GRINCH Mirrors Technical Report

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Introduction

Over the past year I have been working to understand how the GRINCH detector mirror system can be expected to perform. It has been my goal to reproduce the geometry of the detector and to confirm whether or not the current design will be able to meet the needs of the coming A_1^n experiment. At this point in time the mirror frame has been assembled and the mirrors tested in various configurations. The results show that with proper alignment all of the photons expected to be produced can be directed onto the PMT array. This report will detail the procedures used to test the mirror system.

Mirror Tests

Initial Tests and Prototype Mirror Frame

To begin testing the mirror system a prototype mirror frame was assembled which was able to hold a single mirror (Figure 1). The mirror is mounted in slots cut into the two vertical rods. The radius of curvature of the mirror can be adjusted in two ways. The first method is to turn the levers at the top of the rods holding the mirror to cause the mirror to flex. Then by tightening screws on the rods the mirror can be secured in position. The second, and more precise, method of adjusting the radius of curvature is to loosen or tighten nuts on the side of the mirror. This causes the mirror to be either pulled apart or pushed together. Using the three nuts the radius of curvature can be set in a constant position. Figure 2 shows a closer picture of these adjustment methods.

Figure 1. Mirror Frame Prototype. Note: Mirror is held by the two vertical rods during testing.

The mirrors selected for testing were purchased from Airparts inc. which is a hobby store for private aircraft and can be found at https://www.airpartsinc.com/shopexd.asp?id=1782. The mirrors are 0.032 inches thick and are mirror finished on one side. Initially I attempted to polish the mirrors further but found that the reflection could be improved little by this process. The reflectivity of these mirrors was sufficient to reflect the small laser being shined upon them without much distortion. Theses mirrors also

Figure 2. Radius of Curvature Adjustment Methods. The radius of curvature of the mirror can be adjusted by moving the positions of the nuts or by twisting the lever seen at the top of the figure.

proved to be fairly easy to shape to the correct radius of curvature and hold their shape well in the mirror frame.

A small laser was used to simulate incoming photons which allowed me to see if the light was properly striking the PMT array. This laser was secured to a mount which allowed the laser's angle to be adjusted from side-to-side and/or in an up-and-down manner (Figure 3). This mount was then attached to a linear rail system which was controlled via a stepper motor allowing for the laser to be accurately tracked back and forth across the surface of the mirrors (Figure 4). This motor is controlled by SID 2.0 QDHL controller which had to be sent to the manufacturer to be repaired before use. The stepper motor can move in increments of about one step per 0.0006266 cm which far surpasses the accuracy required for these tests. Connecting the motor controller to the linear rail system required some wiring which can be seen in Figure 5. The controller is sent commands through LabVIEW.

The prototype mirror frame was placed on an optics table directly facing the laser on the linear rail system for radius of curvature tests. The laser was sent through two irises to mark the central axis of the mirror. A plastic guide cut to 130 cm was cut in the William and Mary machine shop to help align the mirrors to the correct radius (Figure 6). Initially the radius of curvature was checked by running a string from the focal point of the mirror to where the laser struck the mirror and then measuring the length of the string and applying Equation 1, where R is the radius of curvature and F is the focal length.

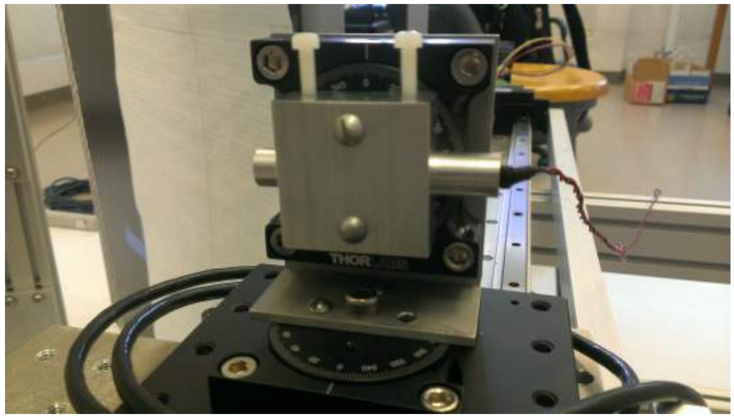

Figure 3. Laser Mount. This mount allows for the laser angle to be adjusted horizontally and/or vertically.

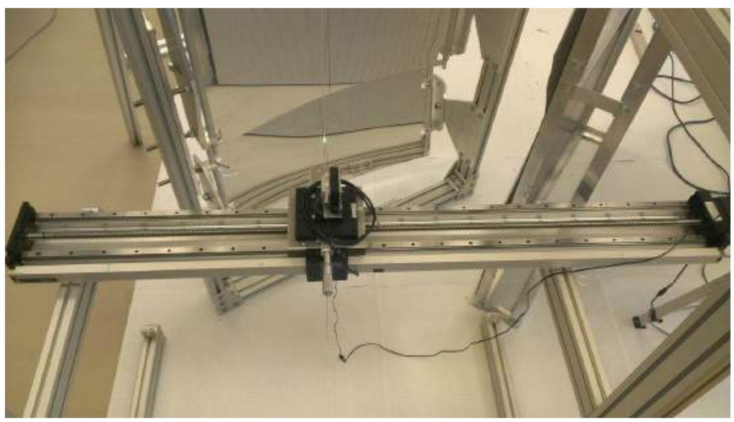

Figure 4. Linear Rail System. This rail allows for the laser to be moved across the face of the mirror.

$$R = 2 * F \tag{1}$$

The focus moves slightly with each different place the laser strikes the mirror. To find the focus of each of these different positions a string was held tight between two optics stands normal to the center of the mirror. Where the reflected laser beam crossed this line was then the focus of that portion of the mirror. Thus by moving the laser across the surface of the mirror and measuring the radius of curvature at each point a mapping of the mirror's deformation could be produced.

Initially the plastic guide was clamped to the back of the mirrors forcing them to hold their shape. The guide was positioned on the central horizontal line of the mirror. Then the nuts on the side of the mirror were adjusted to best fit the guide and the rods were rotated to further fit the desired curvature. This was a successful method of obtaining a consistent and accurate radius of curvature as can be seen in Figure 7 and Figure 8. Note that a 'turn' is equivalent to about 0.508 cm. The turns were from manually cranking the linear rail system before the controller was repaired. It can be seen that the radius is mostly centered around 130 cm as desired with a range of about ± 5 cm at worst. In Figure 9 one can see that

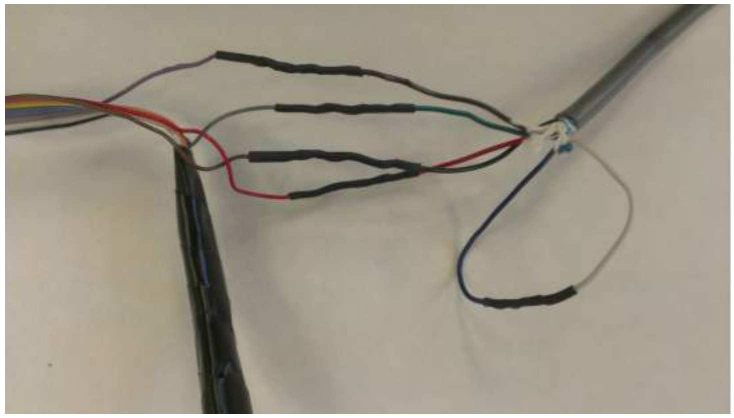

Figure 5. Motor Controller Wiring. The rainbow cable on the left connects to the motor controller and the gray cable on the right connects to the linear rail system. The wires, listed from controller to linear rail system, are connected as follows: purple-to-brown, gray-to-green, brown-to-black and red-to-red. Also the blue and white wires both originating from the gray cable connecting to the linear rail system were connected to one another in a loop.

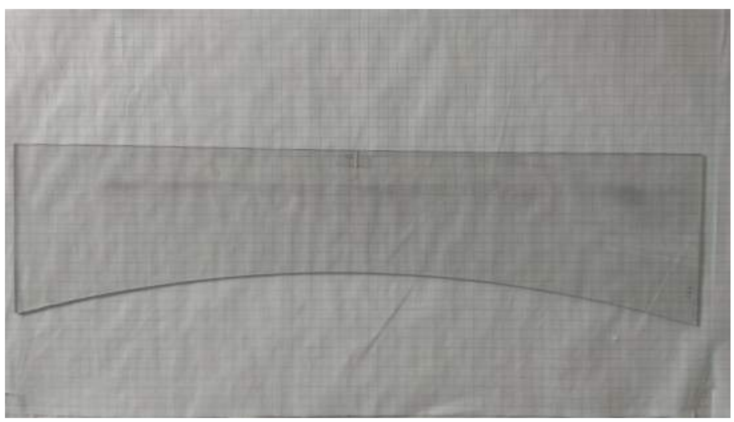

Figure 6. Plastic Guide. This guide is cut to a radius of curvature of 130 cm. By placing it on the back of the mirrors while aligning them a more accurate radius can be achieved.

small variations in the radius of curvature do not have much impact on light collection so these deviations are not particularly worrisome.

Several behaviors were consistently observed in tests of the radius of curvature. One of these behaviors was that at the central vertical line of the mirror there is usually a notable distortion or discontinuity in the radius of curvature. This seems to indicate that the center of the mirrors undergoes a significant warping due to the stresses being applied to the mirrors. Fortunately the center of the mirrors have had little to no problems directing light onto the PMT array so this phenomena is not likely to be an issue.

Another behavior to notice is that the radius of curvature begins to increase as the laser moves towards the edges of the mirror. It appears that it is harder to force the edges of the mirror to take on the radius of curvature desired. I suspect this is due to the way in which the mirrors are held in the frame. The rods holding the mirrors have slits in which the mirror fits but these slits are not curved to the radius of

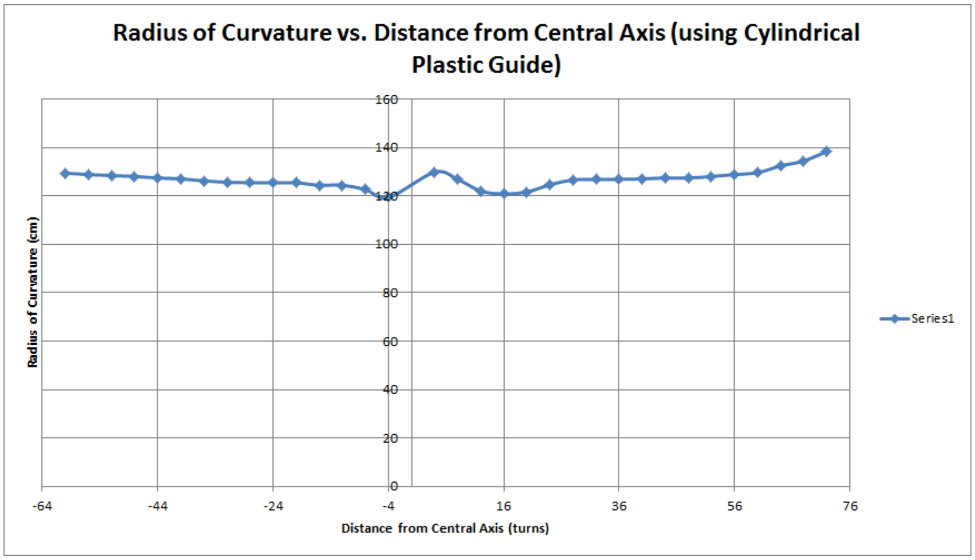

Figure 7. Radius of Curvature Test. This test was performed while the plastic guide was secured to the back of the mirror on the central horizontal line.

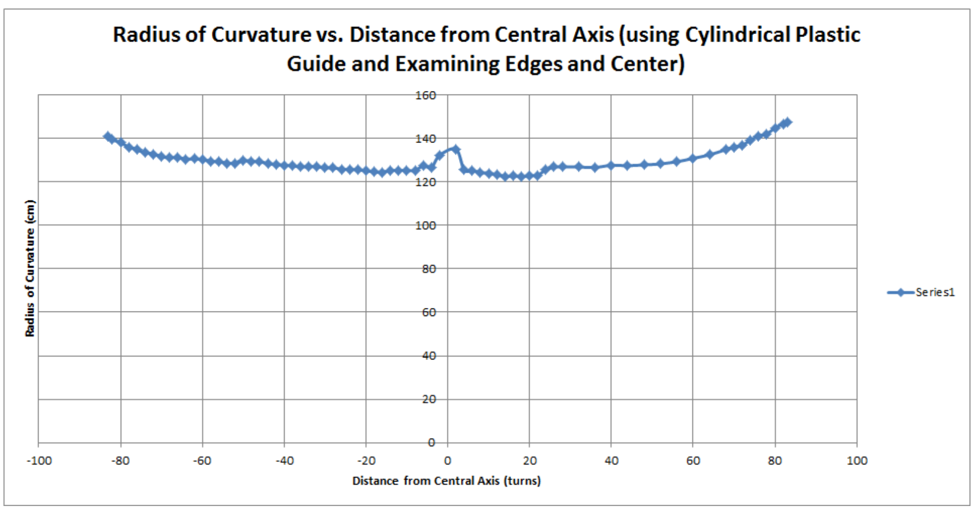

Figure 8. Radius of Curvature Test New Alignment. This test was performed while the plastic guide was secured to the back of the mirror on the central horizontal line. The data were taken after the mirror had been aligned separately from the alignment seen in Figure 7.

curvature. Thus when the rods are rotated they apply pressure to the mirrors' edges discontinuous with the desired radius.

The edges of the mirror can be expected to be the most important regions to align correctly. In tests that will be discussed later in this report the edges were found to be the most problematic, although still manageable, regions. Fortunately much of the mirror's surface is not really collecting light so the most extreme edges of the mirror giving the greatest deviations in radius are not utilized. There is a large

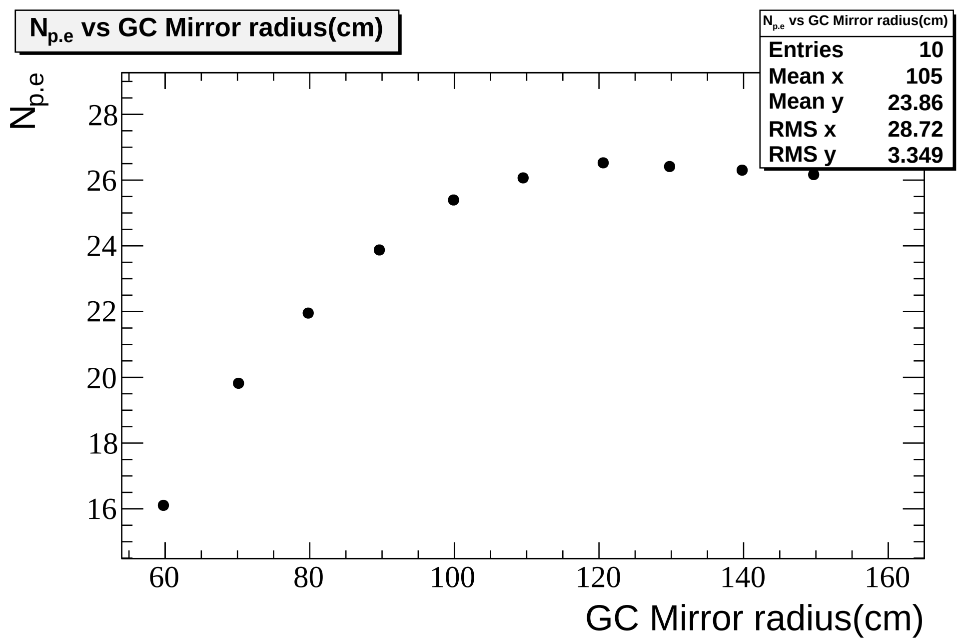

Figure 9. Radius of Curvature Efficiency Simulation. This simulation provided by Huan shows the photon collection efficiencies of various radii of curvature. Around 130 cm there is considerable tolerance in radius variations before photons are lost.

stable region in the radius seen in the central area of the mirror where most of the light will strike. Thus for the active region of the mirrors most of the light strikes an area with the proper radius of curvature.

In the actual detector box the guide will not be attached to the mirrors so the mirrors must be able to hold their shape without the guide being secured to them. Several tests were conducted in the same manner as those shown in Figures 7 and 8 except that once the mirror was shaped with the plastic guide it was removed from the mirror. The first graph seen in Figure 10 represents a very fast alignment that was done with little precision simply to compare to a more exacting alignment. It is clear that not carefully aligning the mirror causes a considerably worse fit.

In Figure 11 an alignment where the plastic guide is removed but where two people very carefully aligned the mirror is shown. This fit is significantly better and centers around 130 cm as expected. This alignment took a greater amount of time but demonstrates that the mirrors can be shaped to the proper radius without keeping the guide attached. Further, the mirror's shape did not distort noticeably over time. To achieve this alignment it was important to adjust the radius at multiple heights, usually level with the adjustment nuts, on the mirror. As seen in previous tests there was still a large distortion in the central part of the mirror and also slightly less stability at the edges. It is possible that part of the central distortion was due to the measurement method. Overall this represents a fairly successful alignment.

To have another independent method for measuring the radius of curvature of the prototype mirror a dial drop indicator was ordered (Figure 12). This indicator was attached to an optical mount which was secured to the linear rail system. The plunger was then placed against the mirror and the rail system moved it across the surface of the mirror. This allowed the depth of the mirror to be measured and this depth could then be converted into a measure of the radius of curvature. The resulting fit can be seen in Figure 13. The fit was found to be about 125 cm. This is consistent with the other measures of the radius of curvature and also within the stable zone for the radius seen in Figure 9. Once again a discontinuity

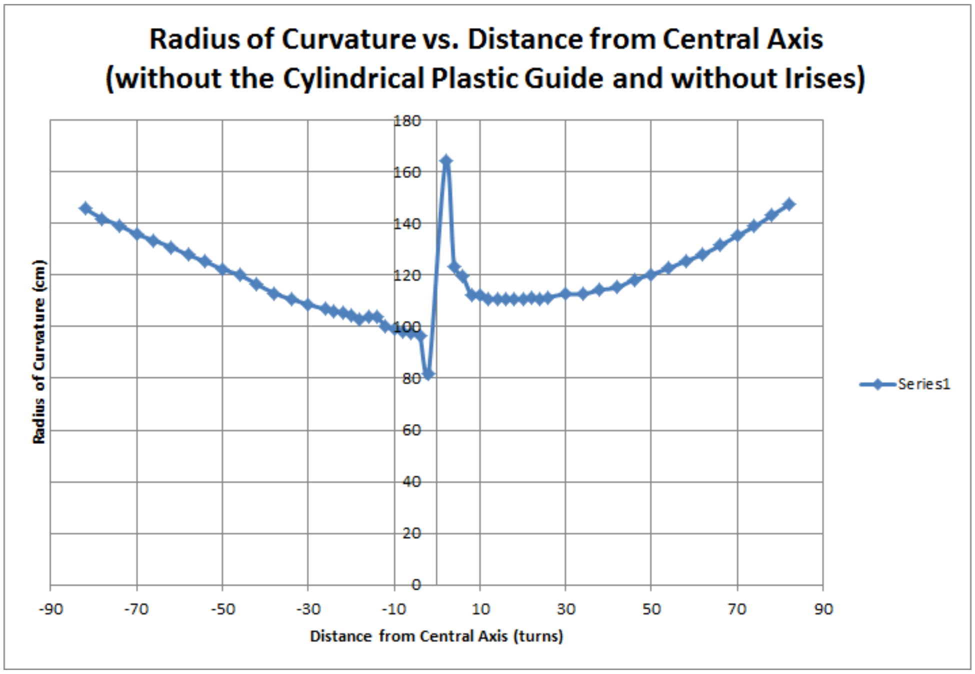

Figure 10. Radius of Curvature Test No Plastic Guide. This graph shows a quick alignment of the mirrors to give a comparison to a better alignment (see Figure 11).

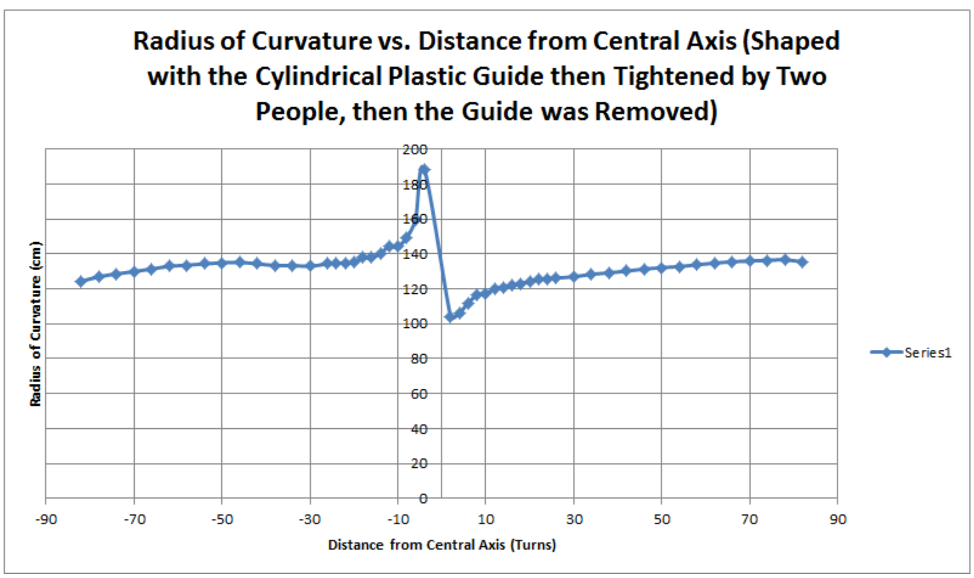

Figure 11. Radius of Curvature Test No Plastic Guide. This graph shows the radius of curvature for a more precise alignment of the radius of curvature.

is seen at the vertical center of the mirror.

Figure 12. Dial Drop Indicator. This dial drop indicator was used to measure the depth of the mirror due to the curvature. This allowed the radius of curvature to then be calculated.

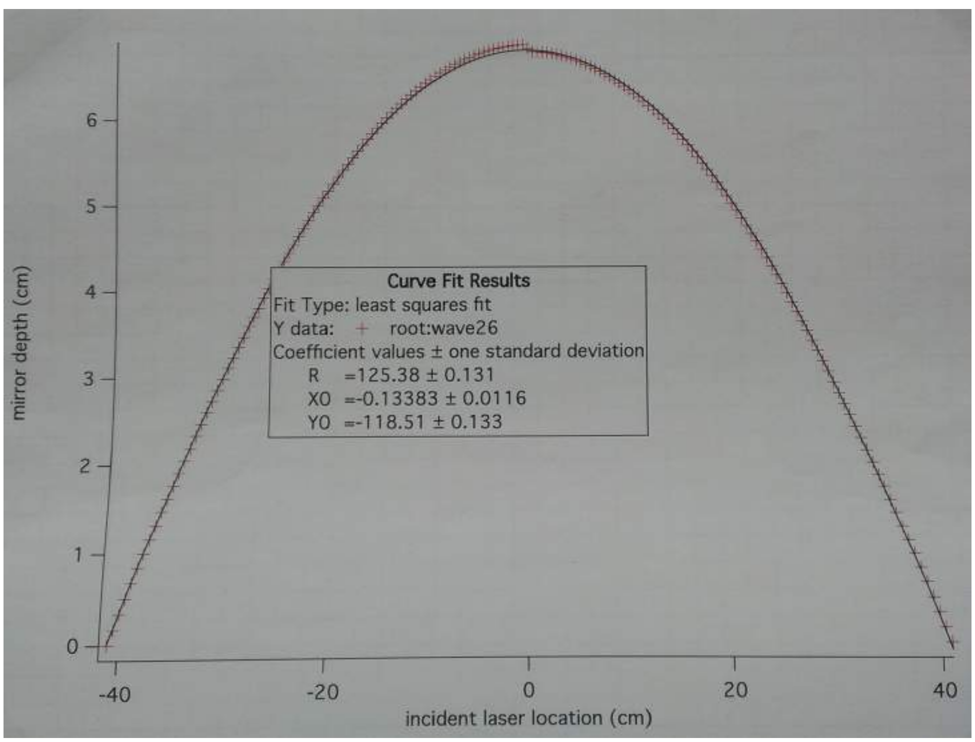

Figure 13. Dial Drop Indicator Measured Radius of Curvature. This fit was done in Igor Pro. The red crosses represent the experimental data and the black line the fit of this data.

Once the tests to confirm that an acceptable radius of curvature could be achieved were completed the next goal became checking if all of the reflected light landed on the PMT array as desired. To do this the prototype mirror frame was attached to an optics table at a 27.5 degree angle to the laser, as it will be in the detector, and a box was placed where the PMT array will stand. Initially the laser was scanned across the mirror surface to see if it was correctly striking the simulated PMT array. It quickly became clear that the light was landing at least close to the desired location. However, a more accurate setup than the prototype frame on an optics table was needed to determine if the light was reaching the array properly.

Actual Mirror Frame and Further Tests

To attain more accurate results that were analogous to the environment in the detector the mirror frame that will be used in the detector was constructed (Figure 14). This frame was constructed by Huan and I over several days and was assembled in the William and Mary clean room to help keep dust off of the prototype mirrors. A frame was also constructed to hold the linear rail system and the laser facing the mirrors (Figure 15). Each of the levels of this frame can be moved up and down allowing for the laser to strike different vertical points on the mirrors. A simulated PMT array was also built to see if reflected laser light was landing where desired (Figure 16). All three of these detector pieces were then arranged to match the geometry of the detector according to the design in Figure 17.

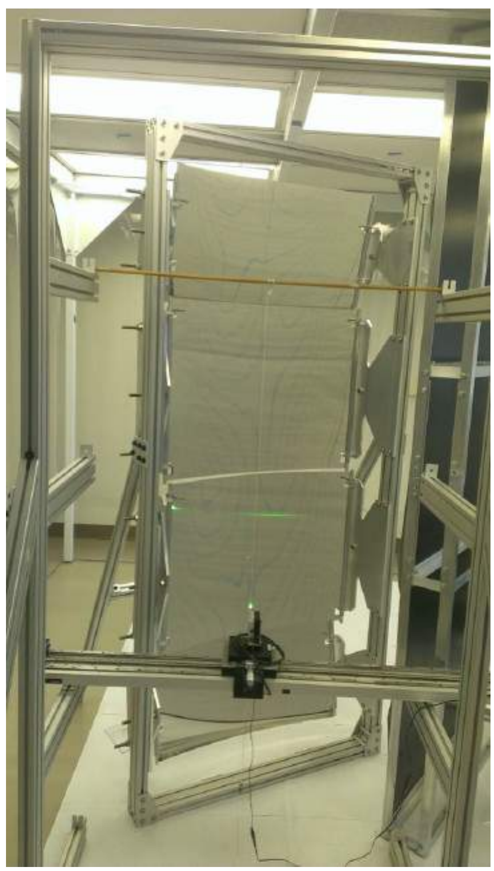

Figure 14. Mirror Frame. A frontal view of the mirror frame holding the four prototype mirrors. In the foreground the linear rail system with the laser can be seen on an independent frame.

Figure 15. Laser Frame. In the foreground the frame holding the laser and linear rail can be seen. Each of the four levels on this frame can be moved up or down. A side view of the mirror frame can be seen on the left. In the central background the black rectangle with paper attached to it represents the PMT array.

Once the proper geometry was replicated the next goal was to check if all of the light actually struck the PMT array. To accomplish this Huan provided an estimate of where photons would enter the detector at the most extreme positions and the most extreme angles for each of the four mirrors. If these photons strike the mirror all photons of less extreme entrance position and angle can be expected to strike the mirror. These 'extreme' photons were found from Huan's Geant 4 simulation of photons hitting the mirrors. The four corners of each of the mirrors were studied to find the most 'extreme' photons with the greatest chance to miss the PMT array if the mirrors are not aligned correctly (Figure 18).

Then a list of the photons positions and angles most likely to land on the edge of the PMT array or off of it was assembled. Each of these positions was then tested using the mirror system to see if the laser fired from them struck the array or not. A table showing these results can be seen in Figure 19. The results show that with some extra adjustment of the mirrors the light from all of the most extreme entrance positions and angles could be made to fall on the PMT array. This also indicates that all of the positions in between the extreme ones should strike the array, and in other tests running the laser at different angles across the mirrors this was found to be true. Numerous other tests where the laser struck the array from different points and angles were also performed. These tests all showed that with

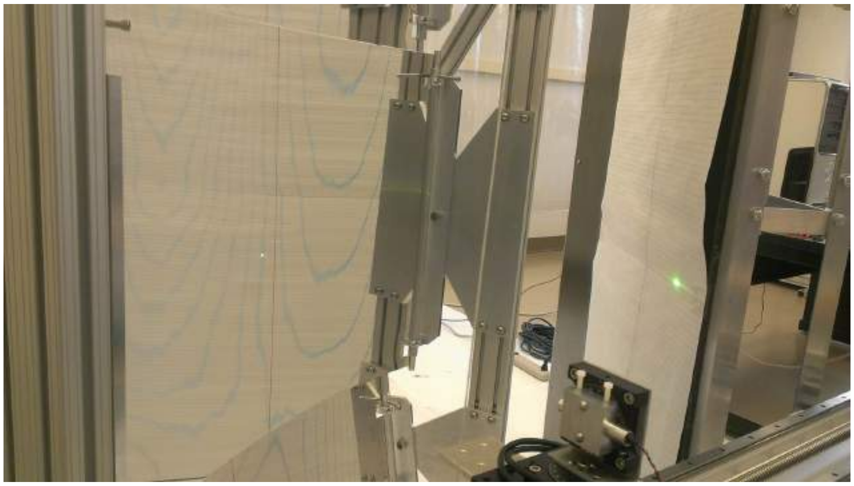

Figure 16. Laser Reflecting onto PMT Array. The laser can be seen reflecting off of the mirrors and striking the simulated PMT array on the right side of the image.

some adjustment all of the light struck the PMT array. This shows that the mirror system will operate as desired if aligned carefully.

After confirming that all of the light could be directed onto the PMT array the path that this light took on the array was examined. To see the pattern the laser makes on the array the third mirror from the top was used with the laser being run along its central horizontal line in two centimeter increments. At each increment a mark was made on a piece of paper on the array where the laser struck (Figure 20). The first thing to notice is that the laser seems to 'backtrack' on the path it was following. This behavior was not anticipated but was found to be natural as I will discuss shortly. Another important feature is that there is some vertical distribution of photons hitting the array. Since this mirror is not angled we should expect the dots to all be on the same horizontal line. This means that the mirrors have some warping on them that causes the surface not to be completely parallel with the PMT array. Fortunately this vertical spread is small, on the order of a few centimeters, and does not cause the light to miss the PMT array.

When the reason for the backtracking behavior was not immediately obvious I created a 2D Mathematica simulation of the mirrors and detector. This has been used to further aid testing and explain the backtracking behavior. This simulation was made by translating the geometry of the detector into Mathematica and then simulating the path of an incident laser beam through the detector using the properties of light rays. An image of this simulation can be seen in Figure 21. Most of the geometry of the mirrors, detector and entrance window were adjustable so that various configurations could be studied. This became a quick method of predicting the laser's behavior and checking to see if the mirrors were matching simulated predictions.

After the Mathematica simulation was completed it was used to study the backtracking behavior. This was done by simulating the laser entering the detector at a zero degree angle and moving it horizontally across the mirror surface as was done in Figure 20. The results of this simulation can be seen in Figure 22. This figure shows where the laser light struck the PMT array. The Y axis is used to indicate if the laser is backtracking. If the value is zero it indicates that the laser is moving across the array in the direction in which it began moving. If the value is one it means that the laser is now moving in the opposite direction of the one in which it began (i.e. backtracking). In the simulation all of the points strike the array in a horizontal line so the height above the ground is arbitrary.

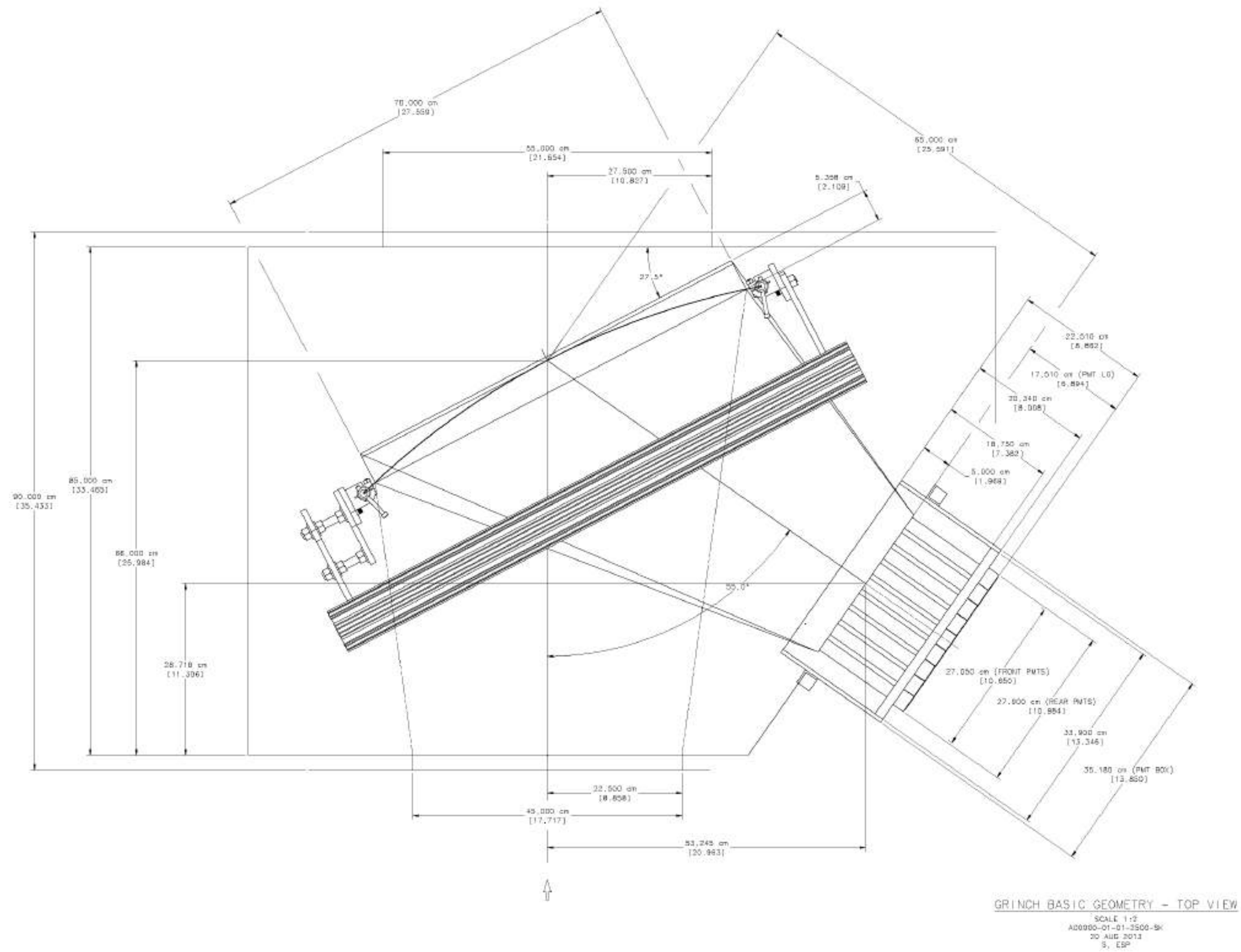

Figure 17. GRINCH Detector Geometry. This image shows the detector geometry which was replicated for testing. This image can also be found on the JLab GRINCH wiki page under design.

Figure 22 demonstrates that this unexpected backtracking behavior is a natural result of the detector geometry. When the conditions used to obtain Figure 20 were plugged into the Mathematica simulation it was found that the laser reverses its course eventually causing the looping patterns observed in the lab. After confirming that the backtracking behavior is to be expected I wanted to map the paths of the laser striking the PMT array after reflecting off of each of the mirrors. This was done at different heights on each mirror to give a full mapping of light on the array.

To experimentally obtain this full mapping of light on the PMT array Austin and I fired the laser at three different levels (top, middle and bottom) on each of the four mirrors and recorded where the light struck the array. The laser was fired at a zero degree angle (i.e. perpendicular to the entrance window) and was moved in increments of two centimeters horizontally across the faces of the mirrors. A

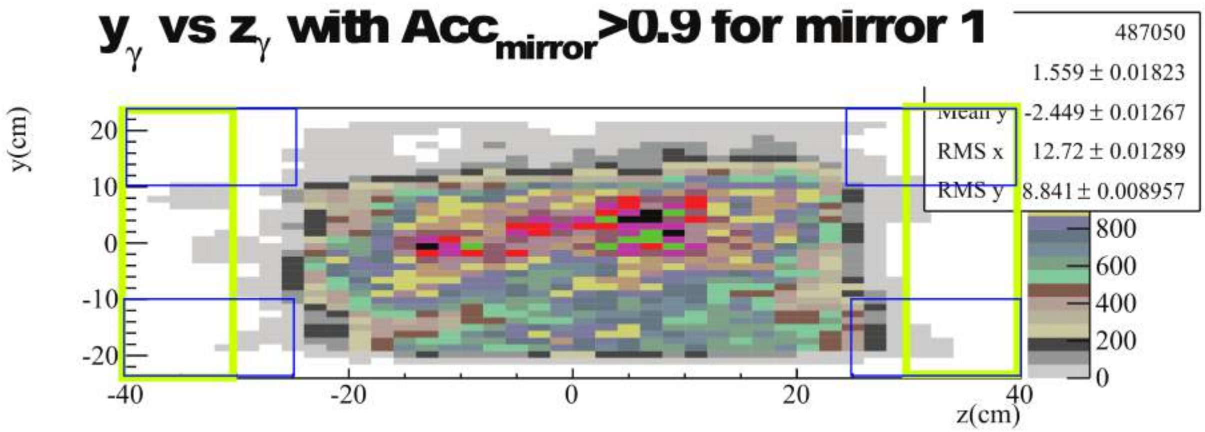

Figure 18. Simulation used to Find 'Extreme' Photons. This image shows where photons will strike a mirror and how many will strike that position. The four corners of the mirror were examined to find the photons that would come closest to not striking the PMT array.

compilation of these paths on the array can be seen in Figure 23. As before each of the paths exhibits the looping pattern already seen. Note that mirror four was not well aligned at the time and some of the light missed the array.

By comparing these laser path results with what is predicted by simulation much can be learned about the alignment of the mirrors. For example if mirrors 2 and 3, which don't have any tilt forward or backward, have the same radius of curvature over their whole surfaces all three of their light paths should look the same. By seeing that they don't we can infer which parts of the mirror have too large or too small of a radius of curvature. As an example we can compare the real data from mirror three with what the simulation predicts (Figure 24).

From Figure 24 we can see that the bottom line of the mirror is the best aligned as it most closely matches the results from the simulation. It is also possible to tell that the radii are too large for each of the three levels with the top level being the worst. This data can then be used to align the mirrors better by knowing in what ways our radii are off. Although we do see deviations from the desired radius of curvature we can see from Figure 23 that all of the light from mirror 3 strikes the PMT array. The comparison of actual data with simulation should now allow for even better mirror alignments further ensuring that all of the light will be directed onto the PMT array.

Conclusion and Future Work

These tests have shown that a radius of curvature of 130 cm is acceptable to collect as much light as possible. It was further shown that the mirrors can be shaped with enough accuracy to achieve approximately the radius of curvature desired and will hold their shapes without deforming notably over time. This process is greatly aided by the use of a plastic guide shaped to the intended radius of curvature. Alignment of the mirrors heavily influences the behavior of the photons and must be done carefully and for each mirror individually to be certain all of the photons are collected. It was also demonstrated that the light entering the detector at the most extreme entrance positions and angles can be directed such that all of the rays land on the PMT array. In light of these results I believe that the current design for the mirror system will adequately serve our purposes and does not require any major modifications.

There is still further work to be done with the mirror system. A method of checking whether the

Mirror	Horizontal Photon Position (cm)	Turns (Horizontal)	Vertical Photon Position (cm)	Max Angle Needed Horizontal	Max Angle Needed Vertical	Was the Laser on the PMT Array?	R/L Side of PMTs (facing PMTs)	Notes	Laser Height from Ground (cm)
Frodo (1, Top) Top Left Edge	-14.13	-22550	82.89	-5.19	10.87	On	R	Very good tolerance for left, right and top after adjustment.	190.84
Sam (2) Top Left Edge	-14.87	-23731	49.94	-5.31	6.48	On	R	Very good tolerance in all directions.	157.89
Merry (3) Top Left Edge	-14.41	-22997	-2.39	-4.88	-2.89	On	R	Very good tolerance in all directions.	105.56
Pippin (4, Bottom) Top Left Edge	-15.35	-24497	-55.63	-6.23	-11.75	On	R	Very good tolerance in all directions.	52.32
Frodo (1) Top Right Edge	14.48	23109	77.95	6.4	12.21	On (needed readjust ment)	L	Very good tolerance for left and right. About 1.5 cm below top PMT line. Needed to tilt top mirror forward a bit.	185.9
Sam (2) Top Right Edge	14.75	23540	48.75	5.63	6.4	On	L	Very good tolerance in all directions.	156.7
Merry (3) Top Right Edge	14.72	23492	-0.54	6.57	-2.49	On	L	Very good tolerance in all directions.	107.41
Pippin (4) Top Right Edge	14.12	22534	-50.25	5.53	-11.57	On	L	Very good tolerance in all directions.	57.7
Frodo (1, Top) Bottom Left Edge	-15.47	-24689	60.1	-5.47	6.78	On	R	Very good tolerance in all directions.	168.05
Sam (2) Bottom Left Edge	-14.99	-23923	6.92	-5.24	-1.58	On	R	Very good tolerance in all directions.	114.87
Merry (3) Bottom Left Edge	-15.14	-24162	-47.81	-4.86	-10.12	On	R	Very good tolerance in all directions.	60.14
Pippin (4, Bottom) Bottom Left Edge	-13.85	-22103	-80.6	-5.35	-14.46	On	R	Very good tolerance in all directions.	27.35
Frodo (1) Bottom Right Edge	14.24	22726	55.5	5.31	7.86	On	L	About 2 cm from L 8 PMT line.	163.45
Sam (2) Bottom Right Edge	14.49	23125	6.41	5.83	-1.05	On	L	About 3 cm from L 8 PMT line.	114.36
Merry (3) Bottom Right Edge	14.31	22838	-45.45	7.04	-9.56	On	L	Very good tolerance in all directions.	62.5
Pippin (4) Bottom Right Edge	15.21	24274	-73.05	6.08	-15.38	On	L	Very good tolerance in all directions.	34.9

Figure 19. Tests to Check if 'Extreme' Photons Strike the PMT Array. The first column indicates which section of which mirror is being examined. For example '2 Top Left Edge' indicates that the second mirror from the top was being examined and the specific extreme photon was in the top left edge of this mirror. (Mirrors have been affectionately named for the four Hobbits Frodo, Sam, Merry and Pippin but are also labeled 1 through 4 in descending order on the mirror frame.) The position on the entrance window can be found in the second column (horizontal position) and the last column (height above ground). The angle of the laser is given in columns 5 and 6 where a negative sign indicates counterclockwise if the angle is horizontal and downward if the angle is vertical. The 7th column lists if the light fell on the array or not, and the 8th column has notes about where the light fell on the array.

mirrors are aligned *in situ* must still be developed. A leading proposal to accomplish this is to attach small lasers to the inside of the detector box frame and fire them at numerous points on each mirror.

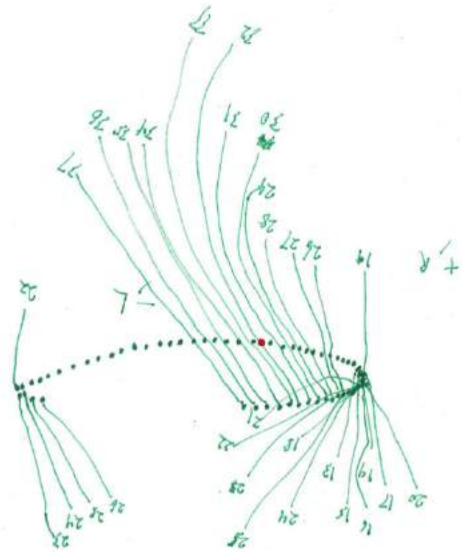

Figure 20. Laser Pattern on PMT Array. This pattern was formed by moving the laser across the central horizontal line of the third mirror from the top. At each of the two centimeter increments the laser was moved in a mark was made on a piece of paper on the PMT array to show where the light fell. Note that an interesting backtracking pattern is made. The red dot represents when the laser was fired at the center of the mirror.

Then by knowing where the light should fall on the PMT array when correctly aligned the mirrors can be calibrated. The Mathematica code will also be helpful by predicting exactly where light should fall on the array when the radius of curvature is correct. This will make the alignment process more precise. These and other issues will be investigated at William and Mary in the near future.

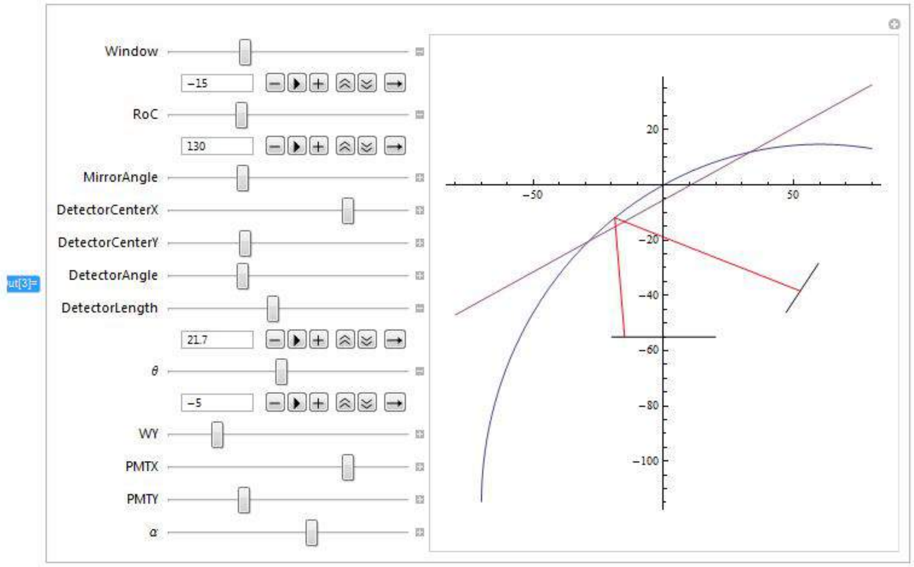

Figure 21. Mathematica Simulation of Mirror System. The horizontal black line represents the entrance window and the angled black line represents the surface of the PMT array. The blue circle represents the mirror surface with the purple line showing the approximate size of that surface. Lastly the red line represents the ray formed by a photon entering the detector and reflecting off of the mirror.

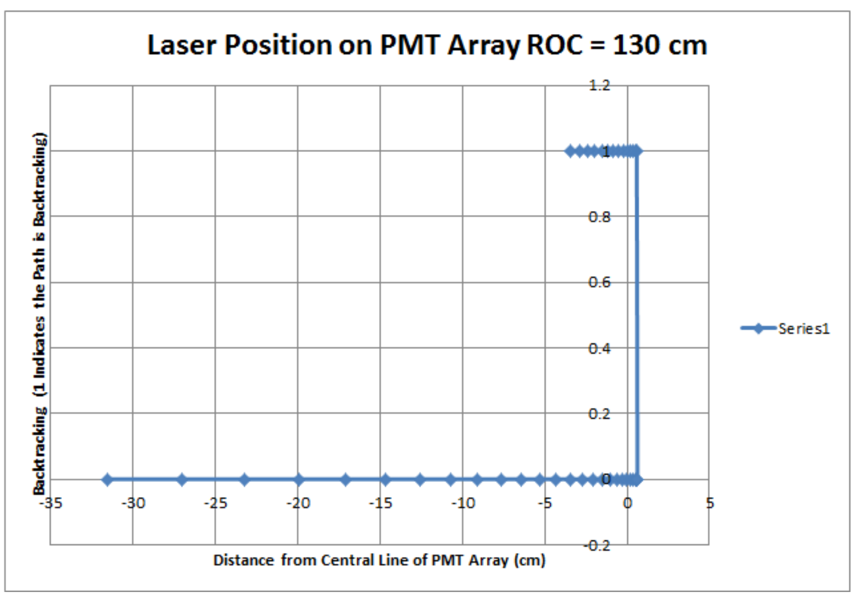

Figure 22. Simulation of Backtracking Behavior. This graph shows a simulation of how the laser should move across the PMT array. A Y axis value of 1 indicates that the laser has reversed the direction in which it was moving. Note that the height above the ground is arbitrary in this simulation as it is only 2D.

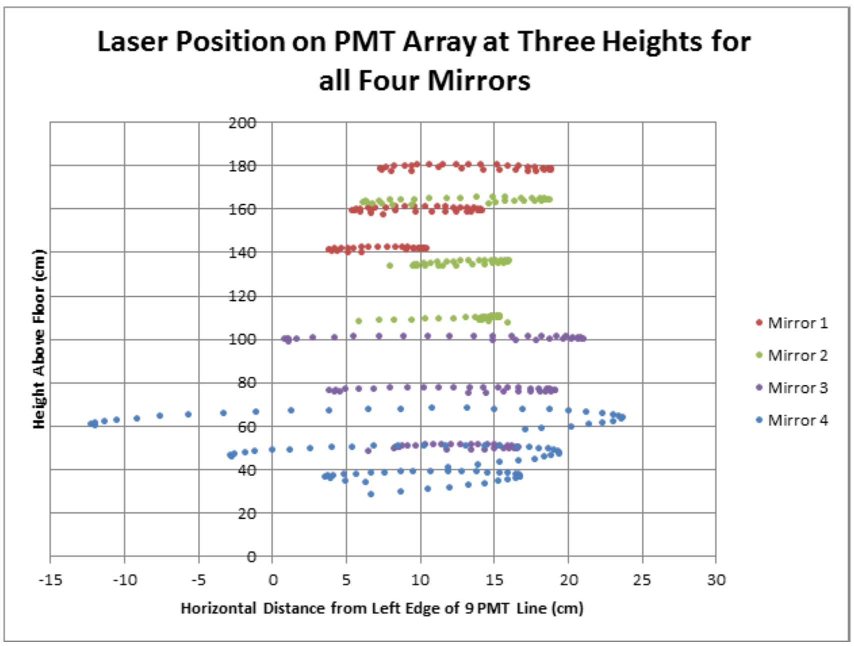

Figure 23. Full Mapping of Laser Paths on PMT Array. This graph shows the path a laser fired at zero degrees onto the mirrors takes on the PMT array at three levels per mirror. Note in this image zero is the left edge of the 9 PMT line not the central line of the PMT array.

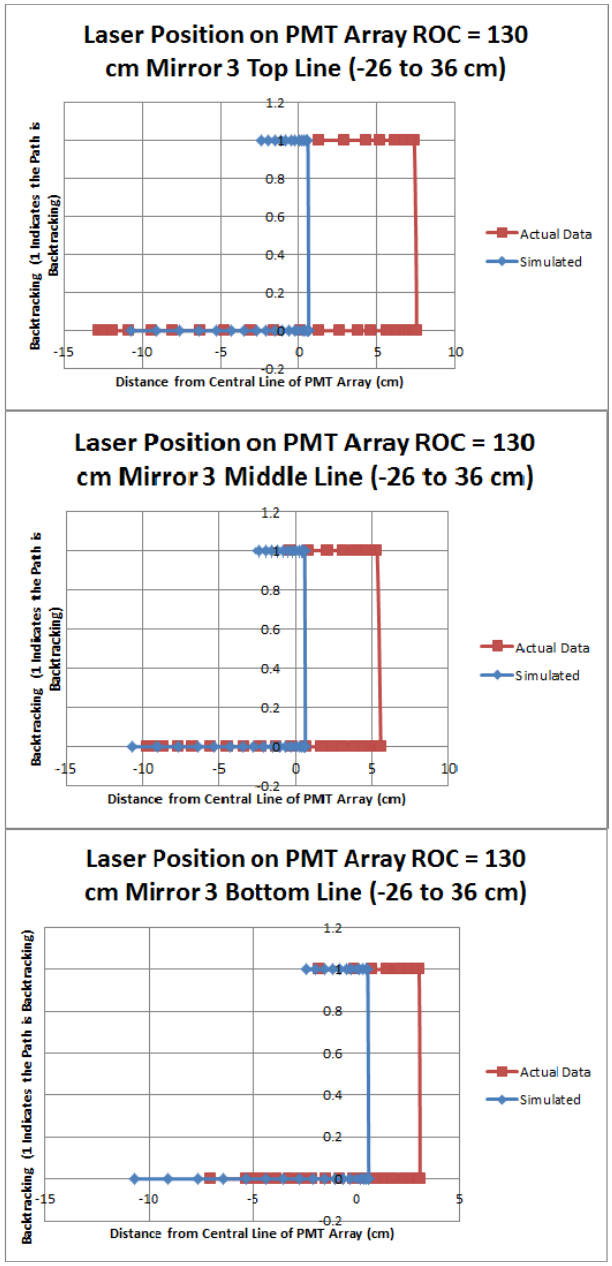

Figure 24. Laser Path on PMT Array Real and Simulated Data Comparison. This graph shows the laser position on the PMT array results for mirror 3 at three different heights compared with the predictions from simulation. The experimental data is given with only the horizontal position. The height was removed to make an easier comparison with the simulated 2D results which do not contain a height.