

# Noise Characterization of the ATLAS Tile Calorimeter Readout System

Christopher J. Meyer  
University of Chicago, Illinois, USA

June 3, 2009

## Abstract

It is shown that the addition of a low pass RC filter to the current ATLAS Tile Calorimeter 3-in-1 card decreases the high frequency noise. A peak in the output voltage is found for 29 Mhz input noise but is filtered out by the same low pass filter.

## 1 Introduction

The data acquisition (DAQ) system for the ATLAS Tile Calorimeter at the Large Hadron Collider (LHC) is important for accurate measurements of energy deposited in the hadronic calorimeter. A perfect system would pass only the signals left by ionizing particles and cut out all other fluctuations manifesting in the form of noise. Practically this is not possible but filters can be placed in the system to decrease the noise as much as possible. Below is a brief introduction to the LHC and ATLAS, with following sections describing the specifics of the DAQ system and the methods and results of filtering out noise.

The LHC is a circular proton-proton (pp) accelerator capable of reaching center-of-mass energies of 14 trillion electron volts (TeV) at the CERN facilities in Geneva, Switzerland. Planned to begin operation in late 2009 it has a designed initial luminosity of  $10^{27} \text{ cm}^{-2}\text{s}^{-1}$  which corresponds to bunches of  $10^{11}$  protons crossing 40 million times per second (40 MHz).

The data generated by these collisions will be read out by two general purpose detectors, ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid). CMS will not be discussed in this paper. ATLAS is a forward-backward symmetric detector composed of three main systems: the inner detector, the calorimetry system, and the muon spectrometer.

The inner detector is composed of high-resolution semiconductor pixel and strip detectors in the inner part of the volume and straw-tube tracking detectors in the outer part. It is permeated by a 2 T solenoid field which bends particles for the purpose of momentum measurements. Its main purposes are pattern recognition, momentum and vertex measurements, and electron identification.

The calorimetry system consists of two main sections, the liquid-argon (LAr) calorimeter and the hadron (tile) calorimeter. The calorimeters provide position and energy information

on the particles they absorb (almost everything except muons and neutrinos). The LAr calorimeter detects electrons and photons while the tile calorimeter provides information about hadrons (bound quark states).

The muon spectrometer is an open structure with three layers of high precision tracking chambers. Immersed in a magnetic field the muons are bent providing excellent momentum resolution. More information regarding the ATLAS detector can be found in Ref. [1].

This paper deals with the readout system for the tile calorimeter, particularly with the processing of the raw calorimeter output before it is digitized and output in a computer readable format.

## 2 ATLAS Tile Calorimeter Readout System

The readout system for the ATLAS Tile Calorimeter consists of a number of 1.4 m long aluminum units called drawers. These drawers house the PMTs and readout electronics which take analog signals from the calorimeter and convert them into serialized digital output. This output is processed and written into data files which are later processed offline. Each drawer is connected to forty-eight PMTs, each of which is connected to a dedicated 3-in-1 card.

The 3-in-1 card takes a PMT signal and (1) passes it through a seven-pole shaper consisting of passive elements, (2) sends it through hi- and low-gain amplifiers, (3) converts the signal into differential form to cut out baseline noise before sending the signal onward.

The clean, shaped analog curve is then converted into a digital signal by sampling at twenty-five nanosecond intervals. This analog-to-digital conversion (ADC) is done on a chip which buffers the input from six 3in1 cards. In total there are eight ADCs to cover the forty-eight PMTs all of which hook into a single read out card responsible for the entire drawer.

In order to cover the wide range of energy deposits the calorimeter will face during operation 16 bits of dynamic range is needed. Due to practical limitations a 16-bit ADC is not feasible so the current Tile Calorimeter readout system uses a bigain 10-bit ADC instead. For the proposed Super LHC (sLHC) upgrade there is an effort to replace the 10-bit ADCs with 12-bit ADCs to account for general improvement in circuit technology and the higher luminosities expected.

The topics mentioned above are described below in more detail.

### Tile Calorimeter

The tile calorimeter is made up of alternating layers of steel and plastic scintillator material in the layout shown in figure 2. The plastic scintillator (active medium) absorbs the energy of incident charged particles and then reemits it in the form of photons. In order to absorb all the hadrons traveling through the tile calorimeter the scintillator would have to be impractically large, so layers of steel are interspersed (called passive layers). The steel layers are much denser so undergo many more strong interactions with the hadrons

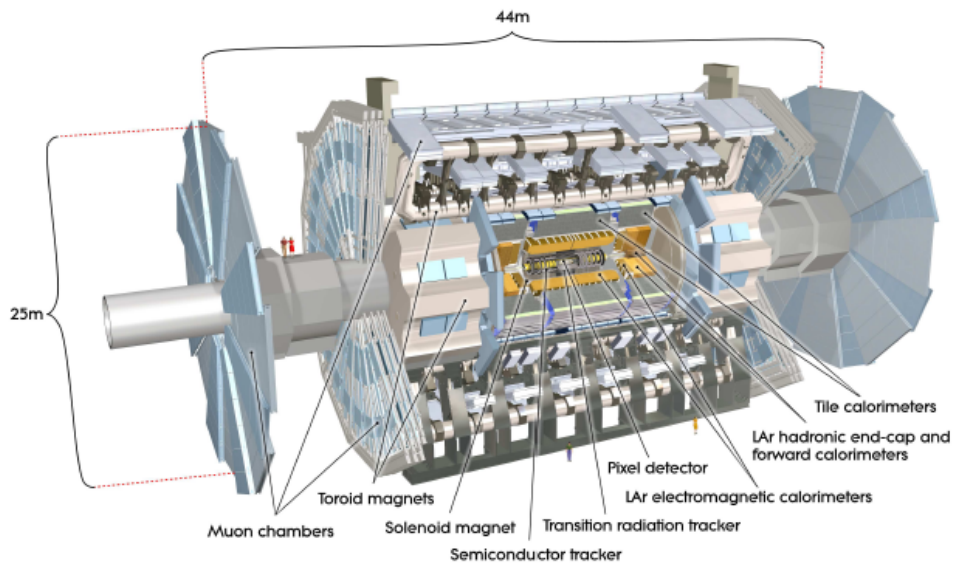


Figure 1: ATLAS detector.

traversing them giving the tile calorimeter a total thickness of 7.4 radiation lengths. These multiple interactions create showers of charged particles only some of which are detected by the scintillator. Since all the energy is not detected it is necessary to rescale the energy at a later time depending on what was travelling through the calorimeter (proton, pion, etc...). More specifics can be found in Ref. [1].

Fiberoptics then take the light from the scintillator and transports it to one of the forty-eight PMT tubes associated with the drawer. The light is then amplified through the PMT and output to the 3-in-1 card. The system is designed for a maximal pulse deposited in any given cell of 2 TeV [2].

### 3in1 Card

The pulse coming out of the PMT generally has a 5.5 ns rise time and 11 ns fall time with jagged edges due to photo-electron effects[3]. The 3-in-1 card shapes this signal into something the ADC can easily characterize. Since the ADC samples at 40 MHz (every 25 ns), the smallest signal which can be accurately sampled and later reconstructed must be no larger than 20 MHz. This corresponds to 50 ns, which is the width the shaped pulse is set to.

The shaping is done by a 7 pole, passive element shaper so as to introduce no new noise into the system. It is based on a Bessel filter with bandwidth at -3dB of 12Mhz and has an effective noise bandwidth of 115%. Outputs for two gain ranges of 1V/800pC and 2V/800pC are provided. An example of the shaped pulse can be seen in figure 3.

While the upper limit on a pulse is 2 TeV corresponding to large showers, 30 MeV is the

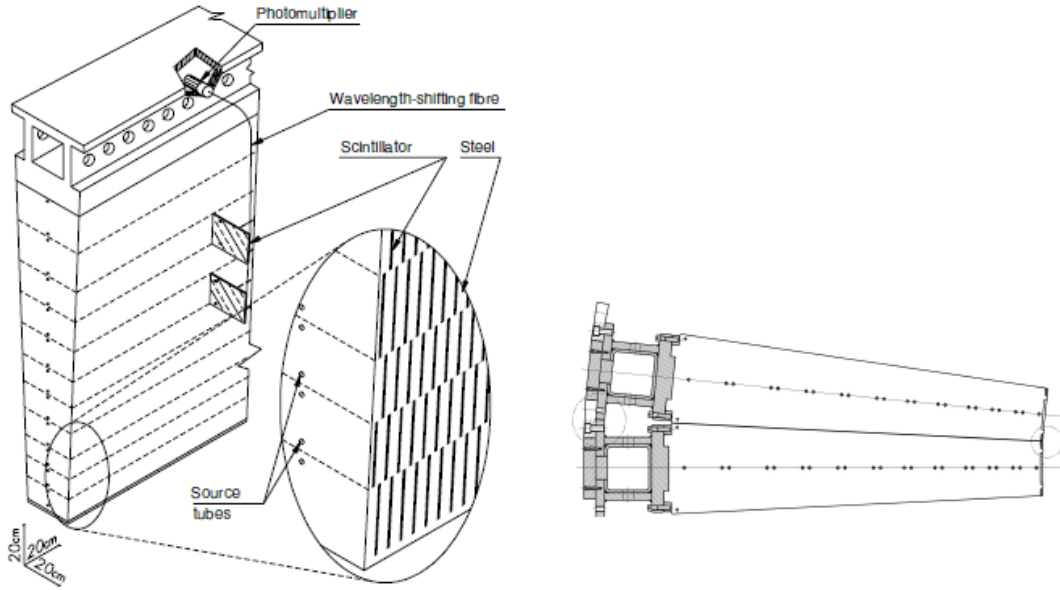


Figure 2: The left shows the arrangement of a slice of the tile calorimeter. 64 of these are arranged to create full cylindrical coverage. The right shows the azimuthal view of how two segments will fit together.

lower limit and corresponds to muons. The dynamic range required to accurately sample this range is then  $2\text{TeV}/30\text{MeV} = 2^{16}$ , so a 16-bit ADC is required. A 16-bit ADC is impractical because of noise and cost, so instead a 10-bit ADC bigain system with relative gain of 64 ( $2^6$ , so  $2^{-6} * 10\text{-bit} = 16\text{-bit}$  resolution) is employed. The high gain channel uses a CLC501 gain-of-16 clamping amplifier on the  $2\text{V}/800\text{pC}$  output, while the low gain channel uses a CLC502 unity gain clamping amplifier on the  $1\text{V}/800\text{pC}$  output provided by the shaper.

The third stage is to switch the signal to differential mode before outputting to the ADC since it is approximately a foot away in the experimental setup. In this way any noise picked up during transport will be removed at the ADC. The low-gain is put through a gain-of-1/2 differential driver while the high-gain channel is put through a differential driver of gain unity. More information can be found in Ref. [2]. A summary of this process is shown in the flow chart in figure 4.

## 2.1 Setup and Preperation

### Hardware

The hardware used for this analysis is composed of a single 3-in-1 card connected to an ADC board. The ADC is connected to a read out card which in turn is connected to a VME control crate which supplies all power and commands to the system. A lynx (unix like) environment is used to interface with the VME crate and control the system from a nearby

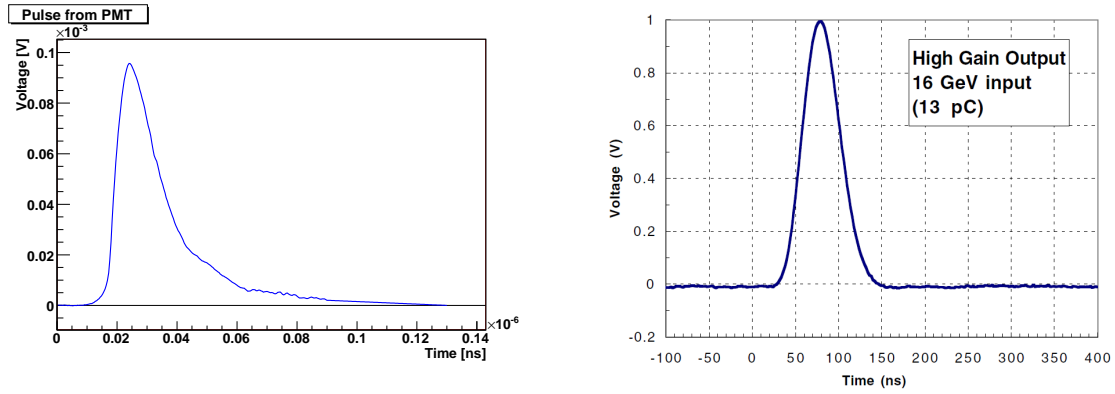


Figure 3: The left is an example of a pulse from a PMT. The right shows what a shaped and amplified pulse looks like.

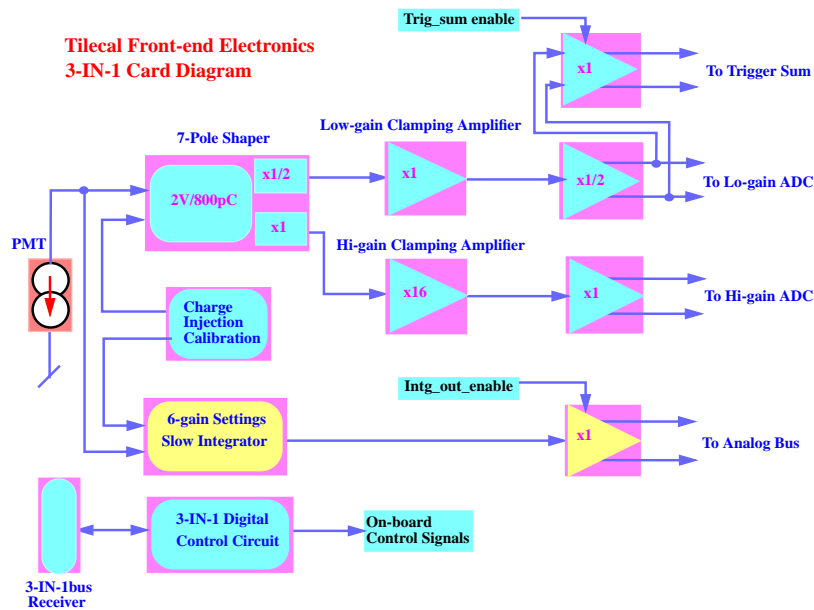


Figure 4: Flow chart of the 3-in-1 card.

computer.

The lynx system is primarily used to view a 16 bin window of digital output from the ADC, where the value of each bin is the integrated average of the signal for 25 ns. The only control functionality of the lynx system used is setting the delay at which the window is viewed. By changing the delay to approximately 30 bins after an injected pulse the background pedestal is read out and can be characterized by taking the root-mean-square (RMS) of the 16 points.

There are two methods of reading noise from the system: (1) find the RMS from the signal read out by the ADC, and (2) unplug the 3-in-1 card from the ADC and plug the signal directly into an oscilloscope. Because simulations do not include the digitizer the second method is used primarily in this study.

Figure 5 shows the schematic of the 3-in-1 card. A Sony Tektronix AWG 2040 function generator is plugged into S.IN (the PMT signal input) in order to simulate  $\pm 10\text{mV}$  sinusoidal noise from 500 khz to 50 Mhz. A Tektronix TDS 3054B oscilloscope is connected to GHOUT+, the high gain output where the noise will have the largest effect.

## Simulation

Before physically modifying the circuit it is simulated in Mentor Graphics. The only modification made a priori to the circuit is to terminate the differential outputs with  $1\text{ M}\Omega$  resistors to simulate the termination of the oscilloscope.

Two simulations were performed. The first was with a single low pass filter at 13 Mhz consisting of  $50\ \Omega$  resistors and a  $120\ \text{pF}$  capacitor placed after the differential stage, while the second was a control case with the unfiltered circuit. A schematic of the filter is shown in figure 6.

Results of the simulations are shown in figure 7. The low pass filter has the effect of decreasing the 3dB point, lowering the total area under the curve thus the total noise. It is important to recall that the purpose of the circuit is to shape and amplify pulses from a PMT. After being shaped these pulses have a fundamental frequency of 10 Mhz so that the 3dB point should occur after this frequency. Adding this filter does decrease the gain of a 10Mhz signal so it will need to be shown that the effects on the readout are acceptable.

It is also of interest to point out that we do not use a high pass filter in an attempt to cut noise before 10 Mhz. This is because the ADC takes care of this for us. By sampling only 16 bins (of 25ns each) noise below a critical level of 1.25 Mhz no longer has time to complete a full rise from trough to peak so begins to appear as only a global rasing and lowering of the PMT signal. Since baseline pedestal levels are subtracted when finding the height of the pulse noise below 1.25 Mhz is removed from the system.

## 3 Results

Using the function generator to input a  $\pm 10\ \text{mV}$  sine wave swept over a frequency range of 500 khz to 50 Mhz produces the results shown in figure 8. The shape of the simulation

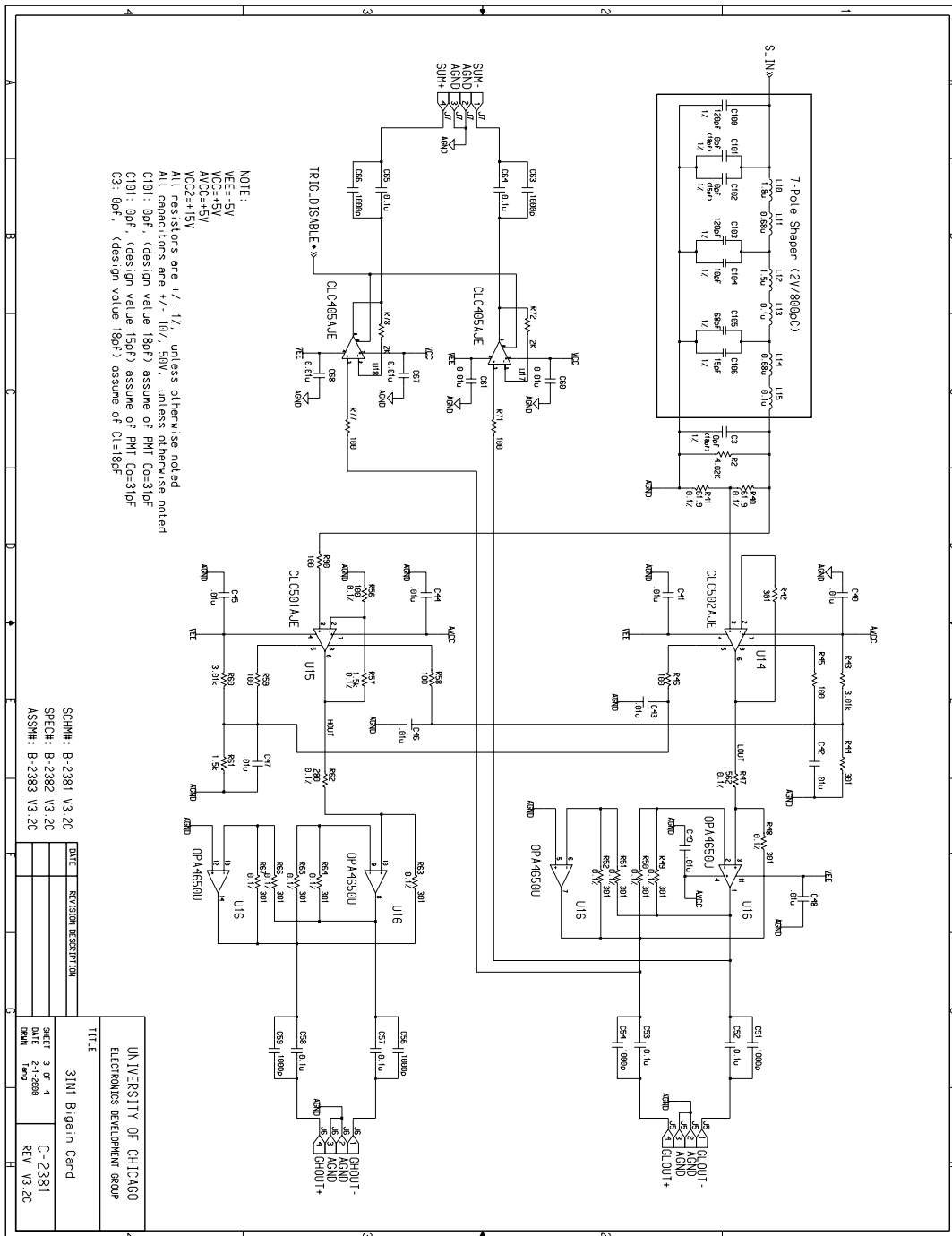


Figure 5: Schematic of 3-in-1 card. The signal enters into S\_IN and is immediately put through a 7 pole shaper. It is then split and sent into a high or low gain amplifier. Following the amplification process the signals are put in differential mode by a two op amp system. The filter will be placed in the output of the differential stage.

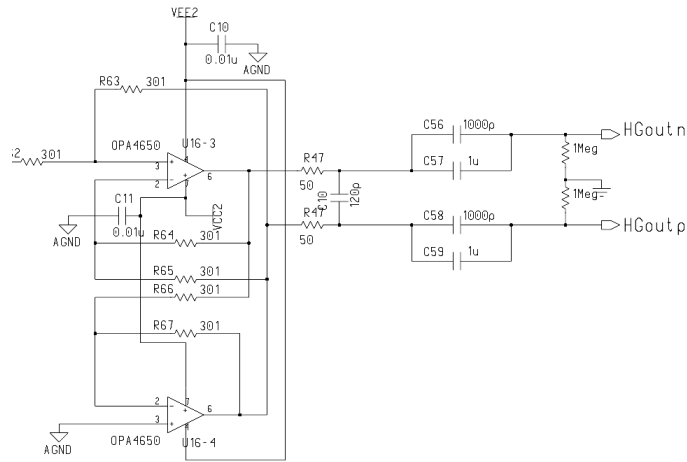


Figure 6: Modification made to circuit for simulation. The  $f_{-3dB} = 1/(2\pi RC) = 13\text{Mhz}$ .

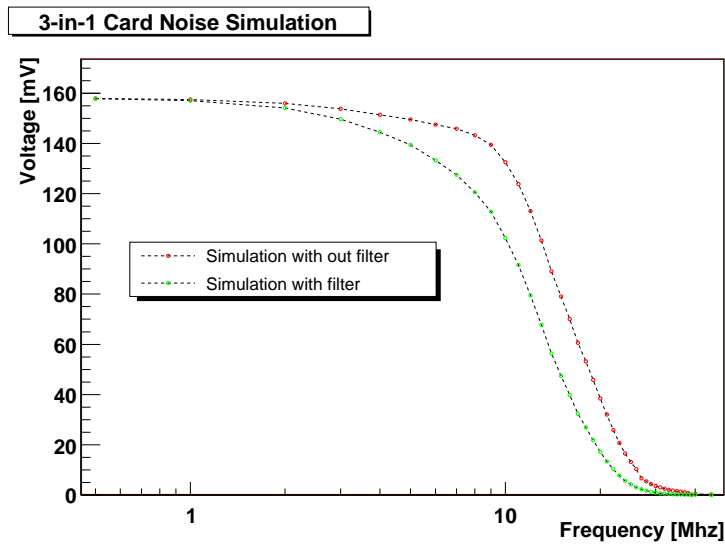


Figure 7: Results of the simulation. Plotted is amplitude of the output sine wave vs frequency. The lower curve shows the effect of adding a low pass filter to the system.

is in decent agreement with data taken of the filtered circuit, however the unfiltered circuit develops a peak at 29 Mhz which is not seen in the simulation, as well as an increased 3dB point.

It is very probable this is caused by stray capacitances due to the physical layout of the board that the simulation doesn't account for. As a first order check two capacitors can be placed between the input to the differential driver op amps and ground. The results are shown in figure 9. The agreement of the filtered circuit is now even better, and although the unfiltered circuit is still far off, it has begun developing a peak in the upper end of the frequency range and has also shifted the 3dB point upwards. The simulation also shows the same dramatic effect in reducing the spike that the data shows.

It is for these reasons the difference in shape is attributed to stray capacitances. The low pass filter successfully cuts them out which accounts for the agreement of simulation with data for this case. This is hardly an optimized filter. Improvement would include retaining the cutoff frequency at 10 Mhz (maintaining amplification of the signal) but maintaining a fast enough drop off to suppress the peak at 29 Mhz. Even though there is a medium decrease in signal amplitude at 10 Mhz the suppression of the peak at 29 Mhz is important enough to seriously consider an additional filter stage.

## ADC Results

It should be noted that noise data was originally planned to be taken through the ADC, where the RMS of the pedestal would serve as a measure of the noise. Taking this measurement revealed that the coupling of the 3-in-1 card to the ADC introduced a large peak at 40 Mhz an order of magnitude above the surrounding frequencies.

Exploration revealed this was most likely due to the 40 Mhz clock the ADC was running on. Because the purpose of this experiment was to observe only the 3-in-1 card the oscilloscope was used instead. It is of great interest outside of this project to explore the cause of this spike, and find a way to suppress it if possible.

## Appendix A: Error Analysis

There are two main sources of error in this experiment. The first is the systematic error of input signal amplitude. The input amplitude was determined by a 1 mV resolution dial on the function generator. Because this signal is first attenuated by a factor of 5 and then put through a transformer before being input into the 3-in-1 card it is difficult to calculate analytically a value for the error.

Instead the oscilloscope was used to monitor the input waveform into the 3-in-1 card, where the peak-to-peak voltage of the signal was  $20 \pm 0.5$  mV. The function generator was set so to output  $19.5 \pm 0.5$  mV and a reading of the 3-in-1 output voltage was taken. The function generator was then set to  $20.5 \pm 0.5$  mV and another reading of the output was taken. Half the difference between these two values is then taken to be the systematic error on the voltage reading. The systematic uncertainty was found to be  $2\%V_{3in1}$  over a range of

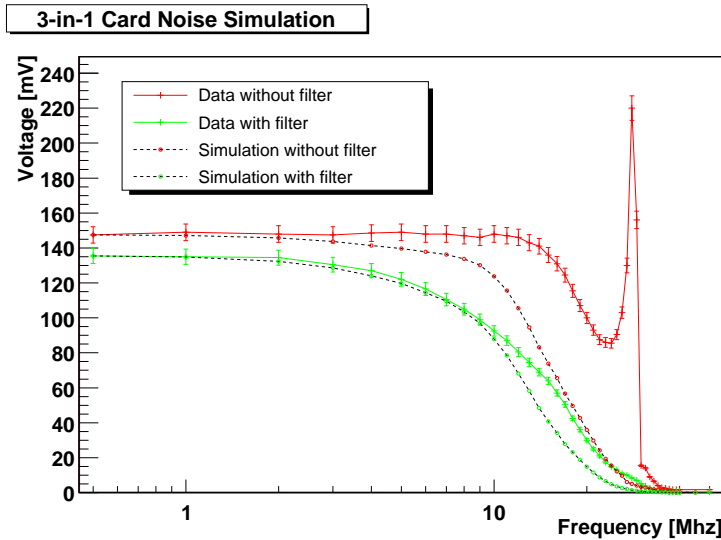


Figure 8: The circles “o” represent the simulation while the plus signs “+” represent data taken. Red is for the unfiltered circuit and green is for the filtered circuit. Notice the peak in the unfiltered circuit and small hump in the filtered circuit at 29 Mhz.

frequencies.

There is also a statistical error on the 3-in-1 output voltage. To determine this the amplitude was histogrammed and found to have standard deviation of 5% the output voltage. When reading the voltage an average of 16 measurements was taken, so that the statistical error on each 3-in-1 voltage measurement is  $5\%/\sqrt{16} = 2.5\%V_{3in1}$ .

Adding the two errors in quadrature yields a final error on the 3-in-1 card voltage measurement of

$$\sigma_V = \sqrt{0.025^2 + 0.02^2}V_{3in1} = 3.2\%V_{3in1}$$

## Appendix B: False Starts

Originally this project was designed to study the effects of noise introduced into the system from the power supply. Simulating this case in Mentor graphics a series of filters was found which had the effect of keeping the 3dB point at 10 Mhz but decreased the slope of the falling edge (cutting overall noise).

In order to study the effect of the noise on the physical circuit a C program is used which sets up the card and collects data after digitization by the ADC. A routine which examined the pedestal, found the RMS and generated a histogram of the results was also devised to characterize the effect of the input noise.

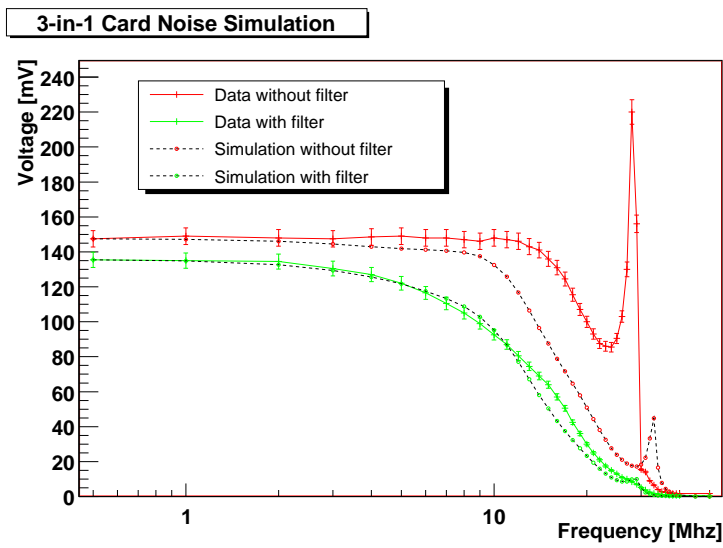


Figure 9: The circles “o” represent the simulation while the plus signs “+” represent data taken. Red is for the unfiltered circuit and green is for the filtered circuit. With the addition of 33 pF of stray capacitance the simulation begins to develop a peak and an increase in the unfiltered -3dB point.

When trying to setup the physical experiment to reproduce the simulation a wall was hit introducing a known noise into the power supply. A function generator could not be put in series with the 5V supply because the input impedance would change. Using a coil of wires acting as a transformer in an attempt to induce a sine wave on top of the 5V line was also unsuccessful. This failure was attributed to the practical necessity that the signal must be attached to the supply line before entering the 3-in-1 card. However once inside the card the supply line goes through a series of filters which completely remove the signal.

In order to maintain precise control over the input conditions of the noise it was decided to introduce noise through the PMT input instead. The setup now took a signal from a function generator and AC coupled it through a transformer directly into the 3-in-1 card. Using the C script to collect data at a range of frequencies a sharp peak at 40 Mhz was noticed. Adding filters to the setup kept the peak intact but shifted it down to 30 Mhz. Unplugging the 3-in-1 card from the ADC a direct measurement on an oscilloscope was taken of the output and the 40 Mhz peak was not found. This means the fault lies somewhere with the addition of the ADC to the circuit.

To see if it could be an artifact of the binning process being in phase with the output sine wave a toy model was created in python where the effect on phase and binning could be systematically studied. The result was alternating peaks and dips at 20, 40, 60, ... Mhz as expected but nothing large enough to explain an order of magnitude peak at 40 Mhz only. For this reason we now believe it is noise from the 40 Mhz clock the ADC is running on.

Since the simulation only involved the 3-in-1 card it wasn't a difficult decision to leave the ADC behind and read results straight from the oscilloscope. It is at this point that the stray peak at 29 Mhz was found, something completely unexpected. With supporting evidence from simulation it was attributed to stray capacitance. This makes the filter which had previously cut signal in the critical 10 Mhz region now perform the important task of suppressing the 40 Mhz peak.

At this point the current results have been written up, but more exploration of both the 29 Mhz and 40 Mhz peaks is planned for the future. Since the card for the sLHC upgrade will be arriving soon it will be important to understand what causes these peaks and if there is a good way of reducing their effects.

## Acknowledgments

Thanks to Professor Mark Oreglia for advising and providing all around support, Kelby Anderson for his expertise on the DAQ system and hardware, and Fukun Tang for general advice concerning the circuit and its simulation in Mentor Graphics. Also, thanks to the Tile Cal group for use of internal documents and diagrams used in this report.

## References

- [1] ATLAS Collaboration, JINST 3 **S08003** (2008)

- [2] Anderson, K. et al., Front-end Electronics for the ATLAS Tile Calorimeter (1998)
- [3] The Tilecal Group, ATLAS TileCal Front End Electronics sLHC Upgrade Environment (2009)