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Methodology for Yield Determination of Surface Shots Over Water

J. D. Nguyen and G. D. Spriggs

Lawrence Livermore National Laboratory
Weapons and Complex Integration
Design Physics Division

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Disclaimer

Auspices Statement

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Abstract

Shockwave analysis is one of the few methods used to determine the yield of a nuclear detonation. It has been noted that the shockwave of surface shots over water are asymmetric. To calculate the yield of these shots using the 1-D, spherical model developed by Taylor, an equivalent radius of the elliptical shockwave must be determined. Armed with the digitized replicas of the original nuclear test films and the latest image processing tools, a methodology for segmenting the shockwave from the digitized film and measuring these shockwaves has been developed to quickly and accurately quantify the shape of these asymmetric shockwaves. With a two-dimensional result from these asymmetric shockwaves, several methods are discussed to transform the final shockwave contour to an equivalent radius that can be used to determine the yield.

Introduction

During the atmospheric testing era, 210 above-ground nuclear tests were performed by the United States of America. Each shot was extensively recorded with high-speed video and photographic equipment. Originally, the radius of the shockwave vs. time was measured using a Kodagraph. The Kodagraph projects and magnifies each frame of the film onto a circular grid. The operator must then try to center the film as best they can and measure the radius of the shockwave using a calibrated grid located on the base plate of the Kodograph. This measurement was done *by eye* and had the potential for human error. With over 10,000 films to analyze, it took a small army of people to analyze all the films over the duration of the atmospheric testing era.

Figure 1. Kodograph Device

Figure 2. An example of a frame of a film being projected onto the grid of a Kodograph.

The *Film Scanning and Re-Analysis Project* currently being performed at the Lawrence Livermore National Laboratory has digitized about 4200 films of these atmospheric test films to date. Armed with high-resolution digital images and the latest image processing technologies, an automated approach to quickly and accurately analyze these scientific films is currently being developed.

Methodology

Determining the contour of the shockwave from a noisy, scientific film yields an image binarization problem which can be broken down into three steps: preprocessing, segmentation, and postprocessing.

Image preprocessing involves gathering preliminary data from the original image in addition to applying several tranformations on the image to allow for better binarization when the image is thresholded in the next step.

The segmentation step comprises the main analysis algorithm to determine the best threshold value to degment the image into the shockwave and background.

Image postprocessing is the step after image binarization where the final shockwave shape is meaasured by fitting a shape to the final contour.

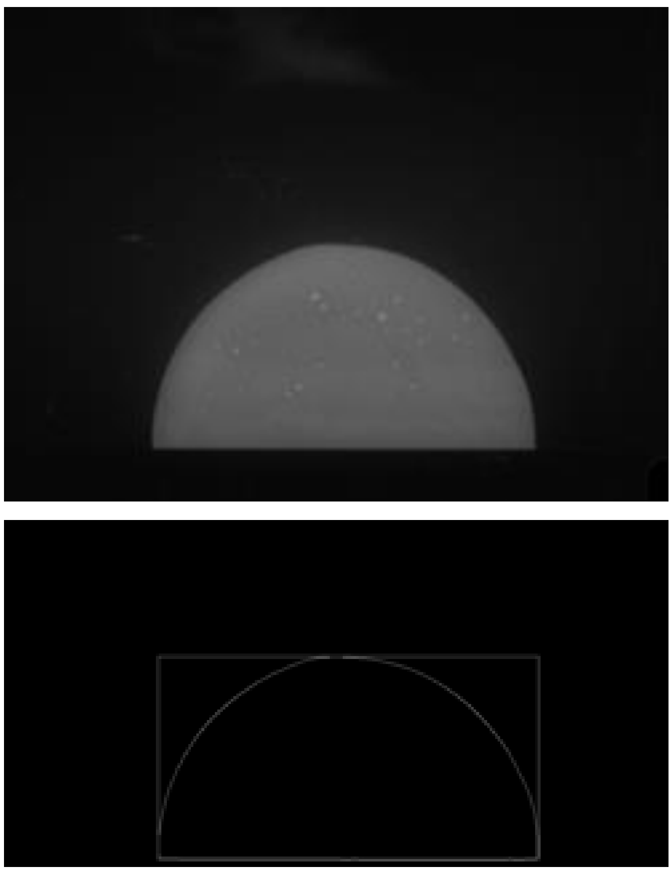

Figure 3. An original frame from a film with the resulting contour and bounding box fit.

Image Preprocessing

When segmenting an image, finding an appropriate threshold is of upmost importance. Preliminary analysis of several fireball films show that the early and late stages of the shockwave do not display a balanced bimodal distribution of the frame's optical density histogram. This unbalanced distribution will cause the algorithms used to find the minimum value between the peaks of the histogram to be skewed towards one peak over the other. This results in an over estimation in the shockwave's size when the threshold is biased towards the higher intensity light, or underestimated when the threshold is biased towards the lower intensity light.

Because of the rapid variation in the fireball light output, the film will usually be overexposed during the early stage of the shockwave and underexposed later in the shockwave evolution. Early in the shockwave evolution, when a majority of the thermal energy is concentrated in a small volume, an enormous amount of light is scattered in the air surrounding the fireball, thus creating a relatively large background light source. Later in the shockwave evolution, under exposure occurs when the temperature of the shockwave front drops below the Draper temperature (~800 Kevin) and the shockwave stops emitting visible light. To correct for these rapid changes, an automatic exposure adjustment loop was devised to correct the exposure of these images. This correction method redistributed the optical densities in the histogram back into a balanced bimodal distribution and increased the separation region in the frame's waveform.

Many image processing programs use a Bezier curve to generate an interpolated redistribution function within the color space of the original image to adjust the exposure. This function creates a lookup table which maps each pixel value of the original image to a different value. The same adjustment method has been implemented in this application. After analyzing the exposure trends of several films as the fireball evolves, we found that the following points generally held true.

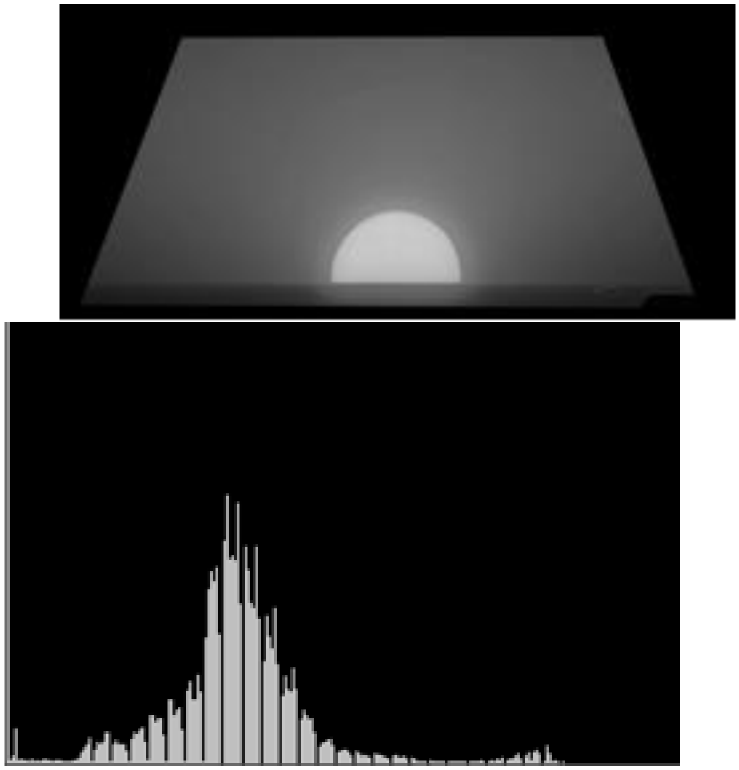

Figure 4. An over-exposed frame with accompanying histogram. The small peak on the far right is the shockwave.

In the first 3 to 8 frames of the detonation, the image is heavily over exposed. The histogram of the over exposed image exhibits more of an edge peak distribution rather than a bimodal one. This is the result of the shockwave and fireball representing only a small portion of the entire frame and the glare in the background creating a smooth buffer between the two 'peaks' and making the appearance of the shockwave peak seem irrelevant with respect to the entire histogram. This can usually be corrected by an exposure curve where the exposure curves fall in the following regions.

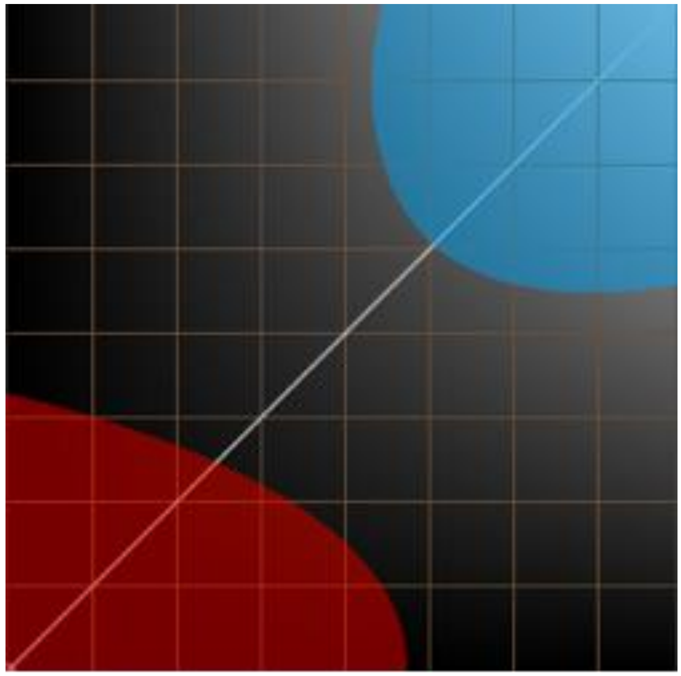

Figure 5. Bezier Curve control point search space for over exposed frames.

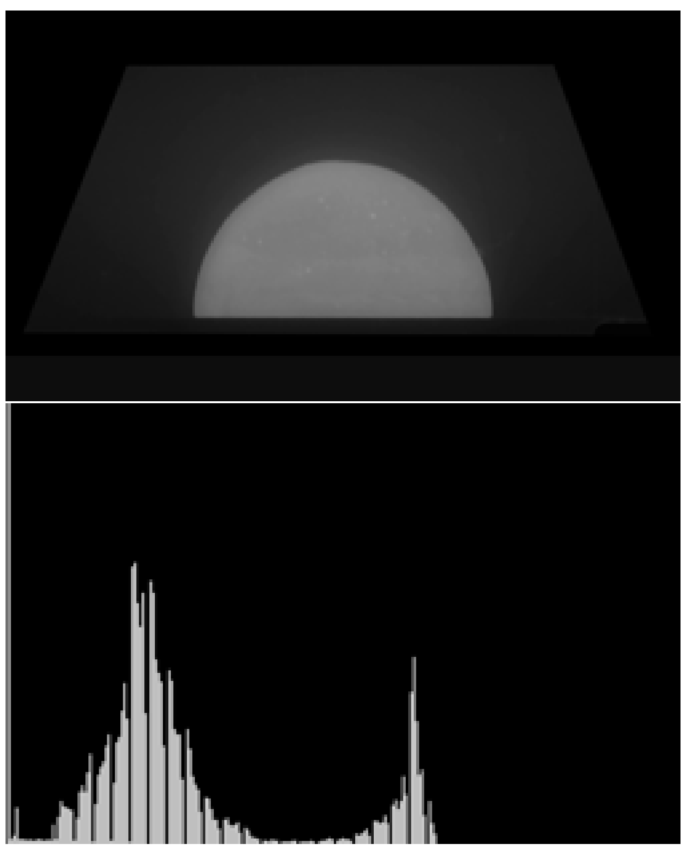

Figure 6. A frame with good exposure.

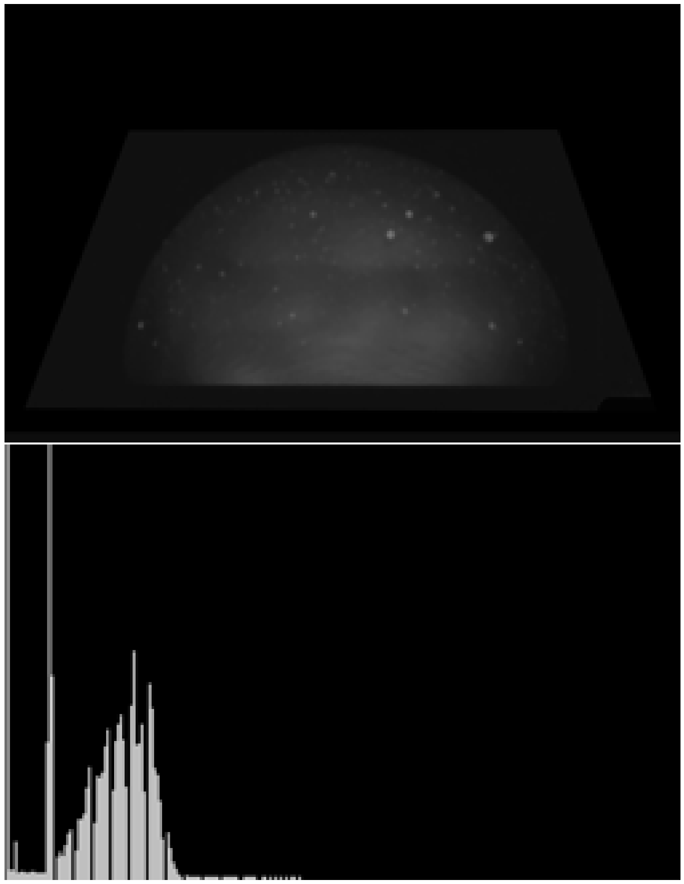

Figure 7. An under-exposed frame. The narrow sharp peak represents the background pixel values.

The frames after the period of extremely high light output has good exposure if the film sensitivity is nominal. The image is crisp and details of the shockwave are clear. The edge between the shockwave and background is extremely well defined. No correction is necessary.

The last 40 or so frames until slightly after t_{min} have extremely under exposed images. The histogram for these frames resemble an edge peak distribution like the under exposed frame, but on the opposite side. Since everything is cooling down, a very sharp peak is formed for all the dark areas of the film and the peak that represents the fireball and shockwave starts to plateau. The separation between the two peaks is not great either. Getting the exposure correct here is important as the data from capturing the separation of the shockwave from the luminous fireball is extremely important. Capturing this separation is difficult because the image processing algorithms used must be very sensitive to subtle gradients in the light intensity without being disturbed by the noisy luminous fireball. We found that a strong exposure adjustment method is the only way to fix this problem as histogram and waveform analysis cannot consistently find the correct peaks to segment the image due to the distraction of the bright spots in the luminous fireball.

Keeping that in mind, several LUT presets have been experimentally generated which linearly interpolate the values of the Bezier curve's control points to control the exposure of the image over time. While exposure adjustment is usually only required in the early and late stages of the detonation, between the frame of first light, and t_{min}, the automatic exposure adjustment will automatically kick in and re-run the entire image processing pipeline if we detect an issue while processing the frame allowing for additional flexibility in the image processing pipeline. Now, assuming the exposure of all the frames is properly adjusted, a preliminary binarization of the image can be performed.

Initially, when writing the image processing application, it was noted that the image's histogram and waveform had a distinct separation region showing the interface between the fireball and the background. Exploiting this phenomenon allows us to define a region of the frame and a range of light intensities that the shockwave front must lie. In turn, we can also define regions we know are just the background or fireball. We are only concerned with finding a threshold value which segments the interface region between the shockwave and the background, so first labeling these regions of the frame will allow us to cut out the areas that we are not interested in, leaving only the data that is vital to finding the threshold value.

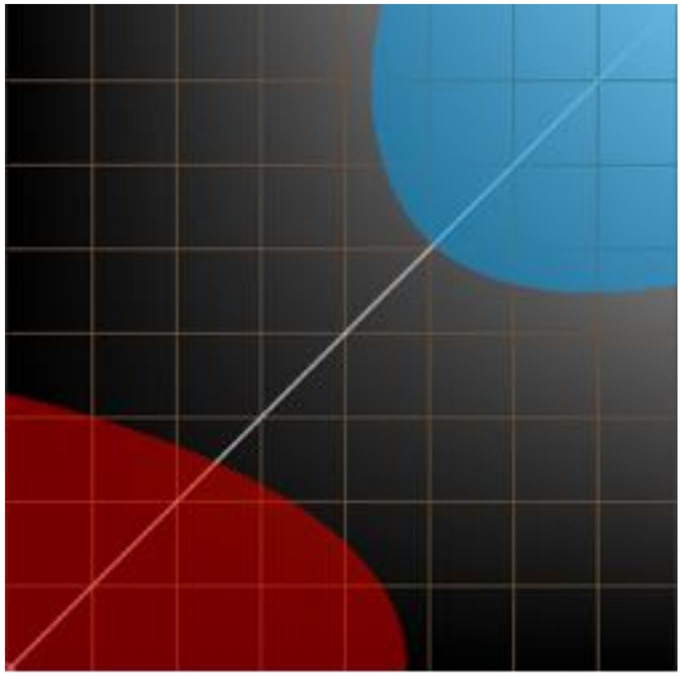

Figure 8. Bezier curve control point search space for under exposed frames.

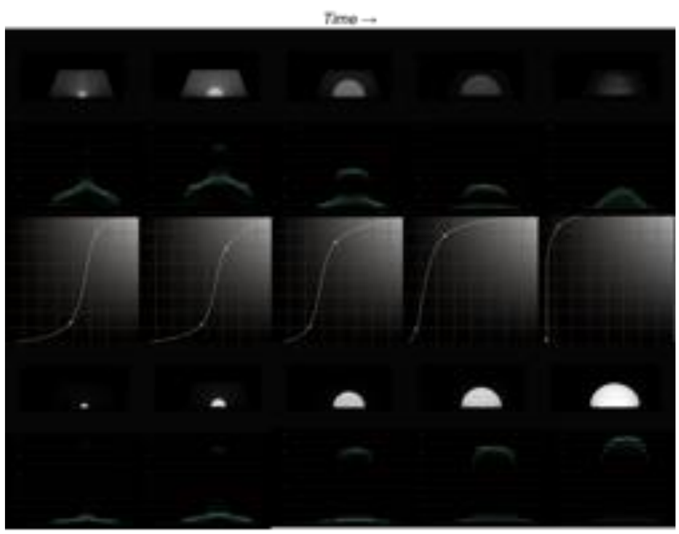

Figure 9. Result of the exposure adjustment. The top row is the original image, the second row is the waveform for each original image, and the third row is the Bezier curve applied to the image. The fourth row is the image with the adjusted exposure. The fifth row is the resulting waveform.

When first approaching this problem of finding the preliminary threshold value, we used only Ostu's Method to find the threshold. Otsu's thresholding algorithm minimizes the intra-class variance of peaks in the histogram, giving us a good value if the image's histogram was clearly bimodal. Since histograms show the light distribution of the entire frame, the histogram values (especially those at the peaks) ignore the spatial aspect of how these values were derived. That is, areas of similar light intensity may appear in unrelated locations in the image, but still contribute to the same histogram value. This introduces noise in our histogram in the form of unintended peaks. This sometimes leads Otsu's algorithm to segment the image in the valley between the peaks that are not representative of the light intensity values of the background or shockwave.

The film analysis application finds a preliminary threshold value by analyzing the waveforms of the image. Waveforms show the light distribution of each column of the image, relating spacial data to light intensity values. By generating a waveform of the frame in both axes, we effectively double our light intensity resolution by being able to analyze two different distributions of it. By running a K-Means Clustering algorithm on the two waveforms, we can breakdown the high-density areas of the waveform into a set of well-defined points which describe the general shape of the of the waveform.

Finding the maximum gradient of the light intensity for these sets of points we can get the two cluster points which represent the edges surrounding the low-density region separating the fireball and shockwave's light intensities from the background's. We then take the arithmetic average of these points to get our primary threshold value.

After thresholding the image with this preliminary value, we then dilate and erode the fireball shape to create a map of the original image. This image map defines the eroded shape as the area we are certain is the fireball, and the dilated shape that we are certain is only background. The difference in these areas define the region of the frame we are certain the shockwave lies in.

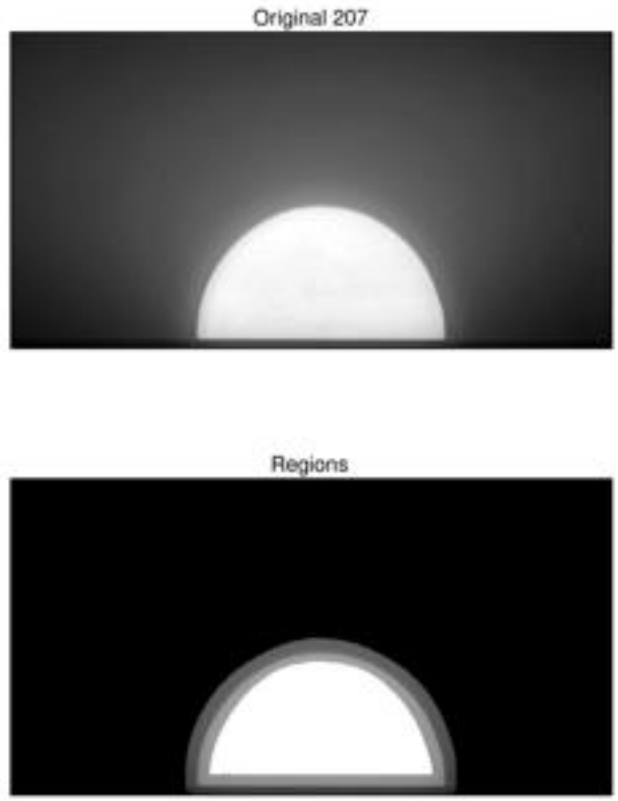

Figure 10. Before and after of the image preprocessing step. See how we set the regions we know is the background as pure black and the region we know is the fireball as pure white.

The waveform analysis algorithm described here can be represented by the following formulation:

$$\lambda_{W(x_i,\lambda_j)} = \arg\max_{\lambda} \left| \frac{\delta}{\delta\lambda}\big(W(x,\lambda)\big) \right| \qquad (1)$$

$$\text{Threshold} = \frac{\lambda_{W(x_i,\lambda_j)} + \lambda_{W(x_i,\lambda_{j+1})}}{2};\left\{ \lambda_j \geq \lambda_{j+1} \right\} \qquad (2)$$

where lambda is light intensity, *W* is the set of points from K-Means clustering approximating the waveform which returns the number of pixels for a particular coordinate *x* and a light value, and *i* and *j* are the indexes of the corresponding value in the set.

With a map of the original image depicting the various regions of the image, we can begin the main segmentation method which will fine tune the edge of our preliminary shockwave. We first generate a histogram of the image with the background marked with a value of 0 and the fireball region marked with a value of 255. By analyzing the histogram with only values from 1 to 254, we effectively remove the noise of the areas that we are less concerned with, that is, the background and the fireball itself.

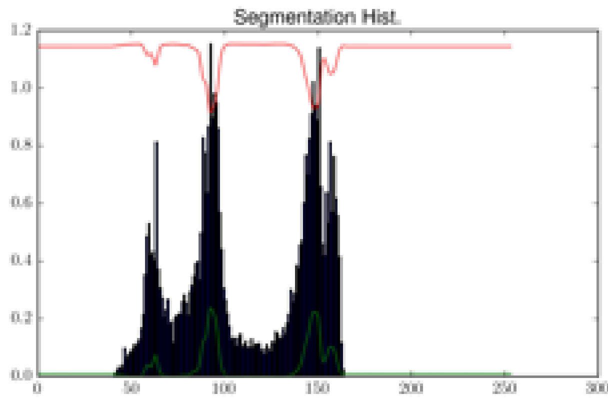

Figure 11. Example of a histogram

This leaves us with only the histogram depicting the distribution of light intensities at the interface region between the background and the shockwave. We then use Kernel Density Estimation to generate a smooth function representing the histogram. Knowing the edge values describing the background and fireball from the waveform analysis performed in the previous step, we will then run a peak detector on the smoothed function to find the high density light intensities of the interface region. Two very distinct peaks should be present which correspond to the edge points found earlier. Selecting the two largest peaks (one representing the majority of background colored pixels and the other fireball), we use Otsu's Thresholding Algorithm to segment the histogram between the two peaks. This gives us a threshold value with maximum inter-class variance. Thresholding the image with this value yields an image segmenting the fireball and shockwave from the background. A canny edge detector is applied to the image to get just the shockwave edge.

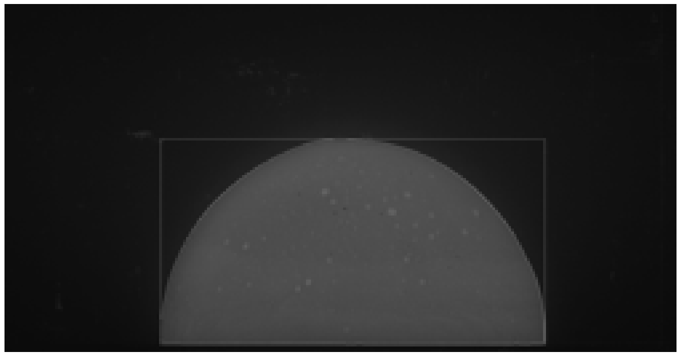

Figure 12. Fit using a bounding box. The height and half the width of the box represent the shockwave's radii.

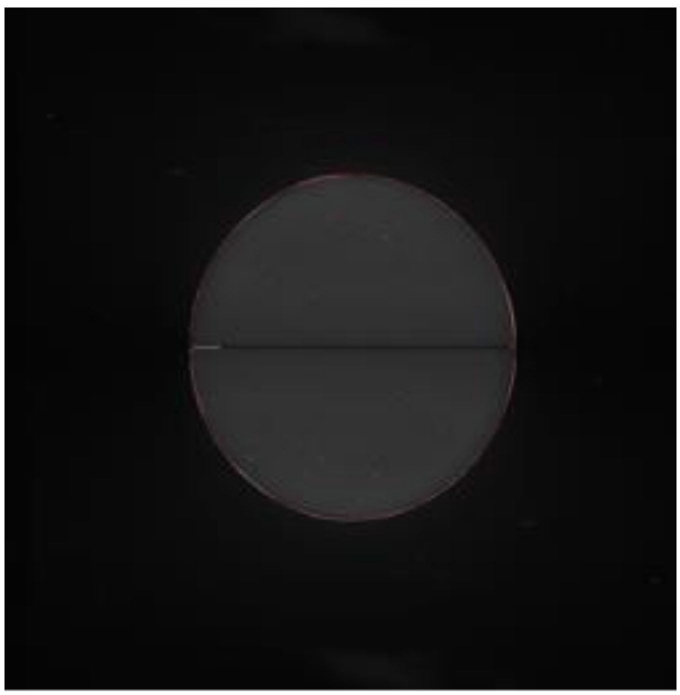

Figure 13. Fit using an ellipse. The ellipse fitting package suppliied by OpenCV can only fit a whole ellipse so we mirror the shockwave over its bottom edge. The ellipse's major and minor radii are used to describe the dimensions of the shockwave.

After getting the final shockwave edge, the final conversion of the shape to a contour and error checking can be performed. For the majority of films, it has been found that a simple bounding box will quantify the dimensions of the shockwave cross section just fine. In the cases where a more advanced fit is required, fitting an ellipse can also be done. To check the results of our dimension for the final contour, we will measure some of the digitized films by hand using a ruler tool on the computer.

Yield Determination

The most widely used method for yield determination utilizing shockwave radius revolves around Taylor's Equation[1].

$$R = \frac{1}{2}\left(\frac{\theta Y_{sw}}{\rho_0 K}\right)^{1/5} t^{\frac{2}{5}} \qquad (3)$$

This equation assumes spherical shockwaves. So, a method for reducing our two-dimensional measurement (a vertical and horizontal radius) to a one dimensional value is required. We will try two methods. One method is using a simple arithmetic average of the two radii. The other method assumes the shockwave contour is symmetrical and uses the radius of a sphere of equivalent volume to our ellipsoidal shockwave.

$$\frac{4}{3}\pi\bar{r}^3 = \frac{4}{3}\pi abc;\ a = b \qquad (4)$$

$$\bar{r} = \sqrt[3]{a^2 c} \qquad (5)$$

To check the validity of our measurements, the contour dimensions were compared to the original EG&G measurements made in the 60s.

Results

Over the duration of this project, 50 fireball films were analyzed by the image processing application. The only human inputs were a listing the frame-of-first-light (FFL) and setting cropping bounds for the image. For the various films that didn't have the FFL listed, the 40th-600th frames were analyzed as that was the original target range for which the shockwave was to be recorded. For films without the shockwave area cropped out, an arbitrary 400 pixels were cropped from the left and right edge of the image to remove the film perforations which would interfere with the analysis of the shockwave.

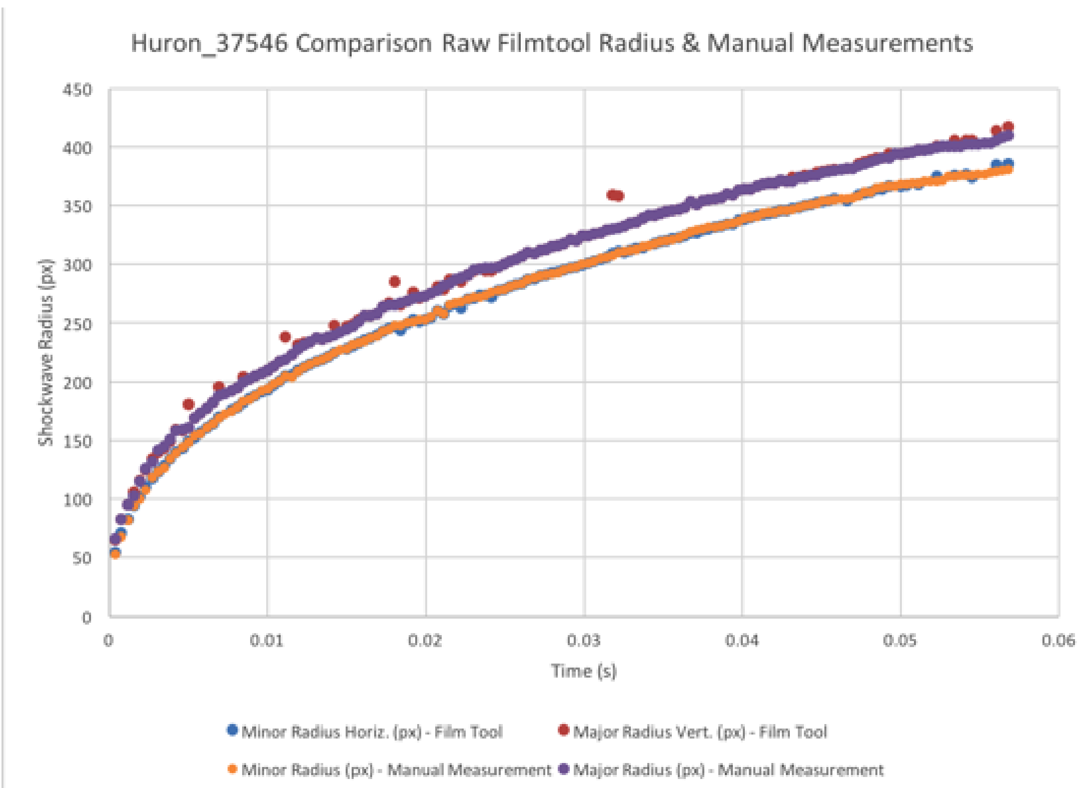

Figure 14. Results obtained using new tool.

Taking a look at the results for shot Huron film number 37546 as an example, the film analysis tool captures the growth of the shockwave quite well. Compared to the measurements made by hand, the film analysis tool result is a close fit. We can see some of the obvious thresholding errors in some of the data from the film analysis tool on the major radius. With so few erroneous data points and the margin of error, the yield calculation should be changed very little since the final radius value derived from the data is averaged twice--once when reducing the measurement dimension and a second time when the reduced radius is averaged. While we don't have a real benchmark to test the film tool results against besides the subjective measurements we made by hand, we can see that the film tool seems to estimate larger radii throughout the film compared to the measurements made by hand.

We will discuss the results of our yield determination methods by looking at the data from shot Maple film number 52184 as an example.

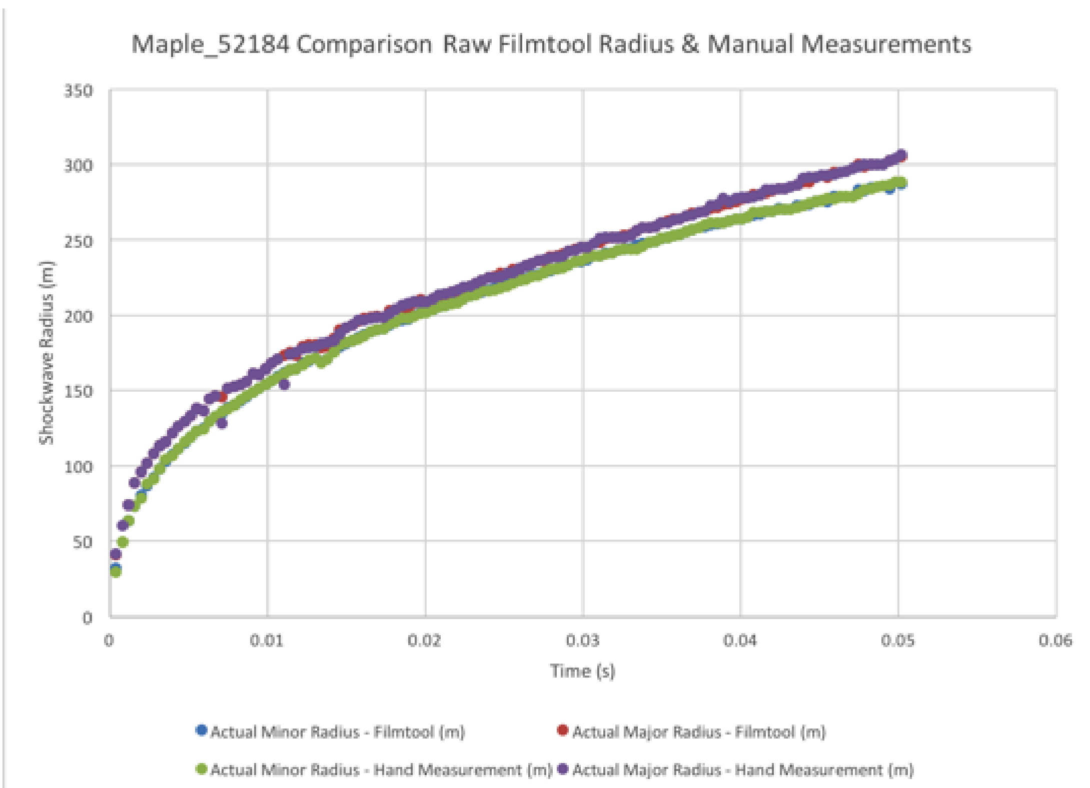

Figure 15.

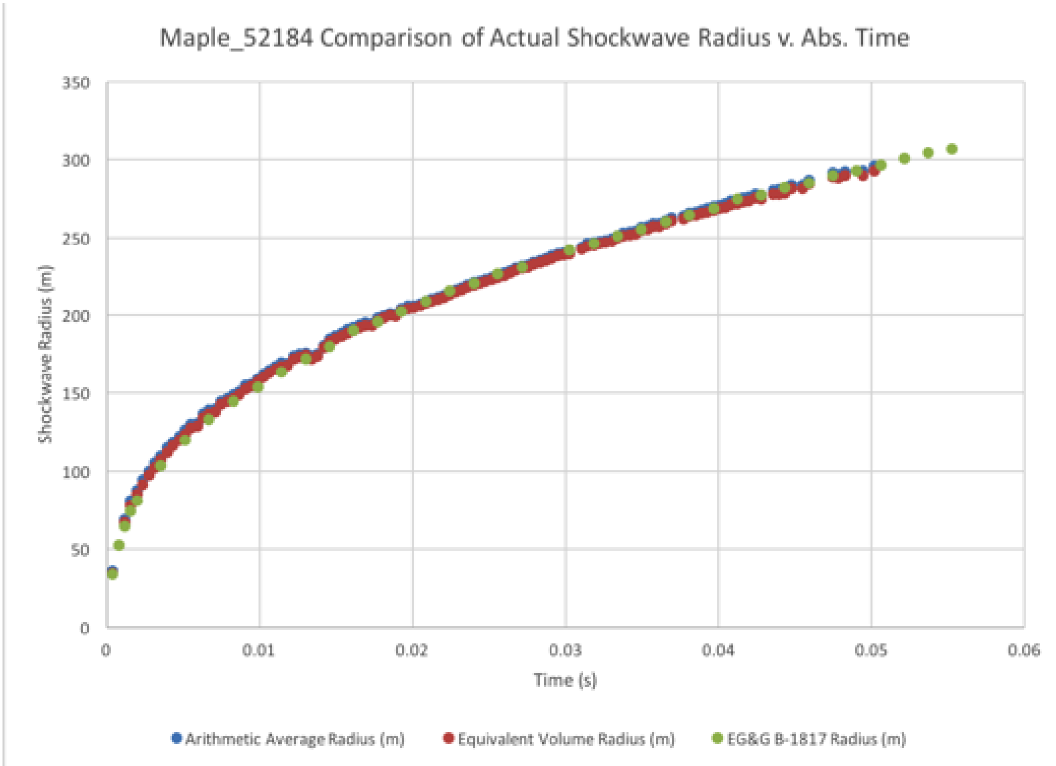

Figure 16.

Comparing our averaged radius methods to EG&G's original data:

Comparison of Average Radius Methods		
	Arithmetic Average Radius	Equivalent Volume Radius
Comparison to EG&G Radius	2.15%	1.40%

While the change does not seem like much, we must keep in mind that Taylor's equation is proportional to the volume of the shockwave at a given reference time, not the radius. Any error in the radius will result in a five-fold increase in error for the yield.

Analyzing the plots for this film, it seems like the EG&G data underestimates the radius early in the detonation and overestimates the radius later in the film. This trend generally holds true across the films analyzed thus far. Comparing the arithmetic average and equivalent volume sphere methods shows a pretty similar fit, but the average radius method is slightly larger throughout the shockwave evolution and the difference is even more pronounced towards the end of the film where separation between the shockwave and luminous fireball occurs.

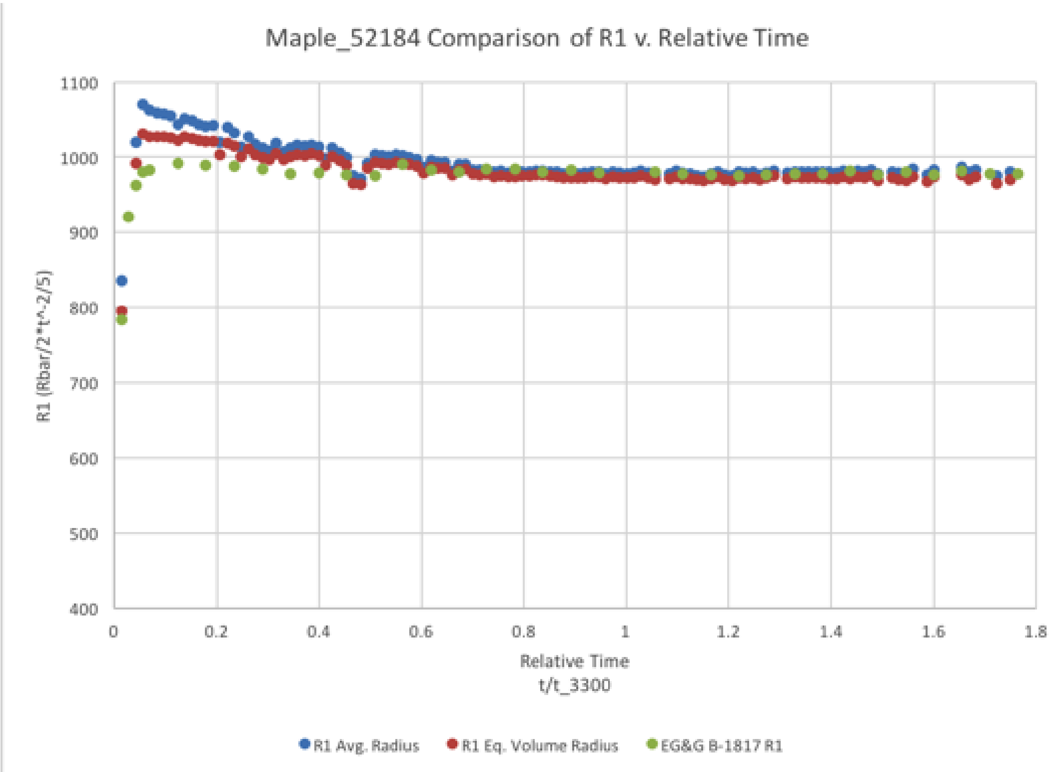

Figure 17.

Comparing the R1 values of each dataset helps us visualize the variable that is directly related (fifth-order relation) to the absolute yield of the nuclear weapon. We know that Taylor's equation is only valid for a certain interval on the relative time scale (~1 to ~2 relative time). Analyzing the data points in this interval seems to show good agreement between all of the datasets. Additionally, we should see the R1 values converge in this region which they do.

Keep in mind that the method of determining yield we are using is modified with more recent models compared to the method EG&G used at the time they analyzed these films. Calculating the corresponding R1 value from EG&G original yield returns a value of 991.3. Note that the reanalyzed EG&G R1 is still based on EG&G's original data. Using the reanalyzed EG&G yield as our control, it is clear that the radius from an equivalent volume sphere is the better method for yield determination of these asymmetric surface shots over water.

Comparison of Averaged R1 Values				
	EG&G Original	EG&G Reanalyzed	Arithmetic Ave	Equivalent Volume
	991.326	970.552	979.293	972.018
Comparison to original EG&G R1	-	2.10%	1.21%	1.95%
Comparison to Reanalyzed EG&G R1	2.10%	-	0.90%	0.15%

Computing the yields of the shockwaves for each dataset gives us the following results:

Comparison of Computed Yields				
	EG&G Original	EG&G Reanalyzed	Arithmetic Average	Equivalent Volume
Absolute Yield (KT)	215	193.4	202.3	194.8
Comparison to original EG&G Yield	-	10.05%	5.91%	9.40%
Comparison to reanalyzed EG&G Yield	10.05%	-	4.60%	0.79%

Discussion

The film analysis code developed during this study accomplished the primary goal, which was to get the contour of the shockwave for a film and get the dimensions of that contour automatically. The tool has been run on a small sample of the large collection of digitized films, but with further tweaking, a more accurate dataset of shockwave radii can be generated for each digitized film. The more accurate benchmark data to be used in the creation of more accurate 1D, 2D, or even 3D shockwave simulation codes.

With many digitized films left to analyze, the film analysis code is still experimental and will require many improvements before it is ready for production scale analysis of the remaining films. One improvement that need implementation is a GUI which allows greater flexibility to change some of the algorithm's variables on the fly as the film is analyzed in addition to checking for any errors. Some parameters that should be on this GUI would be setting the control points of the Bezier curve when adjusting the exposure of the image or setting a bias on the threshold value which segments the image. Another improvement that is necessary is the implementation of smarter exposure adjustment. Currently only linear interpolation of the Bezier curve's control points is implemented which is restricting an extremely large search space which better exposure for an image may exist.

Smarter exposure adjustment using algorithms like gradient descent to minimize inter-class variance (in turn boosting the bimodal distribution) of histogram peaks to clarify the edge region between the shockwave and background can increase the accuracy of the final contour and make the tool more flexible when analyzing films with more extreme noise and exposure.

Additionally, more feedback in each step of the image analysis pipeline should be implemented to reduce errors when segmenting the image.

Finally, the parameters of each algorithm used in this tool should be calibrated more carefully to increase the sensitivity of the application. This can allow for the tool to not only segment the shockwave and fireball from the background, but segment other obstacles such as clouds, ships, etc. from the image as well.

The methods described here should provide a suitable starting point to begin the deeper investigation of the shockwave asymmetry and its relation to the weapon's yield. It is clear that a new shockwave model which takes into account the shockwave contour is necessary to increase the accuracy of the yields determined by shockwave analysis. With the existing models and equations, we know that using the radius of an equivalent volume sphere for our average radius will work best to determine the yield.

Future Research

It is clear that further research needs to be put into both the film analysis algorithms and the yield determination techniques described in this paper. In addition, this research can also lead to interesting research into entrainment effects of the shockwave as it travels over the water's surface and 3-D modeling of the shockwave's contour using the contour of the shockwave composited from multiple camera angles. Additionally, novel research can be put into developing more accurate models of shockwave propagation which take this asymmetry into account and how it relates to yield.

References

[1] Taylor, G. (1950). The Formation of a Blast Wave by a Very Intense Explosion. I. Theoretical Discussion. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Volume* 201, No. 1065, pp. 159 – 174.

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