Evaluation of the ACQ1001-FMC Digitizer

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Abstract: The currently installed digitizer, ICS-710, used for measuring beam intensity at the National Synchrotron Light Source (NSLS-II), has reached the end of its life. As a result, we have purchased a new digitizer, ACQ1001-FMC (24-bit), and evaluated its performance in this study. Unlike the ICS-710, the ACQ1001-FMC comes with embedded EPICS (Experimental Physics and Industrial Control System) IOCs (Input/Output Controllers) which provides all the process variables (PVs). We manipulate those PVs through Control System Studio (CSS), which enables us to assess the digitizer's resolution, accuracy, and precision. Since noise and distortion adversely affect the digitizer's performance, we instead investigate it by measuring the effective number of bits (ENOB). We have accomplished this by connecting a terminator to one of the channels and using Python/NumPy to compute the ENOB. In order to evaluate the digitizer's accuracy and precision, we have also examined the voltage linearity. A precise DC calibrator provides voltages ranging from -10 to 10 volts into one of the channels. We collect the readbacks and plot them with Python's polyfit function. Throughout the study, four trials were conducted to determine the ENOB and the linearity. The measured ENOB and linearity coefficient are consistently 19.73 bits (~ 20-bit) and 0.9995 (very close to 1.0), respectively. The results of this study show that the ACQ1001-FMC digitizer is a good fit for replacing the ICS-710 because, despite the noise and distortion, it is precise, accurate, and has high resolution.

Introduction

The NSLS-II is a third-generation synchrotron facility that provides ultra-bright light with exceptional beam stability and a broad energy range (from infrared to hard x-ray). This bright light originates from the linear accelerator (linac) where the electron gun generates electrons and accelerates them to 200 MeV. The transport system then carries these electrons to the booster ring where they expedite to 3 GeV. Subsequently, the transport system sends these electrons to the storage ring where 500mA of current (at 3 GeV) circulate. Eventually, they pass through superconducting bending magnets known as undulators to produce synchrotron radiation. Ultimately, the beamlines capture this radiation and use it to image samples across different disciplines [Ablett et. al. 2006]. A schematic of the major components of the NSLS-II is shown in figure 1.

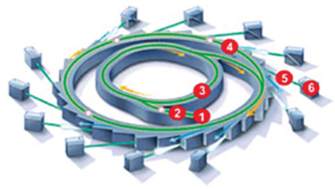

Figure 1- Major components of the NSLS-II: (1) electron gun, (2) linear accelerator, (3) booster ring, (4) storage ring (5) beamlines (6) workstation. Source: https://www.bnl.gov/nsls2/images/synchrotron.gif

At each of the accelerators (linac, booster ring, and storage ring), sensors are placed to measure the charge and current of the electrons. The data that the sensors gather is in the form of analog signals. For the central processing unit (CPU) to interpret these signals, we need to convert them to digital data. Digitizers perform this conversion through a process called pulse code modulation (PCM), as illustrated in figure 2. In this process, the signals are first sampled (based off of Nyquist's theorem), then quantized (to reduce data size), and finally encoded to binary. This conversion ultimately enables software programs such as EPICS and CSS Studio to monitor and display the conditions of the accelerators.

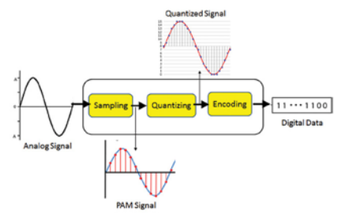

Figure 2- Pulse code modulation Source: https://blogs.synopsys.com/vip-central/files/2015/04/PCM.png

Background

From 2010 to 2011, Yong Hu, a researcher at the NSLS-II, conducted a comparative study to find a suitable digitizer for a variety of applications. These applications measure beam charge and current, beam lifetime, slow machine protection and Cerenkov beam loss monitor (CBLM). The evaluated digitizer includes the Agilent DVM3458, Highland Technology VME digitizer V450, GE ICS-710-BL, Hytec 8401, and NI PXI-4461. After a full evaluation of the hardware components, their voltage linearities, and resolutions, Hu concluded that the ICS-710 met the performance and hardware requirements necessary for the applications. He discusses that although the Agilent DVM3458 performed the best in the precision test, its major disadvantage is its hardware design. Most of the equipment at the NSLS-II connects wirelessly via ethernet, but the Agilent DVM3458 only connects through a general purpose interface bus (GPIB). Similarly, the Highland Technology VME digitizer V450, although high performing, lacks external triggering support, making it unfit for the applications. The rest of the digitizers (the GE ICS-710-BL, Hytec 8401, and NI PXI-4461) do not meet the voltage linearity and resolution requirements. In conclusion, the ICS-710 is a high performing digitizer with excellent accuracy (17 ENOB) and linearity and will be the standard for all low-speed, high resolution digitizing applications.

Materials and Methods

Hardware Specifications

In this study, we examine the ACQ1001-FMC digitizer, manufactured by D-TACQ solutions. This digitizer is made up of two parts: the ACQ1001 carrier and the ACQ430FMC analog input module. The ACQ1001 carrier is a shortbread design which compacts the digitizer circuitry into a simple rectangular box. It encompasses a single slot field programmable gate array (FPGA), Xilinx ZYNQ Soc Z-7020, which runs on Linux [Milne, 2014]. The carrier also connects to the console, ethernet, and a 12V DC supply through the front panel. The rear panel consists of eight ACQ430FMC analog input channels that sample at a high speed of 128k bits per second (bps) [Milne, 2015]. The specification of the ACQ430FMC is shown in figure 3.

#	Parameter	Value
1	Number of Channels	8
2	Sample Rate High Speed Mode High Resolution Mode	Per channel simultaneous 128 kHz 52 kHz
3	Resolution	24 bits
4	Coupling	DC, Differential Input
5	Input Impedance	1MΩ
6	Input Voltage Range	±10 V
7	Input Voltage Withstand	±30V
8	Offset Error	0.01% FS with numerical calibration
9	Gain Error	0.01% FS with numerical calibration
10	INL	±0.002% FS
11	CMRR	>60dB @ 1kHz FS Input
12	THD	-106 dB*
13	SFDR	107 dBc*
14	SNR High Speed Mode High Resolution Mode	 104 dB* 108 dB*
15	Analog Input BW	80kHz
16	Crosstalk	<90dB @ 1kHz FS Input
17	Digital Filter:Pass Band Digital Filter:3dB Digital Filter:Stop Band Digital Filter:Attenuate	0.453 Fsample 0.490 Fsample 0.547 Fsample 95 dB

* Typical values measured at full scale with a 9.76kHz input

Figure 3- Performance specification of the ACQ430FMC [Milne, 2015]

Additionally, the rear panel has three LEDs to indicate functionality: CLK, TRG, and ACT.

- CLK lights green to indicate the usage of a valid clock signal
- TRG lights green to indicate usage of a valid trigger signal
- ACT flashes green to indicate detection of Linux activity.

The images of the front and rear panels are shown in figure 4.

Figure 4- View of the front panel (left) and rear panel (right) of the ACQ1001-FMC digitizer

We first establish communication to the digitizer through the console. Subsequently, the terminal emulator program, Minicom, facilitates the login to root and enables the setup of a static IP address. This IP address establishes a transmission control protocol (TCP) allowing the exchange of data through channel access. D-TACQ solutions provide an easy method to control the digitizer. They have a repository on GitHub containing operator interfaces (OPIs) that are compatible with CSS. These OPIs connect to and graphically display all the PV values embedded in the FPGA. After running the simulation, we abstract the values of the PVs through EPICS using the "caget" command. A schematic of this process is shown in figure 5. We use this platform to perform the resolution and voltage linearity tests.

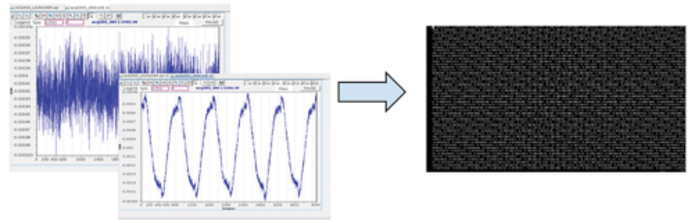

Figure 5- Schematic of how EPICS retrieves 4,096 voltage samples through the "caget" command and puts it into a text file

Resolution Test

The effective number of bits (ENOB) examined in the resolution test evaluates how the internal and external noise affects the digitizer's performance. We study internal noise by connecting a terminator (figure 6) to one of the channels, thereby eliminating external noise.

This test is run on the CSS Studio Volts Live Plot OPI, and we collect the values with EPICS. Once the configuration is set up, the simulation is run for about ten minutes before the data condenses into a text file. We perform the tests and analyze the results across four days. Using Python, we take the values from the text file and find its standard deviation (figure 7).

$$\sigma = \sqrt{\frac{\Sigma\,(X - \overline{X})^2}{n - 1}}$$

Figure 7- Standard deviation formula

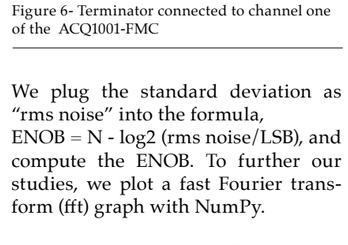

Figure 6- Terminator connected to channel one of the ACQ1001-FMC

We plug the standard deviation as "rms noise" into the formula,
ENOB = N - log2 (rms noise/LSB), and compute the ENOB. To further our studies, we plot a fast Fourier transform (fft) graph with NumPy.

Accuracy and Precision Test

In the accuracy and precision test, we examine voltage linearity. A precise DC calibrator (figure 8) connects to one of the channels and feeds in voltages ranging from -10 to 10 Vs. Similar to the previous test, the simulations are run on the CSS Studio Volt Live Plot OPI. We collect the readbacks every 1 V and use EPICS to compress the data into a text file. We gather the data for four days and compute the average of each data set with Python. These averages are then put into a comma separated value (csv) file. Using the polyfit function in NumPy, we graph the line

of best fit and incorporate error bars. Finally, we abstract the linearity coefficients from the graph.

Figure 8- DC Calibrator

Discussion

Across the four days of testing, the terminator ENOB consistently reported 19.73 bits (~ 20-bit). We hypothesize that the noise and distortion come from the differences in grounding. The digitizer grounds with its 12V DC supply whereas the CPU grounds with a power outlet. These two grounds conflict because they are at different potentials, thus creating a ground loop (galvanic path). This ground loop is the probable cause of the voltage fluctuations we call noise. A schematic of this ground loop is shown in figure 18.

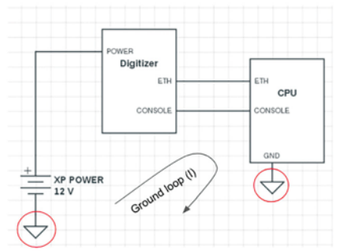

Figure 18- Ground loop between the CPU and the digitizer

On the other hand, the ENOB without a terminator varies across the four days. It is difficult to determine why we observe this variation because we did not record how loud the external background noise was. However, on July 6th, the ENOB without a terminator is the highest and the ENOB with a terminator is the lowest. On that day, we note that it was raining and the humid air could contribute to the lower terminator ENOB.

The fft plots show that the noise averages around 50-60 dB without the terminator and 10-20 dB with the terminator. Subtracting the 50-60 dB of overall noise with the 10-20 dB of internal noise, we presume that 40-50 dB of noise is external noise. Furthermore, this suggests that 10-20 dB of internal noise is the cause of the net loss of approximately 4 bits of resolution, resulting in a 20 bit ENOB.

The voltage linearity coefficients are consistently 0.9995, with one value being 0.9993 on July 6th. The reason for this could be the same reason that on the same day we report the terminator ENOB to be lower than the rest of the days (due to humidity). Overall the coefficients across the four days show that the ACQ1001-FMC is a precise and accurate digitizer because the linearity coefficients are very close to 1.

Results

A. Effective Number of Bits

Date	June 29	July 5	July 6	July 10
With terminator	19.72671775	19.7348454	19.69047274	19.73076437
Without terminator	14.47750989	15.95844621	16.87532671	15.70751698

Figure 9- Table of the computed ENOB with and without a terminator, across four days

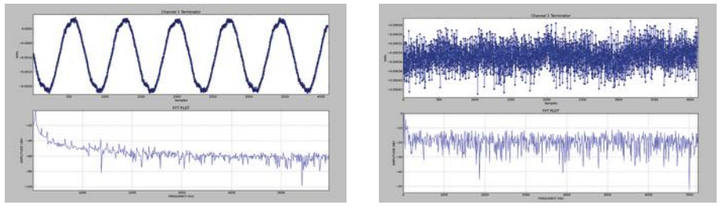

Figure 10- June 29th's fft plots without a terminator (right) and with a terminator (left)

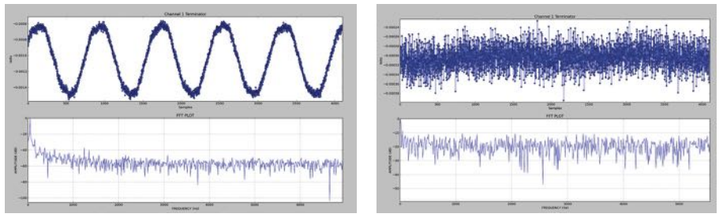

Figure 11- July 5th's fft plots without a terminator (right) and with a terminator (left)

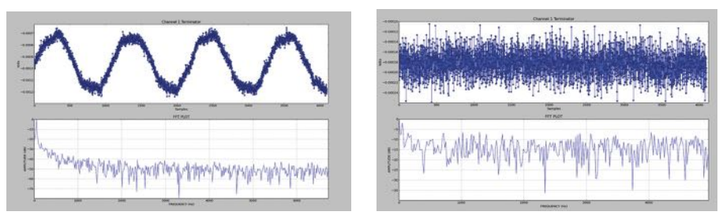

Figure 12- July 6th's fft plots without a terminator (right) and with a terminator (left)

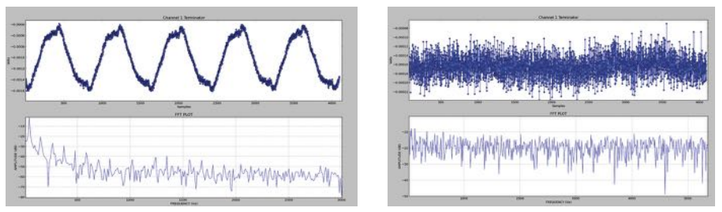

Figure 13- July 10th's fft plots without a terminator (right) and with a terminator (left)

B. Voltage Linearity

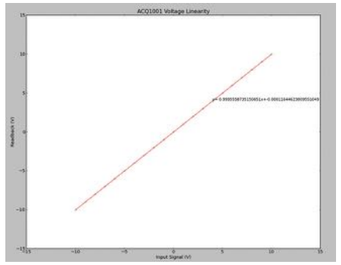

Figure 14- July 3rd's voltage linearity data

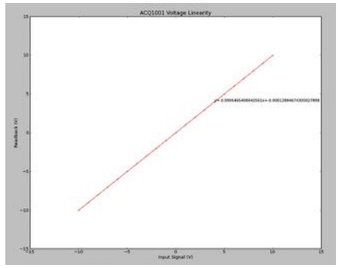

Figure 15- July 5th's voltage linearity data

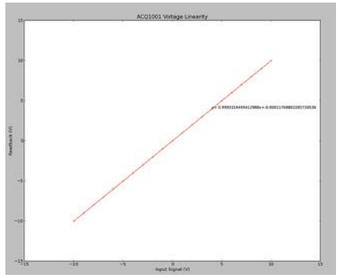

Figure 16- July 6th's voltage linearity data

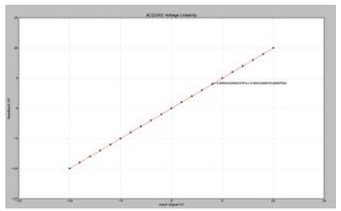

Figure 17- July 10th's voltage linearity data

Conclusion

The ENOB is very close to 20 bits, with only a loss of 4 bits due to internal noise and distortion. Additionally, we can describe the voltage linearity curve with a first-degree polynomial. These results support that the ACQ1001-FMC is a precise, accurate, and high-resolution digitizer because it exceeds the performance of the currently installed digitizer (ENOB= 17 bits). Therefore, we believe that the ACQ1001-FMC is a good fit for replacing the ICS-710.

Further Work

We could perform supplementary tests to enhance our understanding of the digitizer. One test essential to understanding the July 6th deviation would be the thermal drift test. This test would enable us to assess whether we could use the digitizer for thermal-sensitive applications or whether we need to implement temperature compensation means. Moreover, since the digitizer's function at NSLS-II is to measure beam intensity, it would be crucial to perform the beam loss monitor (BLM) stimulator test in further studies. This stimulation would allow us to assess whether the digitizer meets the resolution requirements.

Other enhancements to this study would be to continue to perform the tests for longer, allowing us to see if its performance is stable. Additionally, we could perform a comparison study to see how this digitizer's performance contrasts with others on the market.

References

1. Ablett, J, et. al. Conceptual Design Report National Synchrotron Light Source II. Brookhaven National Laboratory, Dec. 2006, www.bnl.gov/nsls2/project/CDR/NSLS-II_Conceptual_Design_Report.pdf.
2. Milne, Peter. ACQ1001, ACQ1002 Hardware Installation Guide. D-Tacq Solutions Ltd., Apr. 2014,www.d-tacq.com/resources/InstallationGuides/ACQ1001_Installation_Guide_Rev_3.pdf.
3. Milne, Peter. ACQ430FMC Product Specification. D-Tacq Solutions Ltd., 14 Jan. 2015, www.d-tacq.com/acq400ds/acq430fmc-product-specification.pdf.

Appendix

```python
import numpy as np
from math import sqrt

def mean(lst):
    """calculates mean"""
    sum = 0
    for i in range(len(lst)):
        sum += lst[i]
    return (sum / len(lst))

def stddev(lst):
    """calculates standard deviation"""
    sum = 0
    mn = mean(lst)
    for i in range(len(lst)):
        sum += pow((lst[i]-mn),2)
    return sqrt(float(sum) / (len(lst) - 1))

data = np.loadtxt('noisy.txt')

print stddev(data)
```

Figure 19- Python code to calculate the standard deviation

```python
import numpy as np

data = np.loadtxt('neg10V.txt')

mean =np.mean(data)

print mean
```

Figure 20- Python code to compute average

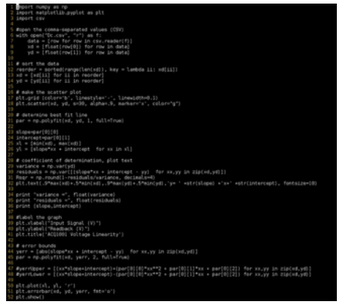

Figure 21- Python code to plot the voltage linearity graph

```python
import numpy as np
from numpy.fft import fft
from numpy import log10
from pylab import subplot,plot,show,grid,xlabel,ylabel,title
import matplotlib.pyplot as plt

numpt = 4096
fclk= 43407.5
Doutw = np.loadtxt("noiseless.txt")

subplot(211)
plot(Doutw[:4096], '-o')
xlabel('Samples')
ylabel('Volts')
title('Channel 1 Terminator')

Dout_spect=fft(Doutw)
Dout_dB=20*log10(abs(Dout_spect))
maxdB=max(Dout_dB[1:numpt/2])
subplot(212)
plot(np.arange(0,numpt/2-1)*fclk/numpt,Dout_dB[1:numpt/2]-maxdB)

title('FFT PLOT')
xlabel('FREQUENCY (Hz)')
ylabel('AMPLITUDE (dB)')
grid ('on')

show()
```

Figure 22- Python code for the fft plot.