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Introduction/Background

Since the signal produced by gravitational waves through the Hanford and Livingston detectors is very weak, it is of utmost importance to cancel as much signal "noise" as possible. One of the main sources of signal noise is the affect of scattered laser beams on the differential phase of the main, collimated laser beam. The scattered light that reflects off of un-baffled and reflective surfaces in the detectors, surfaces that are not isolated by suspension, can eventually recombine with the main laser beam, disrupting the measured differential phase of the laser beams when they recombine at the beam splitter. Thus, figuring out which un-isolated surfaces scatter the most laser light is of particular importance so that baffles can be placed most efficiently and effectively in the detector to decrease signal noise.

The LIGO Hanford and Livingston lasers have a Gaussian profile, so the area of the chamber we are most interested in scanning is localized around the beam path since that is where the strongest scattered light will be coming from. The surfaces we are interested in are not only the un-isolated ones, but also surfaces perpendicular to the beam since the scattered light off of those surfaces are more likely to recombine with the beam and cause the noise error in the detection.

Therefore, a systematic way to determine which surfaces need baffling would be to create a scanning system or device that could be placed in a chamber along the beam path and recreate a light source as well as hold a light detection instrument to the surfaces of interest as it scans.

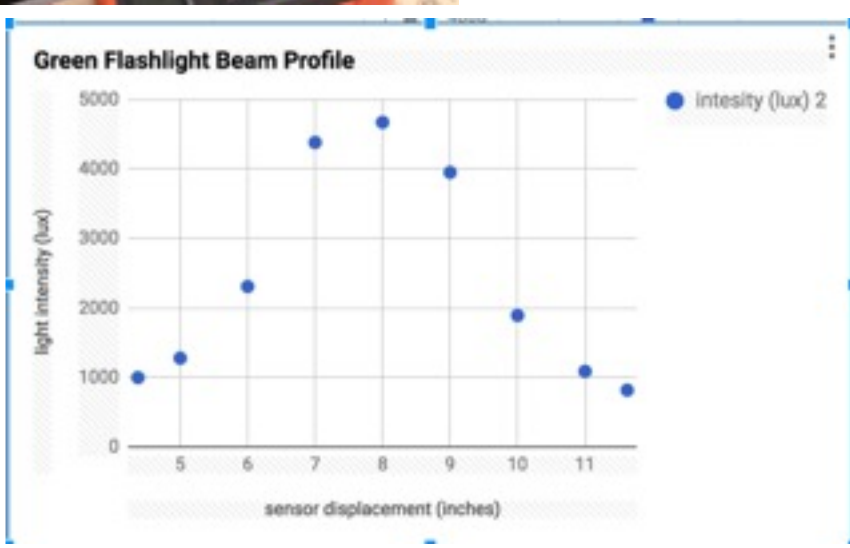
Objective/Purpose

The following experiment was performed in order to get a sense for the plausibility and effectiveness of a scanning device in order to determine to what extent the system can and should be implemented at the detector sites. Additionally, the test scans would be of a small array of the baffles LIGO is considering to absorb light in the detectors. This choice can give LIGO a better sense of the practicality of mounting and using the baffled materials themselves as well as a way to compare the images of these baffles in light with the data of these baffles from the spectrometer.

Methods and Materials: Scanning Procedure

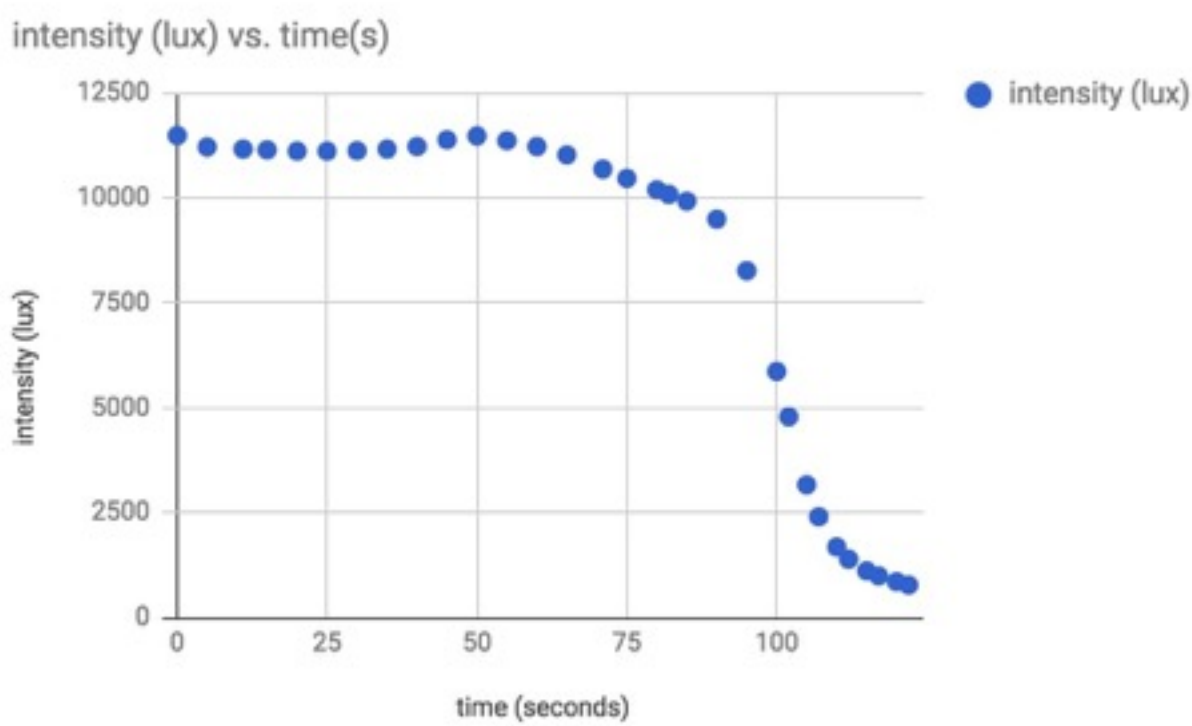
The four main components of this device/test procedure are the light source, the light detector, the mount for these two different instruments, and the mount for the baffle array that would be scanned.

For the light source, the main decision was between using an actual laser beam or another collimated light source in the visual spectrum (a highly collimated flashlight). We decided to use the collimated flashlight since setting up a laser room would be time consuming, and the beam width for the flashlight is significantly greater than that of a laser beam, in which case a scan with many more images would be necessary, and the image processing would therefore take a very long time. Of the three flashlights (one white light, one red light, and one green light), only the green and red ones (both Cree Fixed Star flashlights) were mountable and easily maneuvered on the adapted camera tripod. Before finalizing the flashlight choice, each beam was profiled using a Dr. Meter brand light intensity meter mounted to a lab jack so that it could be raised and lowered along the vertical cross section of the flashlight beam.



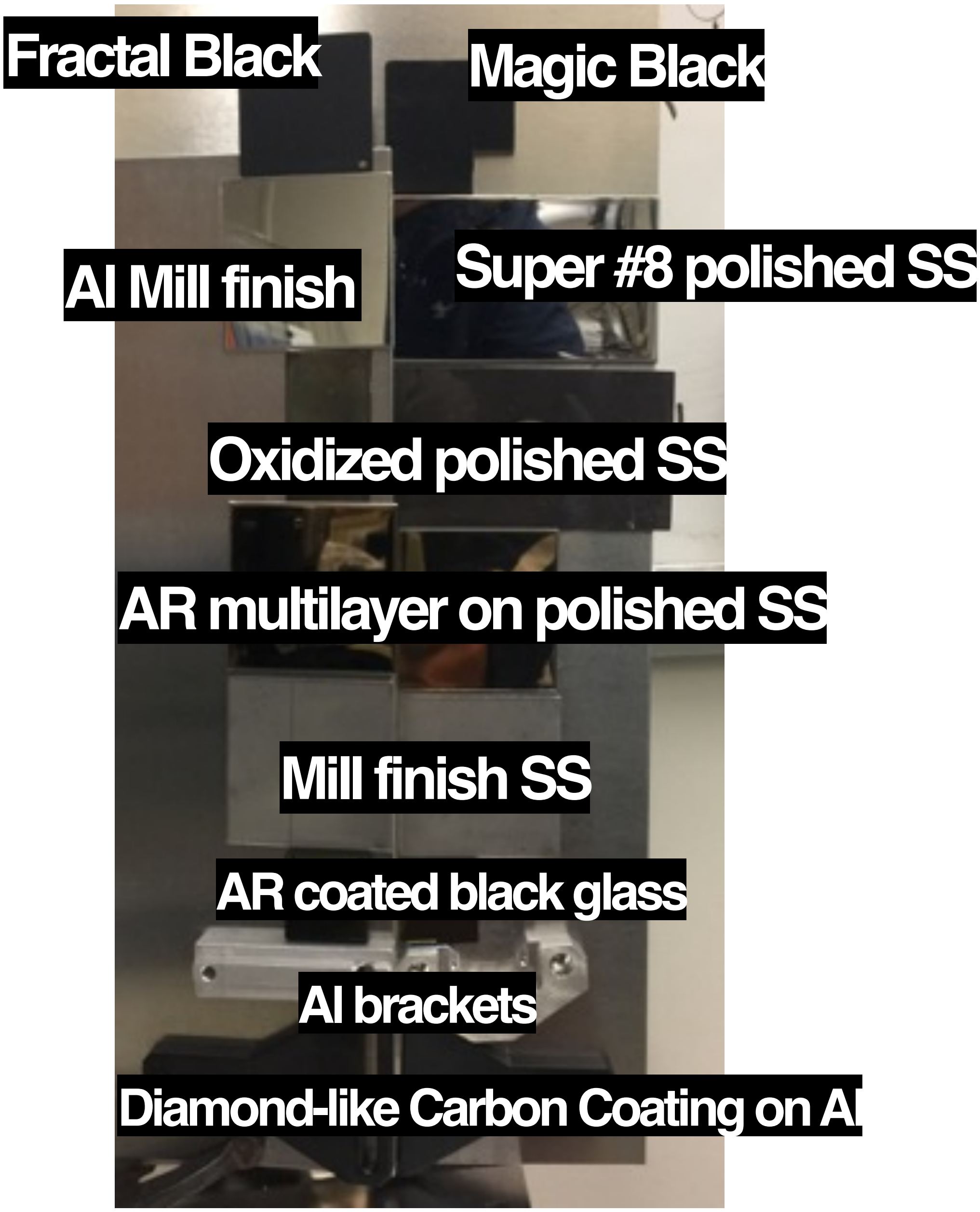
As evident from the beam profile data, the white light flashlight doesn't have a totally Gaussian profile and therefore should not be used. Between the red and green flashlights, the green one was chosen since the light it emits is in about the center of the human visual spectrum. Green is also a higher energy color, and from casual observation of preliminary images, the light looked brighter and more intense.

Since the green flashlight runs on rechargeable lithium ion batteries, the experimenter would need to know how long to use the flashlight before the battery would need to be replaced. Taken over about 2 hours, the following light intensity data was obtained by shining the most intense and collimated part of the flashlight beam at the center of the photo detector and taking measurements every five minutes. In order to prevent the photo detector from heating up and creating error in the data collection, a sheet of aluminum foil was places in front of the flashlight beam until a data point was ready to be collected. The data for the second trial of that small experiment is shown below.



The lithium ion batteries in the green flashlight could only be used for about 60-65 straight minutes before needing replacement. This information was worked in to the experimental procedure.

Finally, the collimated flashlight needs an aperture to block out the light from the less



intense edges of the beam's Gaussian profile without significantly affecting the recorded intensity of incident light (since the high intensity collimated beam is meant to loosely mimic the light of a laser beam). Through trail and error, an aperture one inch in diameter was attached to the end of the flashlight 2.5 inches (+ or - .375 inches) away from the edge of the flashlight face.

For the light detector, we had a choice between two Nikon cameras, a Nikon model D40x and a Nikon model D7100 The decision to use the Nikon D40x was due to a complication with the Nikon D7100 camera-laptop connection cord needed to eventually transfer the data images via email to a main Desktop computer for image and data analysis.

The goal of the light detecting segment of the experiment was to find a device that collected image data which reflected as exactly as possible the intensity of the light being emitted into the camera lens from the reflected collimated flashlight light. In order to keep the experimental variables unchanging, the camera was put in manual mode so the experimenter is always aware of the exact camera exposure settings for every image despite small changes in the surrounding light environment that a camera in automatic mode would covertly compensate for.

There are three components that affect the exposure of a camera: shutter speed, film speed (or ISO), and aperture. Shutter speed is the measure of how long the photo detector in the camera is exposed to the light of the image, so an image taken with a fast shutter speed would have less exposure and would be darker. The difference in light intensity for two areas of an image that are very bright to the naked eye would be more clear since the pixels in these two areas would not be over saturated with photons over such a quick time.

Film speed (or its digital equivalent, ISO) is the measure of how much the light intensity of the image should be amplified to create a brighter image. The problem with using a high ISO in a dark, low-exposed image (fast shutter speed) is that there are not a lot of photons per pixel in the first place, so amplifying the dark image a lot would also amplify the small errors in the number of photons per pixel that naturally occur. This amplification produces grainy, unsharp images which are not ideal since the experiment is concerned with the potential reflectivity of small optical components as well as even smaller nuts, bolts, and screws. Higher definition images is optimal, so therefore the ISO should be as low as possible on the camera's manual settings.

Finally, aperture is the measure of the size of the hole the light goes through in the camera before hitting the photodetector. The aperture is connected not only to the amount of light that is entering the camera, and therefore the image "brightness," but also with the depth of field. For a very large aperture, the items in the image that are in focus are in a very narrow range of distance from the camera. Items a few inches or more in the foreground or background of the focused image are blurry and undefined. Since the interior of the detector is long and there are many layers of perpendicular surfaces to analyze with the scan, a small aperture should be used to increase the depth of field. Obtained through trial and error and taking many test-photos, the final camera settings used for this experiment were a shutter speed of 2000 s^-1, an ISO of 200, and an aperture f-number of 22.

The camera and the flashlight could only be mounted separately on the two available tripods which made alignment of their positions relative to each other particularly important but very difficult to keep consistent across the five scans and several hundred images taken over the course of the preliminary and final experimental scans. The heights were easily adjusted by using a tape measure to keep their vertical alignment in check, but the horizontal alignment was less securely tracked by marking with tape on the ground the location of the tripod legs. The distance from the two mounted instruments to the baffle array was measured using a tape measure as well.

Below is a graphic of the final and thus implemented experimental set-up.

The mount for the baffle array was C-clamped to a lab jack laid on its side so that the array could move horizontally without the need to adjust the horizontal positioning of the flashlight and camera tripods. The lab jack was positioned atop a optical suspension structure in order to put the scan target within the range of the tripods' vertical range. The baffle array itself is composed of two plates of mill-finish aluminum. The first is arranged nearly perpendicular to the camera and flashlight plane and the second at an 8 degree angle towards the camera. On each plate is a strip of baffles almost identical to each other, their positions and names shown in the graphic below. The scan down and along the perpendicularly-arranged array would have images showing the intensity of a spectral reflection of the baffles, and the tilted array would show the intensity of the baffles' scattered light. For more information on the baffles, visit DCC document T1700128

The distance of the baffle array from the camera and flashlight is determined by how many images a single scan of the array should take.

A single scan is composed of five sets of thirty images. Each vertical scan consists of thirty images starting at the top and moving down by roughly half-inch steps until
The scan methodology is as follows:

1) Record the relative positions of the flashlight, camera, baffle array as well as the angle between the center of the camera's view and the center of the flashlight's beam. Of all error, the one for keeping this angle value constant is the greatest since every image is a result of a different adjustment of the tripod to lower both the light and the camera.
2) Turn off surrounding lights in the room.
3) Measure the initial intensity of the flashlight using the light intensity meter.
4) Adjust the lab jack so that the camera and flashlight point to the upper right corner of the array
5) Using the mirror-like reflectivity of the polished stainless steel squares, adjust the flashlight and camera so that one can see the reflection of the flashlight bulb in the center of the camera eye hole
6) Take a single image every half inch from the top of the baffle array to the bottom by adjusting the camera tripod and flashlight tripod in between each picture with a tape measure.
7) Once at the bottom of a scan, adjust the horizontal lab jacks so that the attached baffle array moves to the right a half of an inch and begin the next scan. Continue for five scans which was until the

Methods and Materials: Image Processing

All the images are saved in one folder and then subdivided into five folders based on which vertical scan they are a part of. The images are kept in the order they were taken in and

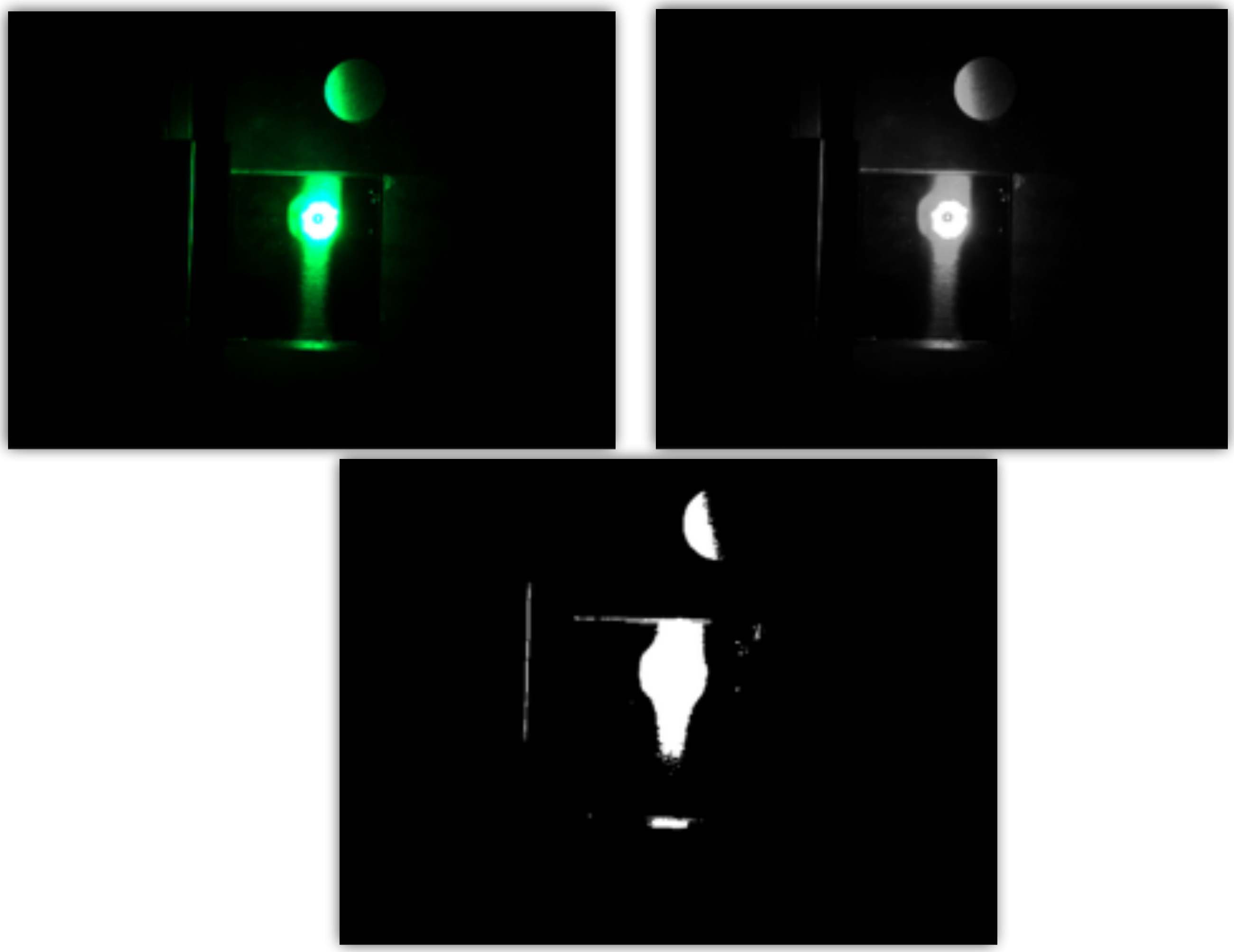


Figure 9: Each of these three images are the same original image at different stages in the image processing. The first is the Nikon RAW image file; the second is the grayscale image, and the third is a threshold image at 30%.

renamed Scanx_071017(y) where x is the scan number between 1-5 and y is the number of that image within the scan.

Using Matlab for images processing, the code loads the images from one scan and then converts to a grayscale image (where each pixel is assigned a brightness value between 0 and 255). Then based on the preference of the coder, the image can be converted into a binary image were every pixel above a certain brightness is defined as one and every other pixel is a zero. This process makes adding and subtracting image values easier and faster for Matlab. The desired threshold for our experiment was 30% of the total exposure based on the ability to make out details of the baffle array.

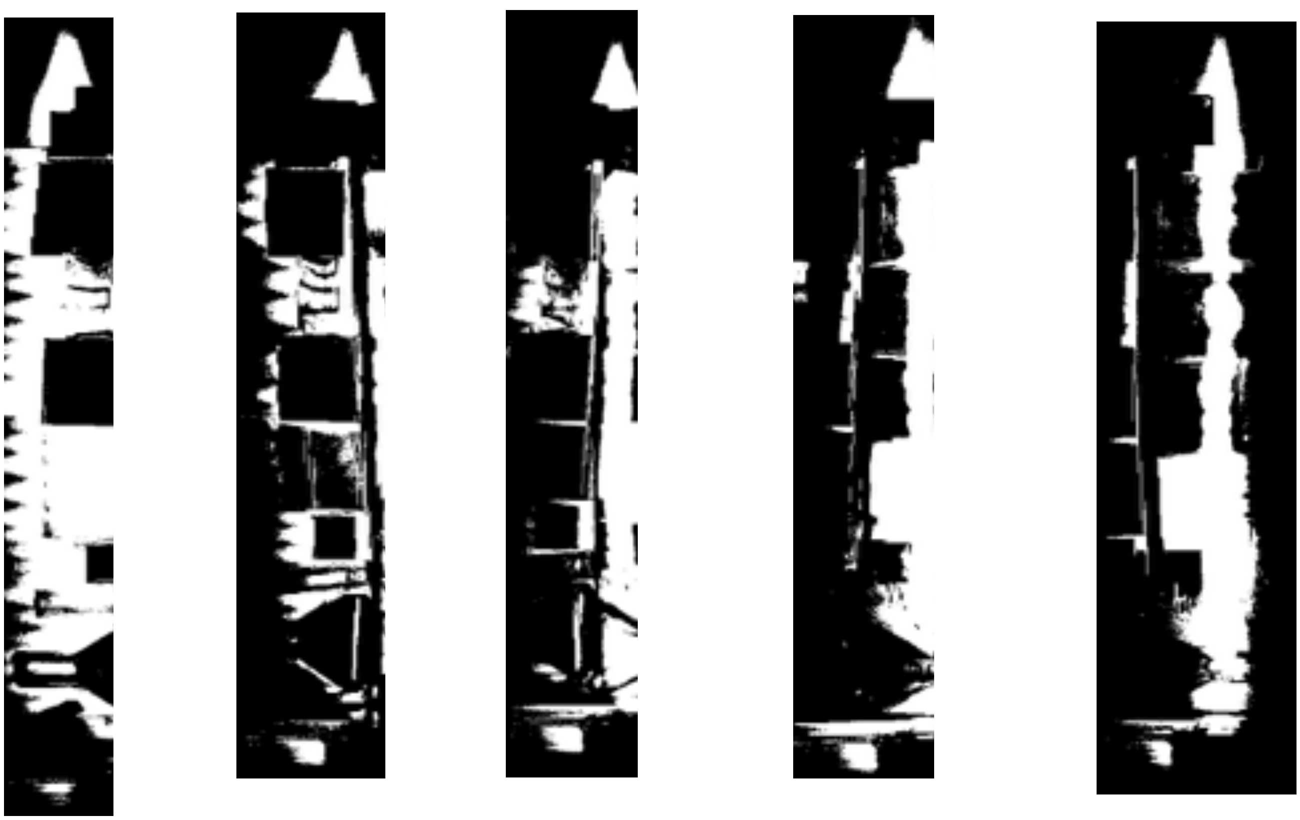
The images were combined by adding pixel values and shifting each image the half-inch equivalence in pixels (about 300 pixels).

The effect of this procedure would be to show an image of the baffle array were any location that reflected light back above the desired threshold was white and therefore susceptible to scattering light around the room and back into the incident collimated beam.

The next iteration of the image analysis was to take the grayscale images and combine them by overlaying the images on one another with the proper displacements to create the original spectacle. Then, whatever pixel had the maximum value (based on a 0-1 intensity spectrum) of the thirty values overlaying that one pixel, the final combined image uses that one maximum value for each pixel. This method allows for a more detailed look at the baffles and grants the ability to differentiate between two high-performing baffles or two low performing materials.

Result/Progress

While the process was long and labor-heavy, the results confirmed what we knew about the baffles and coatings. These five images are that of the five scans taken of the baffle array using the Nikon D40x camera and a green, collimated flashlight:



Further Work

The future of this project is to take the concept of a light detector and a light emitter and mount them to an XY stage in order to automate the scanning process and decrease the positioning errors as well as save man-power and time.

The total time to take the images manually was about 8 hours for a 3 inch by 15 inch combined image. The images processing time was shortened by decreasing the 255 different divisions of image brightness for the grayscale image to 30 different divisions which did not affect the visual analysis of the scan.

The next step for research is to use a single, divergent laser beam and a single image instead of a combined scan array of multiple images to determine what surfaces in the detector scatter the most light.
The chamber is 60 ft long, so the ideal situation would be to find a laser and a lens that would illuminate the diameter of the chamber almost perfectly as to encapsulate the whole area with light but also have the light intense enough to mimic (to a degree) the effect of high energy laser light reflecting and scattering on those surfaces.
A small experiment took place to determine the viability of this procedure. With a small red LED laser and an iris, the following images are taken of one of the aluminum baffle array sheets using this divergent beam: