Enhancements to the Calorimetric Measurement System on the Omega Laser

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1. Abstract

Different analogue-to-digital converter (ADC) systems and calorimeter insulations were tested to improve calorimetric measurements for the OMEGA laser. It has been demonstrated that the current 16-bit ADC used on OMEGA has a less than optimal accuracy at low calorimetric energy readings of 0.1 J or less. The first three new systems tested were (1) a 24-bit version of the current system, (2) a system that used the Fluke 8508A reference multimeter, and (3) an ADC that was controlled by a Raspberry Pi computer (PiADC). These tests were carried out on three different calorimeters, at 1.0 and 0.1 J of energy, and in an insulated or non-insulated state. The PiADC performance was comparable to the Fluke 8508A at a much lower cost. A newer, smaller, and cheaper PiADC was then developed. This new PiADC system (without additional calorimeter insulation) was tested on a 1" calorimeter in OMEGA and was able to obtain energy measurements with an accuracy ten-times better than the current ADC system. Bench tests with additional insulation around the calorimeter demonstrated that an accuracy 32-times better than the current ADC system is possible.

2. Introduction

The calorimeters on the 60-beam OMEGA laser work by absorbing incoming energy in an absorbing glass (Fig. 2.1). This glass then heats up, and the heat transfers from the glass through several Peltier cooling modules to a heat sink. The Peltier modules consist of two junctions between dissimilar metals, where one junction receives the heat and the other is tied to a heat sink that acts as a thermal reference. When the calorimeter absorbs light and heats up, a voltage is created in the Peltier cooling modules that is proportional to the temperature difference between the heated junction and the heat sink. This voltage is then measured by an analogue-to-digital converter (ADC) over the time it takes the system to regain thermal equilibrium, the resulting graph resembling Fig. 2.2. From these graphs the time constants of the calorimeters, sensitivity of the calorimeters, and energy absorbed by the calorimeters can be calculated. Different calorimeters have different time constants and sensitivities [1] due to their different thermal masses and amplification circuitry. The time constant (in seconds) is a measure of how quickly the calorimeter

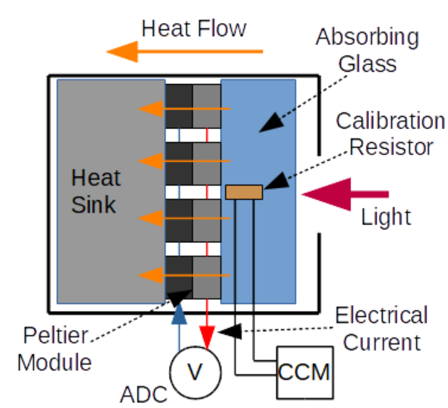

Fig. 2.1 Calorimeter Cut-away
The calorimeter absorbs light and then the heat flows through the Peltier modules to the heat sink and a measurable voltage is produced.

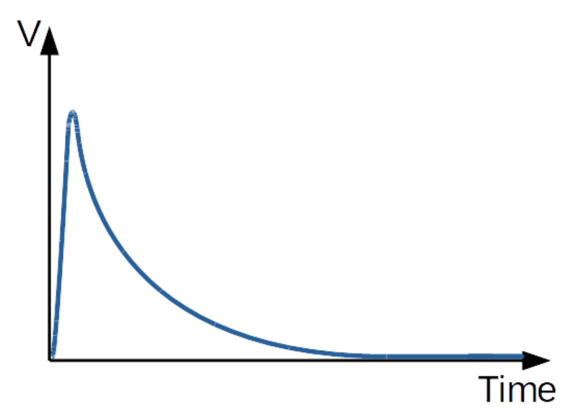

Fig. 2.2 Ideal Calorimeter Voltage Curve
Energy is applied to the calorimeter, causing the spike. The system then slowly loses heat and returns to thermal equilibrium.

dissipates the heat absorbed, while the sensitivity is how many Volt*seconds (Vs, the area under the curve in Fig. 2.2) of signal correspond to a Joule of energy. The approximate time constants and calorimeter sensitivities for the calorimeters used are listed in Table 2.1.

Table 2.1 Constants for Three Different Calorimeters

Calorimeter:	Time Constant in Seconds:	Sensitivity in Volt*Seconds/Joule (Vs/J):
1” Calorimeter without an Amplifier	12.6	0.5
1” Calorimeter with an Amplifier	10.8	10.3
2” Calorimeter with an Amplifier	25.5	9.0

The values above were found through calorimeter calibration. Calorimeters are calibrated using the Calorimeter Calibration Module (CCM). The CCM produces a voltage across the calibration resistor in the calorimeter (Fig. 2.1) for a short time to deliver heat energy to the calorimeter. The resulting voltage curve from the calorimeter is then integrated to get Vs, and then divided by the energy delivered by the CCM to get Vs/J. The time constant is found by fitting an exponential curve to the voltage curve from the calorimeter.

In order to improve the accuracy of the calorimeter’s energy measurements the noise in the voltage curve must be reduced. This noise increases uncertainty during both integration for calorimeter calibration and integration for an actual measurement. To decrease the noise different ADCs and calorimeter insulations were tested. At 0.02 J of energy, which is a typical 1” scatter calorimeter measurement at low OMEGA shot energies, the 16-bit ADC has a signal-to-noise ratio of between 10:1 and 32:1, whereas an ADC controlled by a Raspberry Pi computer (PiADC) has a signal-to-noise ratio of between 316:1 and 1000:1. The PiADC resulting from this work was able to perform with a ten-times greater accuracy than the current ADC used on OMEGA, and has the ability to perform 32-times better if additional insulation around the calorimeter is present.

3. Experimental Setups

3.1 LON-Based ADC System

The currently used 16-bit ADC and the 24-bit version that was further tested in this work run on a Local Operating Network (LON) system (Fig. 3.1). Both the Calorimeter Calibration Module (CCM) and the Generic Analogue-Digital Module (GADM) cards are hooked into a box known as a LON "cart" or "rack" that interfaces with a PC.

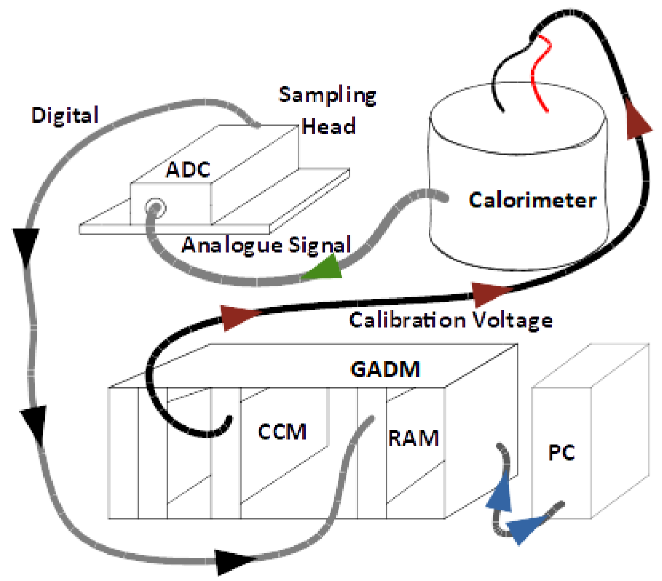

Fig. 3.1 LON-based ADC system
Both the CCM and GADM cards are hooked into a box known as a LON "cart" or "rack" which is then controlled by a PC. The CCM sends a known energy to the calorimeter, and the sampling head measures the resulting voltage. The GADM then records the digital voltage values and sends them to the PC.

The CCM operates by receiving an energy request from a PC. The CCM then sends a specific current at 24 V for a period of time through a heater in the calorimeter, which delivers the energy that was requested by the PC [2]. The sampling head converts the resulting voltage values from the calorimeter into digital values, which are then processed by the GADM [3] and sent to an Excel file on the PC. When running tests, the GADM was set to take 600 samples at a sample rate of 5 Hz. More samples could not be taken due to the GADM board's 8 kilobytes of RAM.

3.2 Fluke 8508A Based System

The Fluke 8508A is a high-precision 7.5-digit-accuracy reference multimeter. The system that was built around it (Fig. 3.2) was used to determine the limits of the calorimeters' performance so the effects of an ADC on the signal could be distinguished. However, its large size and prohibitively high price disqualified it from further consideration as an implementable system. In this system the CCM is still controlled by the PC and delivers a specified energy to the calorimeter, but the GADM and the sampling head are only used to supply the calorimeter with ±15 V and ground. The Fluke 8508A is controlled by a LabVIEW program on the PC that sets the sample rate to 5 Hz and collects the signal data from the calorimeter.

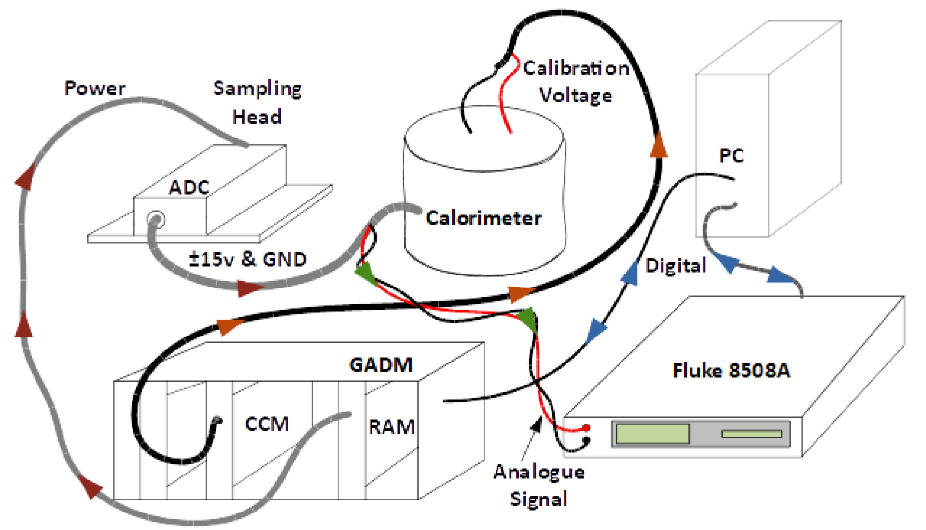

Fig. 3.2 Fluke 8508A based system
The CCM operates in the same way as Fig. 3.1. However, the GADM and sampling head are no longer used to collect data. Their sole function is to power the calorimeter's amplifier with ±15 V and Ground. The Fluke 8508A measures the voltage and writes the data to a LabVIEW program on the PC.

3.3 First PiADC System

The first PiADC system (Fig. 3.3) was developed at LLE and was originally designed to read pressure transducers [4], which added some extra complexity to the setup. Pull-up and pull-down resistors, hereafter referred to as terminations, had to be added in order to create a positive offset voltage so the system would be stable. It was found that these terminations had to be "tuned" to a very specific offset on the positive and ground wires in order to get the best performance out of the system. The analogue voltage from the calorimeter goes through the terminations and then is converted to a digital signal by the ADS1256. This signal is sent through a couple of field-programmable gate arrays before going to the Raspberry Pi, hereafter referred to as Pi, which sends the data to a Real Time Socket Server (RTSS). The RTSS system operates at 40 Hz and communicates with its clients every 25ms. A LabVIEW program on the PC then reads the data from the RTSS. Due to the design, setting an exact sample rate of 5 Hz was not possible.

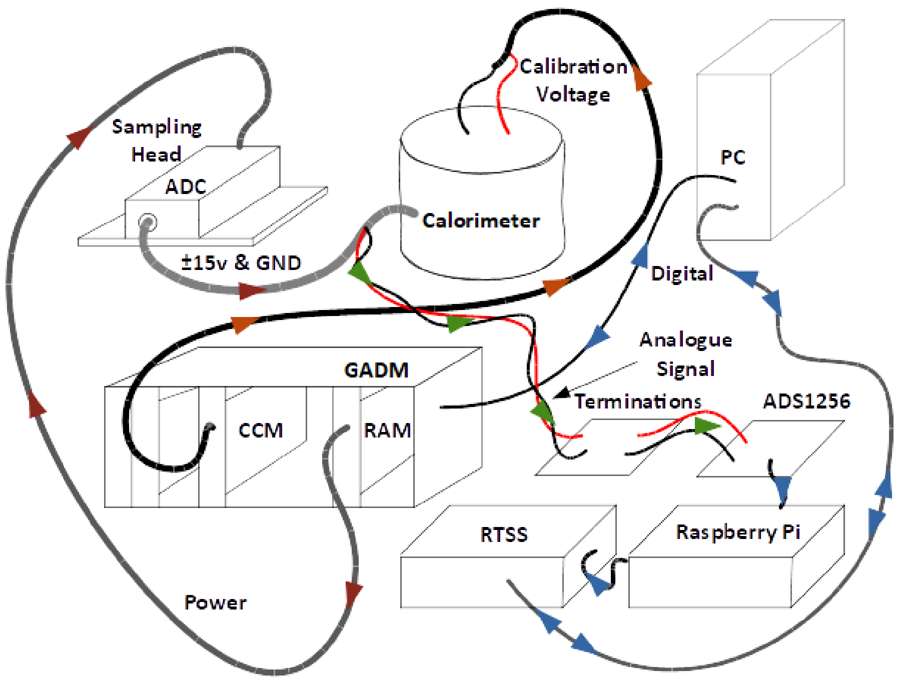

Fig. 3.3 First PiADC system
The CCM, GADM, and sampling head operate in the same way as described in Fig. 3.2. The analogue signal from the calorimeter goes through terminations to the ADS1256 ADC which outputs a digital signal. This signal eventually goes to the Pi to the RTSS, where a LabVIEW program on the PC reads the data from the RTSS.

3.4 Second PiADC System

The second PiADC system (Fig. 3.4) was built to simplify the issues present in the first system and be able to operate in OMEGA. The analogue signal from the calorimeter is processed in the ADS1256 on a commercial board [5], which is controlled by a C program [6] that was modified for file manipulation on the Pi. A Python program was used to interface with the LEDs and buttons on the control panel and calls the C program to start sampling. For the tests on OMEGA, another cable was added to remotely enable the Pi to begin acquiring data 20 seconds before the shot.

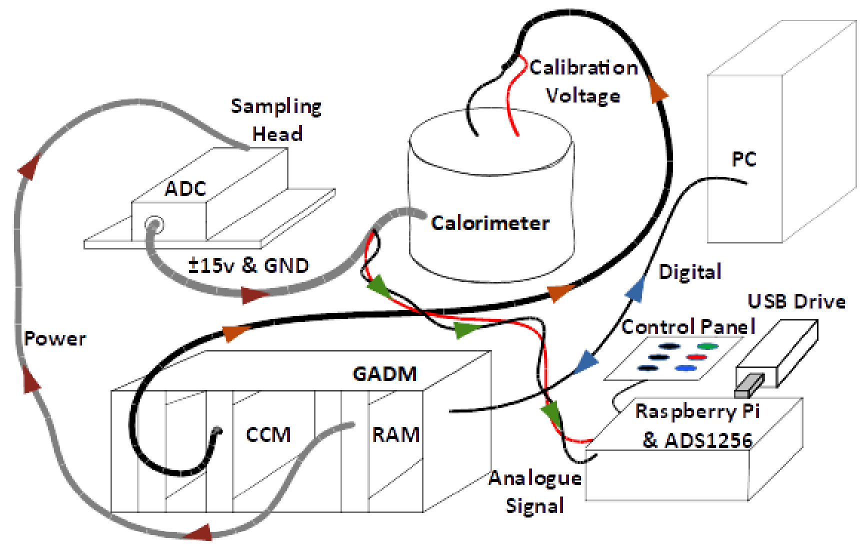

Fig. 3.4 Second PiADC system
The CCM, GADM, and sampling head operate in the same way as described in Fig. 3.2. The analogue signal from the calorimeter goes to the ADS1256 and then the digital signal travels directly to the Pi and is recorded on a USB drive. Unlike the first PiADC, this system was not connected to RTSS because OMEGA network clearance could not be acquired within the timespan of the project. The control panel is used to run the Pi without a monitor or keyboard.

The general procedure for all the systems while using the CCM to deliver energy was to begin data acquisition five to ten seconds prior to the calorimeter receiving energy so a baseline signal could be established. With the 1” calorimeter the sample time was around two minutes for 0.1 J of energy, and with the 2” calorimeter the sample time was around three minutes for 0.1 J of energy. It is important to note that a 1” calorimeter without an amplifier was also tested; in this case, the sampling head and GADM were not needed to power an amplifier. Therefore, for the 1” calorimeter without an amplifier the GADM and the sampling head were not used in the Fluke 8508A system or the PiADC systems. The advantage of the non-amplified calorimeter was that no noise was added by an amplifier. However, the signal was so small that only the Fluke 8508A system could get a substantial dynamic range with it.

4. Data Processing

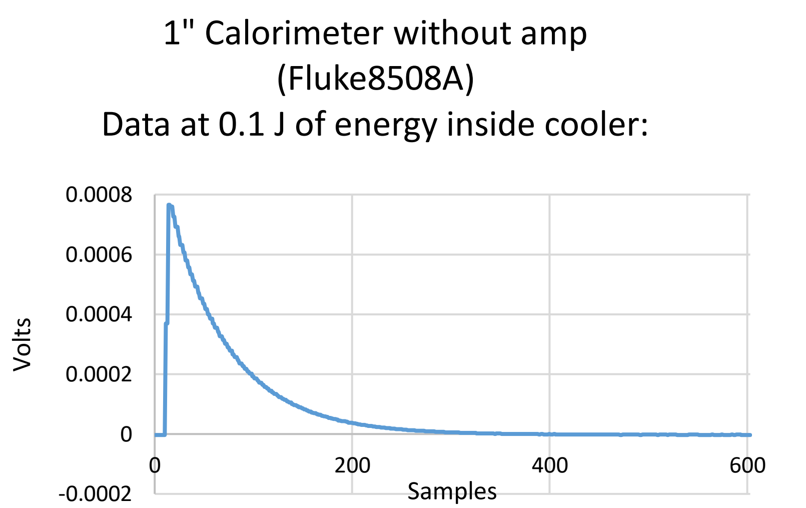

Fig 4.1 Graph of data before processing
A graph of the raw signal data directly from sampling. The samples were taken at 200 ms intervals, so the total sampling time was 120 seconds.

Fig. 4.1 is a graph of the raw signal obtained from the Fluke 8508A for the 1” calorimeter without an amplifier at an energy of 0.1 J, used to illustrate how data are analyzed.

The data are first adjusted by subtracting out a negligible amount less than the minimum (to avoid a zero on a logarithmic plot) from all values and then normalized by dividing all values by the new maximum. The data now have a maximum of one. The sample numbers on the horizontal axis are also multiplied by $\frac{1\ second}{5\ samples}$ to get seconds. These data are then plotted on a semi-logarithmic graph as in Fig. 4.2. As the signal approaches smaller orders of magnitude on the y-axis, the noise is magnified. This format makes comparisons between experiments much easier because a more successful test will reach lower orders of magnitude. One order of magnitude is the distance between 1 and 0.1 on Fig. 4.2, two orders of magnitude are the distance between 1 and 0.01, etc. The 32:1 signal-to-noise ratio of the 16-bit ADC corresponds to about 1.5 orders of magnitude, since $10^{1.5}$=31.6 (Fig. 4.3). If the signal's beginning is at 0.1, peak at 1.0, and end at 0.1, then the graph is said to have a dynamic range of one order of magnitude. In Fig. 4.2, the graph has a dynamic range of three orders of magnitude. All subsequent plots of signal vs time are given in the same form as Fig. 4.2.

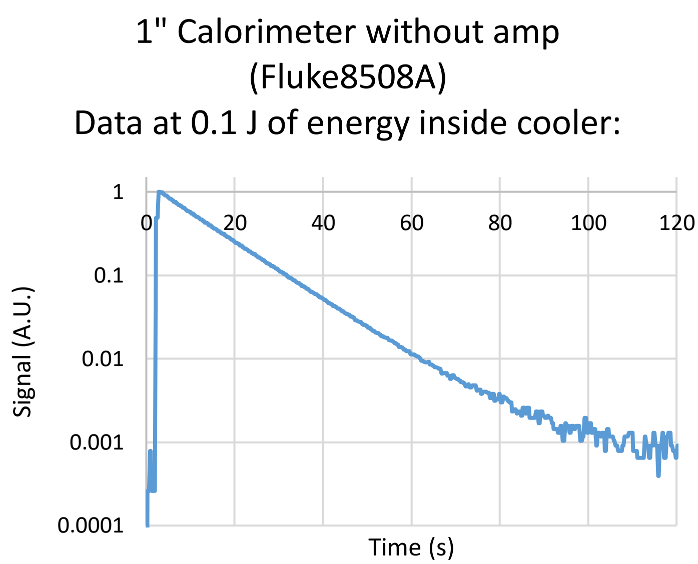

Fig 4.2 Graph of data after processing
A graph of the normalized data in arbitrary units on a semi-log plot, with the sample numbers converted to seconds.

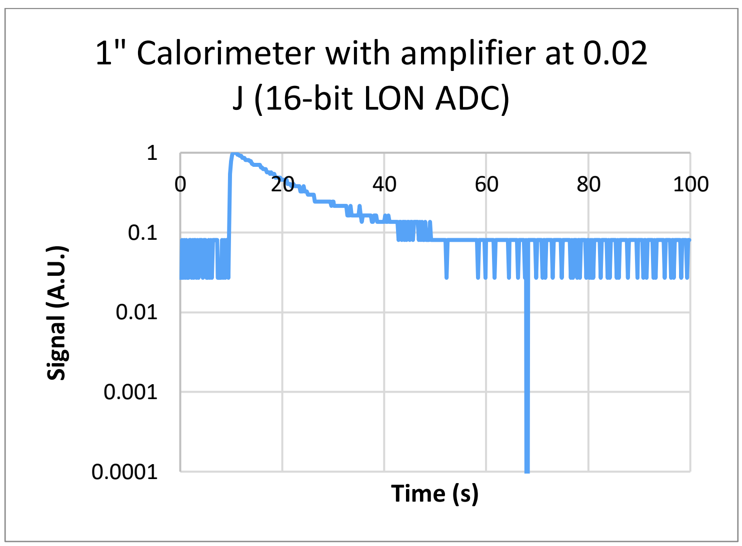

Fig. 4.3 Dynamic range of the 16-bit LON-based ADC that is currently used on OMEGA
As seen on the graph the 16-bit ADC can reach a dynamic range of 1.5 orders of magnitude at 0.02 J.

5. Effect of Insulation on Variability in Early ADC Experiments

Experiments started out with the three calorimeters listed in Table 2.1 (1” with and without an amplifier and a 2” with an amplifier), using three ADC systems at two energy levels (0.1 and 1.0 J), and the calorimeter being either inside or outside a Styrofoam cooler. Tests at 1.0 J or outside the cooler were not found to be useful and are not presented in this report. 1.0 J is much higher than what any 1” calorimeter will measure on OMEGA and is the highest that any 2” calorimeter will measure. Some of the tests outside the cooler were found to reach a thermal equilibrium tens of microvolts above the baseline signal due to room temperature effects, but this behavior (known as drift) was not consistent. Fig. 5.1 demonstrates these effects in a test where no energy was supplied to the calorimeter.

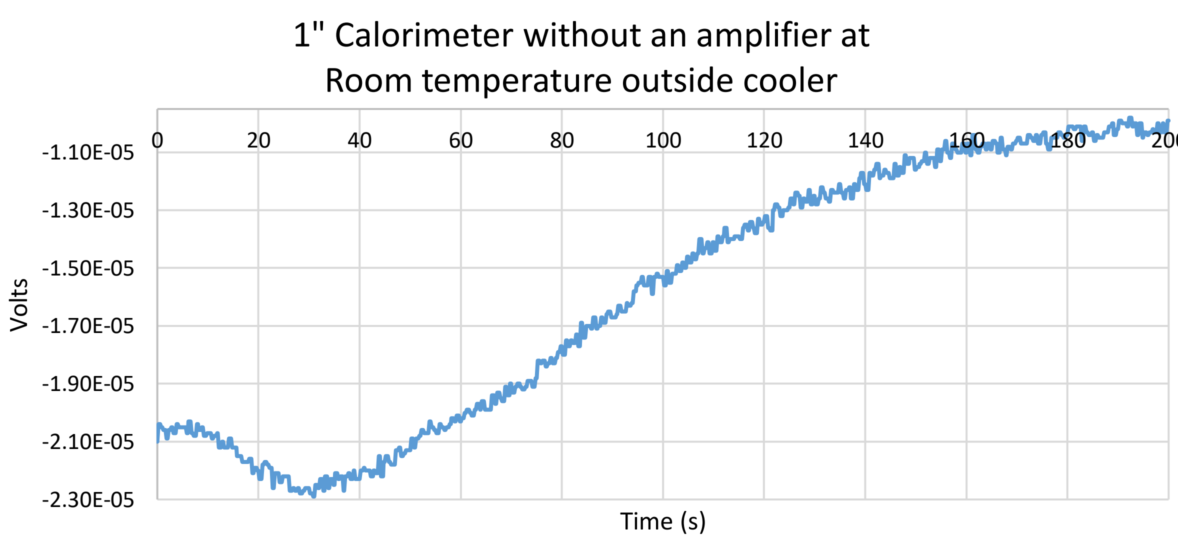

Fig 5.1 Voltage fluctuations caused by temperature fluctuations recorded by the calorimeter
As shown in the graph, temperature fluctuations can cause a drift of 12 microvolts over the course of 3 minutes.

The peak signal of the 1” calorimeter without an amplifier, from which these data were acquired, is 750 microvolts at 0.1 J of energy (see Fig. 4.1). This means that the drift could account for 1.6% of the signal (12 microvolts), but the temperature change is not linear and isn't always present. Thus, when drift like this is present, it is impossible to have a measured-energy calculation that has a smaller margin of error than ±1.6%. Fig. 7.4 (below) is an example of drift when energy was supplied to the calorimeter.

In order to better control the test temperature, all further tests were performed inside the cooler. It is important to note that this drift issue wasn't completely solved by the cooler, and some tests still showed limited drift. Table 5.1 summarizes the results from the three calorimeters and the three ADC systems. The numbers in the table are the orders of magnitude for the dynamic range and drift for each specified case. For example, "Drift: 3 to 2" means that the signal's baseline (initial value before energy was supplied to the calorimeter) on a plot such as Fig. 7.4 (below) was 0.001 and the signal's final value was 0.01. A drift of none indicates that the baseline is equal to the signal at the end.

Table 5.1 Dynamic Range and Drift for 3 ADC Systems with 3 Different Calorimeters*

Data taken at 0.1 J of energy inside a cooler	24-bit LON-based ADC (Fig. 3.1)	Fluke 8508A System (Fig. 3.2)	First PiADC** (Fig. 3.3)
1" Calorimeter without an amplifier	Dynamic Range: 1 Drift: None	Dynamic Range: 3 Drift: None	Dynamic Range: 2 Noise Issue Present
1" Calorimeter with an amplifier	Dynamic Range: 1.5 Drift: 3 to 1.5	Dynamic Range: 2 Drift: 3 to 2	Dynamic Range: 2 Drift: 2 to 3
2" Calorimeter with an amplifier	Dynamic Range: 2 Drift: None	Dynamic Range: 1.5 Drift: 3 to 1.5	Dynamic Range: 1.75 Drift 2.5 to 1.75

**Numbers indicate orders of magnitude*

***These tests were before the PiADC was "fine-tuned" with the terminations shown in Fig. 3.3*

These data weren't very consistent and were more a demonstration of what was possible across all the systems at 0.1 J. The test with the Fluke 8508A system measuring the 1" calorimeter without an amplifier, shown in Figs. 4.1 and 4.2, revealed that a dynamic range of three orders of magnitude was possible. That result became known as the "gold standard" that all future tests would be compared against. The PiADC was very inconsistent during these tests but was still able to perform between the 24-bit LON-based ADC and the Fluke 8508A system. From these tests, a new goal of getting the PiADC to consistently perform as well as the gold standard with the other calorimeters was put in place. Note that because the 1" calorimeter without an amplifier isn't used on OMEGA, testing with it stopped.

6. First PiADC Fine-Tuning

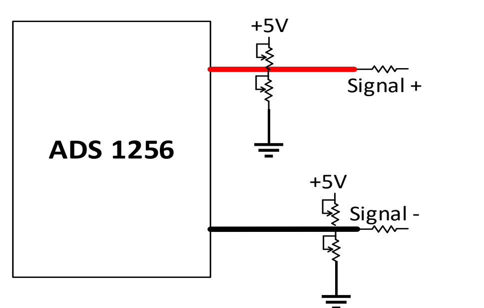

Fig. 6.1 First PiADC Terminations
The terminations consist of four tunable 10 k Ω potentiometers. Two additional series resistors on the Signal + and Signal – wires were added to reduce noise.

Due to an oddity of the C code on the PiADC, a 1.4 millivolt offset would come into effect if the analogue value came too close to zero, creating 1.4 millivolts of noise. Terminations were added before the ADS 1256 ADC to create a tunable offset (Fig 6.1) that both solved the 1.4 millivolt offset issue and further reduced noise. Resistors in series with the "signal +" and the "signal –" wires as shown in Fig. 6.1 were also found to reduce smaller-amplitude noise. The best offset was found to be +2.498 volts on the positive signal wire and -2.495 volts on the negative signal wire with 10 k Ω series resistors on both wires. The results of tests with this offset are all similar

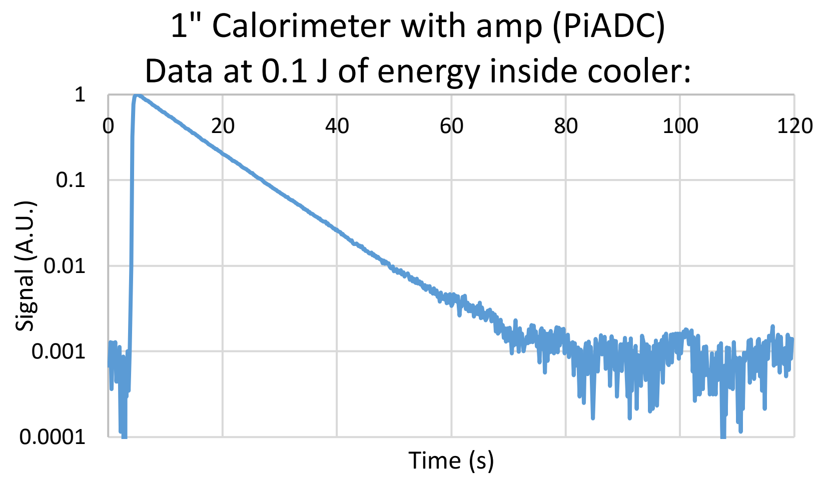

Fig. 6.2 Graph of the first PiADC reaching the gold standard
With the proper offset and 10 k Ω series resistors the first PiADC system was able to have a dynamic range of three orders of magnitude.

to Fig. 6.2, which demonstrated that a PiADC could perform as well as the Fluke 8508A system. Further tests were performed in order to obtain the gold standard at 0.1 J with the 2” calorimeter. However, due to the 2” calorimeter’s larger thermal mass the signal was smaller. This smaller signal meant that the 10 k Ω series resistors had to be replaced with 5 k Ω series resistors. Table 6.1 summarizes the 2” calorimeter test results, where 0.4 and 1.0 J were also tested because the 2” calorimeters usually handle higher energies than the 1” calorimeters.

Table 6.1 Dynamic Range and Drift for Different Offsets and Energies on a 2” Calorimeter with 5 k Ω Series Resistors

Positive signal wire offset: Negative signal wire offset: Energy Level:	+2.558 V -2.548 V 0.1 J	+2.498 V -2.495 V 0.4 J	+2.498 V -2.495 V 1.0 J
2” Calorimeter with an amplifier	Dynamic Range: 2.5 Drift: None	Dynamic Range: 3 Drift: None	Dynamic Range: 3 Drift: None

By adding the terminations, tuning them, and creating an offset, the drifts that were present in Table 5.1 were practically eliminated. The tests also had consistently large dynamic ranges of 2.5 to 3 orders of magnitude. However, this PiADC was designed for different applications. In order to further improve measurement accuracy and make the PiADC practical to use in OMEGA, the PiADC had to be made cheaper, smaller, easier to use, and developed for calorimetric measurements on OMEGA.

7. Second PiADC System

After setting up the second PiADC system, tests at 0.1 J inside the Styrofoam cooler demonstrated that the system could reach a dynamic range of at least 3 orders of magnitude (Fig 7.1). Further noise reduction using voltage regulators to supply a 1.5 V reference to the ADC was attempted but was found to be ineffective. At that level of accuracy, the temperature drift and noise from the calorimeter's amplifier were the dominant noise producers.

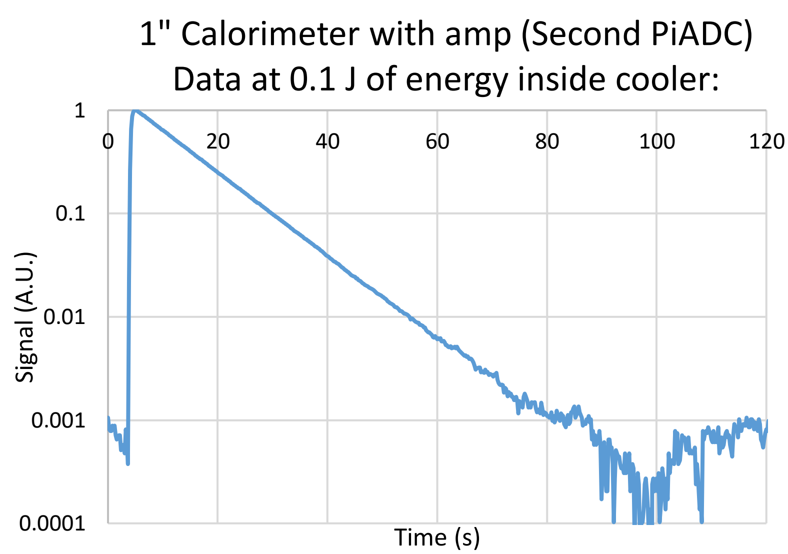

Fig. 7.1 Graph of the second PiADC reaching the gold standard with less noise than the previous version.
With this test the second PiADC demonstrated better performance than the first PiADC (Fig. 6.2) with a smaller size and lower price.

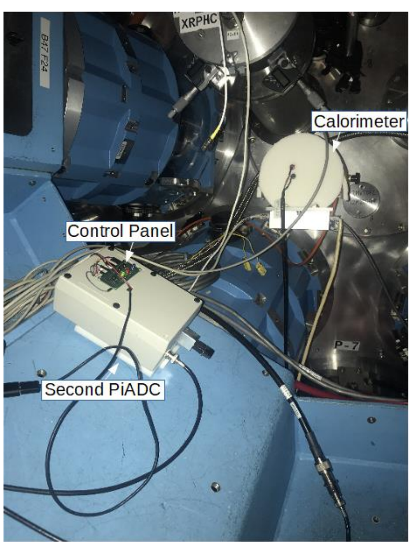

Fig. 7.2 Second PiADC on OMEGA
The PiADC in a box is left of center, and the H8 calorimeter with extra insulation is right of center.

The next set of tests were performed on the H8 scatter calorimeter on the OMEGA target chamber (Fig. 7.2), but without the extra insulation around the calorimeter that is depicted in Fig. 7.2. High energy shots on OMEGA involve all

60 beams, but these tests were with six-beam shots, so the calorimeter only detected about 0.02 J of energy that scattered off the target. The resulting data can be seen in Figs. 7.3 and 7.4. Due to the lower energy level and lack of extra insulation around the calorimeter, the best result (Fig. 7.3) had a dynamic range of only 2.5 orders of magnitude. However, there were also multiple tests that showed drift, such as Fig 7.4 where the signal leveled out at a value one order of magnitude higher than the signal's baseline.

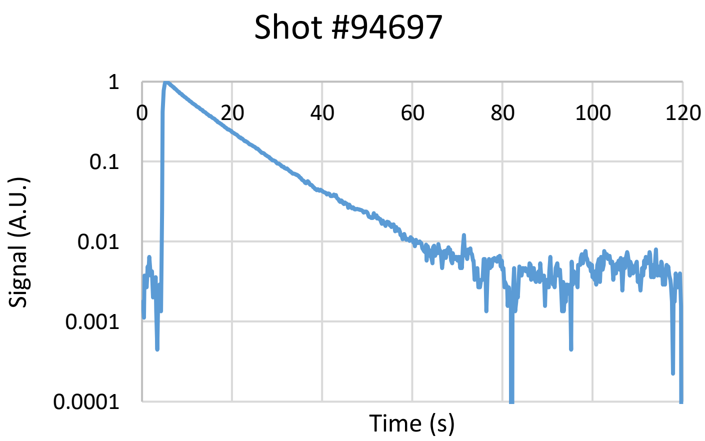

Fig. 7.3 Best result from the first set of OMEGA tests
The data have a dynamic range of 2.5 orders of magnitude and no drift due to temperature fluctuations.

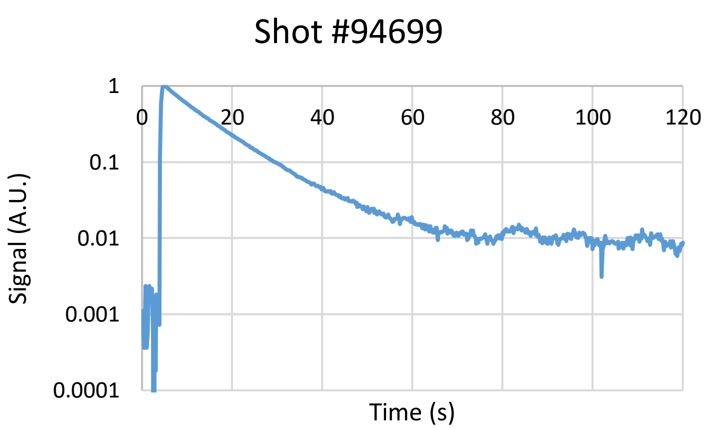

Fig. 7.4 Typical result with drift from the first set of OMEGA tests
The data could have a dynamic range of 2.5 to 3 orders of magnitude, but there is an order of magnitude of drift due to temperature fluctuations.

Even at an energy that was 20% of what the PiADC was tested at and on a calorimeter without extra insulation, the PiADC was able to collect some data with a dynamic range of 2.5 orders of magnitude. However, the results with drift showed a need for additional insulation around the calorimeters to further improve consistency and accuracy.

Insulation bench-tests on the 1” calorimeter with an amplifier at 0.02 J of energy followed. Thick paper, paper folded in a corrugated design around the calorimeter, bubble wrap, one layer of foam, and two layers of foam with a 7 mm air gap in between (Fig 7.5) were all tested. Only the one layer and two layers of foam showed a noticeable reduction in drift.

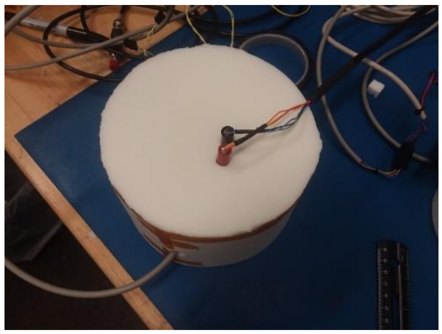

Fig. 7.5 (a) Top view of two-layer foam insulation on a 1” calorimeter

Fig. 7.5 (b) Side view of two-layer foam insulation on a 1” calorimeter

Each layer of foam reduced the drift by a considerable amount (Fig. 7.6). Tests without additional insulation around the calorimeter resulted in 1.5 orders of magnitude of drift; tests with one layer of insulation resulted in 1 order of magnitude of drift; and tests with two layers of foam insulation showed little to no drift. There was a consistent dynamic range of 2.5 to 3 orders of magnitude in the tests with two layers of foam insulation.

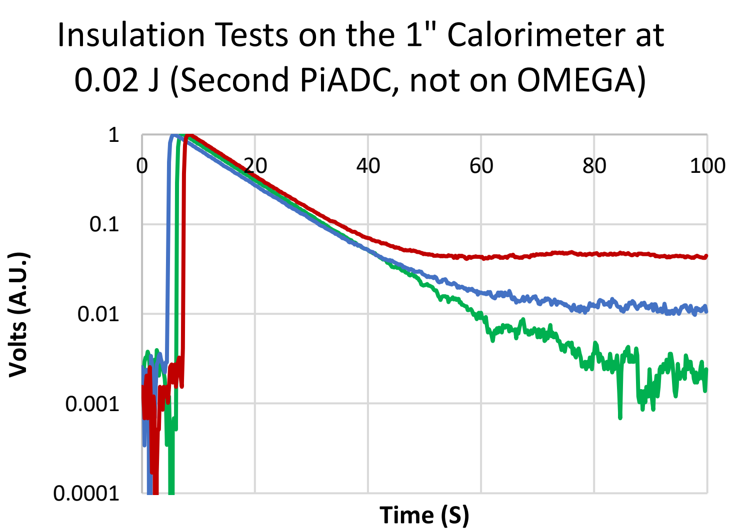

Fig. 7.6 A comparison of drift between no insulation, 1 layer of foam insulation, and 2 layers of foam insulation.
Red is the plot with no insulation
Blue is the plot with one layer of insulation
Green is the plot with two layers of insulation

This insulation was tested on OMEGA as depicted in Fig. 7.2, but the PiADC’s program stopped working during the shots. The probable cause was that the PiADC logged-in two users, which doubled the processor usage. This drew power away from the ADS1256 and caused an error. This error was corrected in the latest version of the PiADC's program.

8. Conclusion and Future Research

This work has made it possible to improve the accuracy of calorimetric measurements on OMEGA by an order of magnitude, with the potential to be 1.5 orders of magnitude better than the current system if the calorimeter is insulated as shown in Fig. 7.5. After three different ADC systems were tested, a fourth system using a PiADC was created to further improve accuracy. Before the second PiADC is to be installed on OMEGA it must be configured with RTSS to improve reliability and properly shielded from neutron radiation. Connecting the second PiADC to RTSS would enable real-time data collection and a way of detecting program errors. The current plan to shield the PiADC is to separate the Raspberry Pi from the ADS1256 ADC and run fiber optic between them so that the ADC can still be close to the analogue source.

The simplest way to further improve energy measurement accuracy is to add the two layers of insulation depicted in Fig. 7.5 onto OMEGA calorimeters. Once temperature-based drift is no longer an issue, linear regulators can be added to the circuitry. A linear regulator is an integrated circuit that adjusts its resistance based on the current, resulting in a very steady voltage. Linear regulators could be used to supply the ±15V required to power the calorimeter's amplifier in order to potentially reduce amplifier-based noise. They could also be used to supply the ADS1256 with a smaller and less noisy reference voltage. Beyond that, additional optics would have to be installed to increase the amount of light absorbed by the calorimeter.

This additional absorbed energy would create a larger analogue signal, which means a larger dynamic range. Further accuracy would require either calorimeters that are designed for lower energies or the use of bolometers. Bolometers do not use a thermal reference like calorimeters. In theory the heat sink that acts like a thermal reference in calorimeters could drift due to room temperature effects, meaning bolometers could be more resistant to drift than calorimeters. However, the cost and effectiveness of many of these concepts would need to be addressed.

9. Acknowledgments

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Thanks to Christian Stoeckl for guidance organizing the tests that were done on OMEGA.

Thanks to Heath Ferry for letting me borrow the First PiADC system.

Thanks to Dr. Craxton for his work organizing the High School program at LLE.

10. References

[1] Scientech. Astral Series Calorimeters Setup and Operating Procedures. PN9458P.

[2] Mark Donovan. Calorimeter Calibrator Operation Manual. E-CA-M-03 Laboratory for Laser Energetics. 06/25/2004

[3] John Canosa et al. Hardware Description Generic A/D Module. E-AD-M-02 Laboratory for Laser Energetics. 02/23/1994

[4] Heath Ferry. In-person communication. 07/17/2019

[5] Waveshare. High-Precision AD/DA Board (https://www.waveshare.com/wiki/High-Precision_AD/DA_Board)

[6] John Beale. DataAcq / ADS1256_read.c (https://github.com/jbeale1/DataAcq/blob/master/ADS1256_read.c)