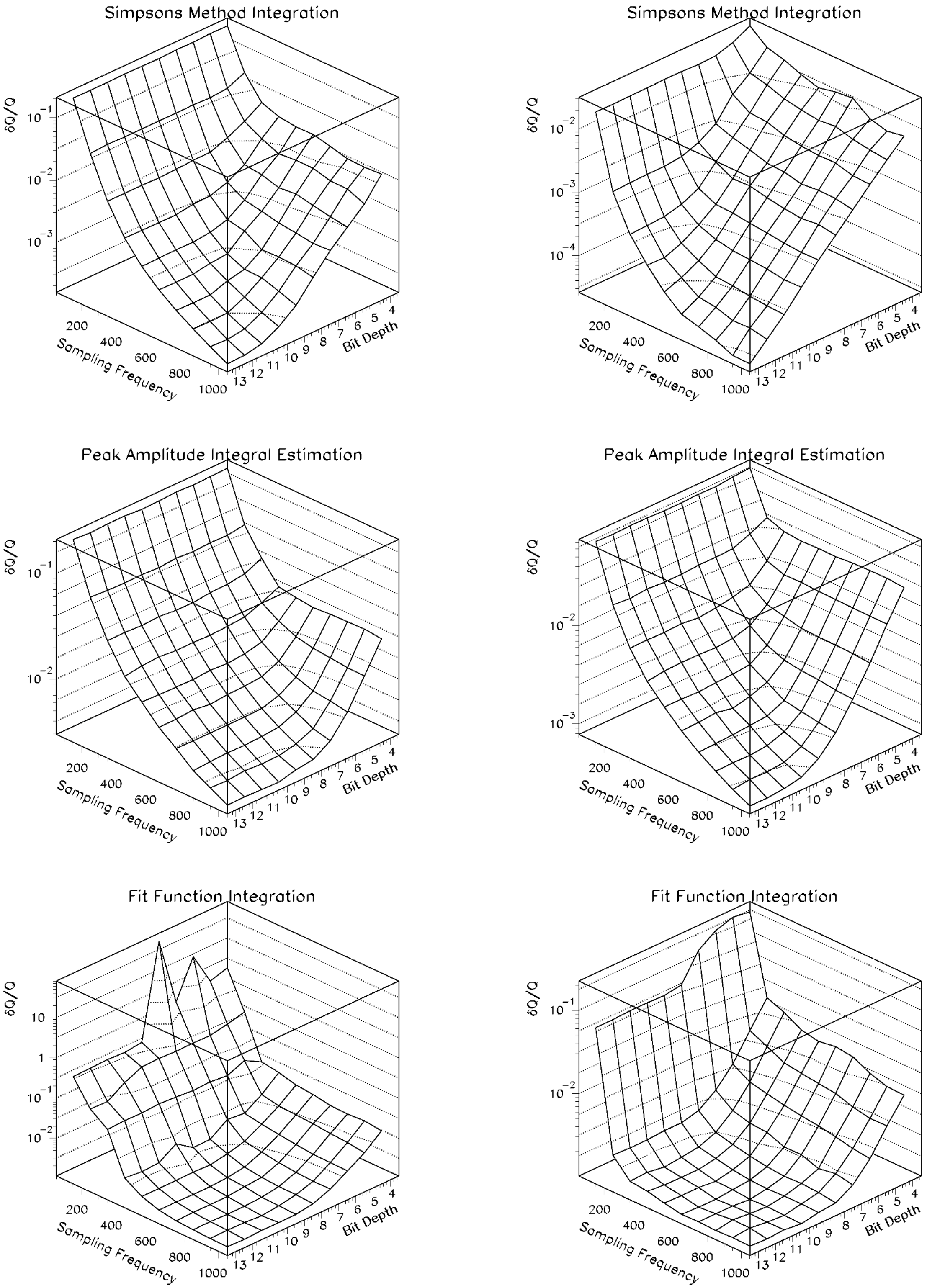


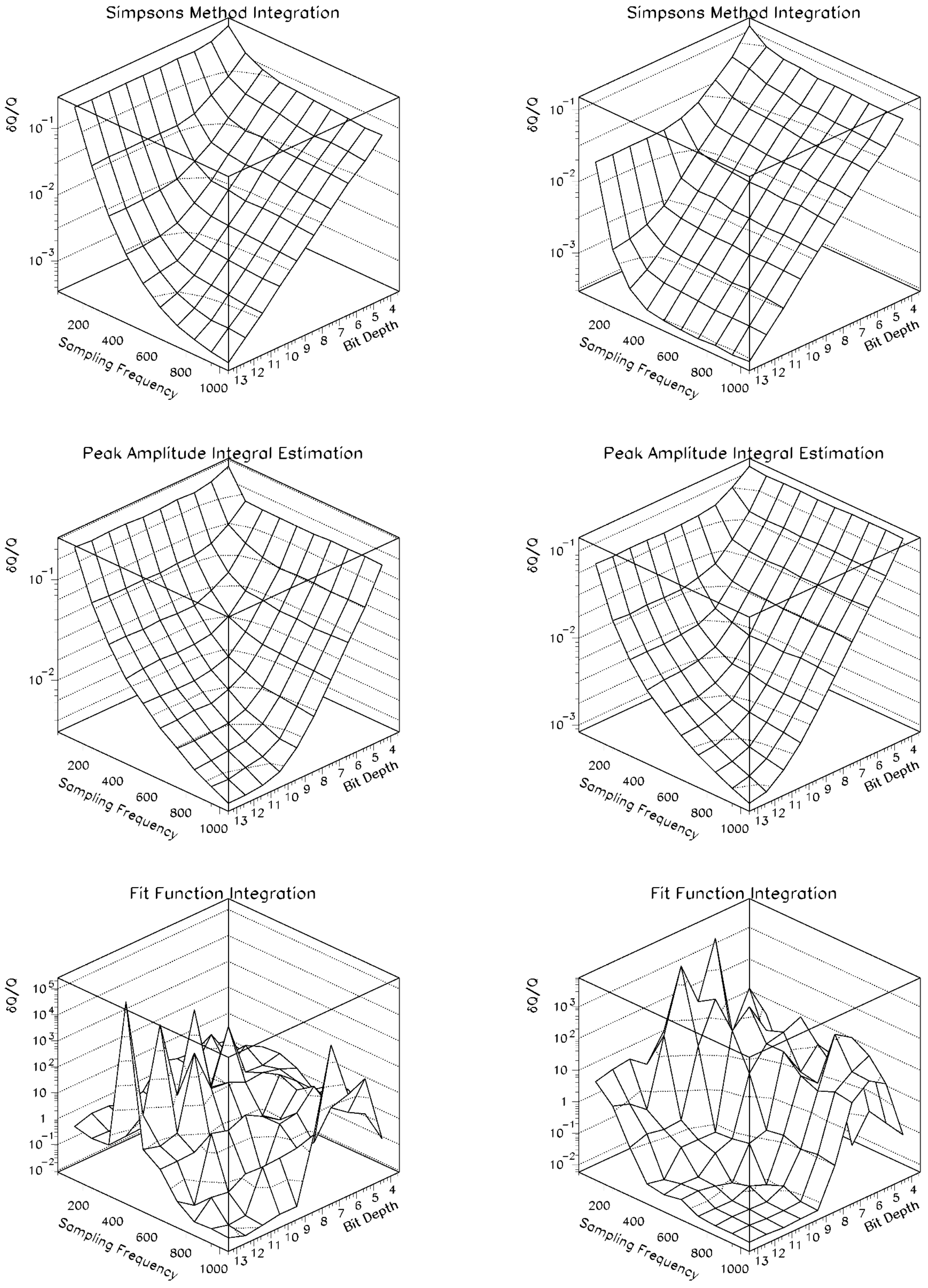
Figure IV: Resolution at Amplitude 70%-80% of Maximum Scale



FEU-115

FEU 84-3

Figure V: Resolution at Amplitude 10%-20% of Maximum Scale


FEU-115

FEU 84-3

Figure VI: Resolution at Amplitude 10%-90% of Maximum Scale

FEU-115

FEU 84-3