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**Title:** Calculation of Velocities from Explosive Shot Test Fast-Frame Imagery


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# Calculation of Velocities from Explosive Shot Test Fast-Frame Imagery

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LA-UR-24-XXXXX

# Goals

- A cylinder of the experimental HE is detonated inside of an aquarium and sequential fast-frame images are taken of the resulting shock wave.
- We wish to use the sequence of images to extract quantitative data regarding the detonation velocity and velocity of the shock wave which can then be used to tune the parameters of the equation of state for the experimental HE material.

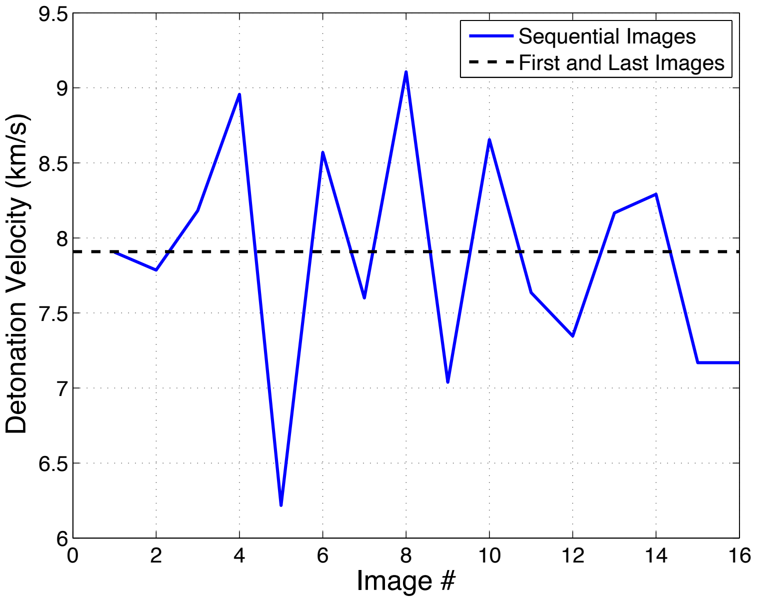
# Experimental Details

- We are looking at the aquarium shot from 10/18/2012 as the imagery was particularly good from this test.
- The HE cylinder measured 2 inches in diameter and was 9 inches long.
- The time between images for this test was 1.625 μs.

# Fast-Frame Imagery Animation

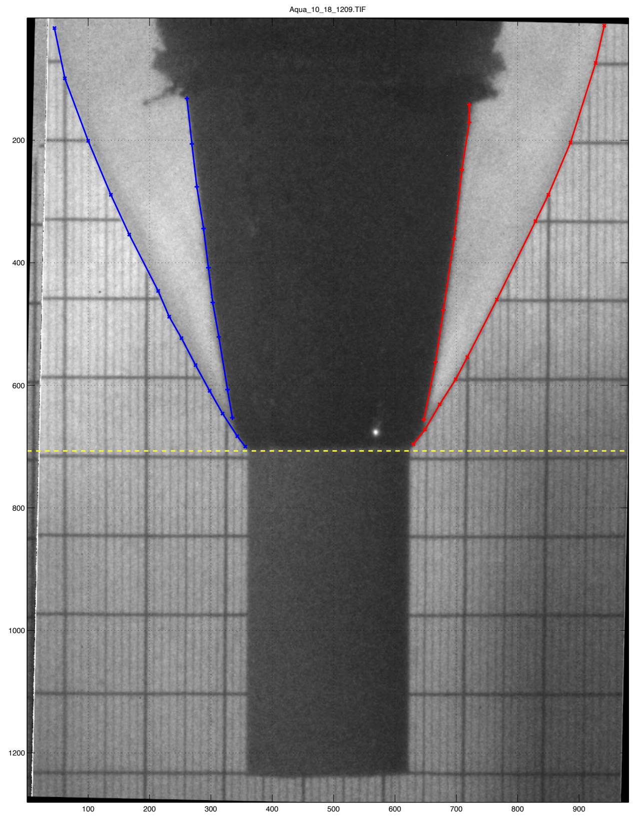
# Detonation Velocity – Aquarium Test

- Using a simple difference in undetonated length of the HE cylinder between sequential images we get the blue line in the plot of detonation velocity to the right.
- The variation of detonation velocity using this method is non-physical (if it were otherwise there would be evidence of it in the shape of the shock wave). It is instead due to errors in the measurement of the length of undetonated material and possibly the elapsed time between sequential images.
- Since the detonation process ideally occurs at a constant rate, measuring the detonation velocity over the entire shot will provide a much more accurate value of 7.908 km/s.



# Shock and Product Gas Profiles

- The shock and product gas profiles are derived from data points that are graphically defined by the user in the GUI.
- A third order polynomial fit of these data points is then used for analysis.
- Note that the shock surface produces a magnification effect due to the difference in the index of refraction between the shock and the surrounding water.
- The profile of the product gases must be corrected in order to get an accurate estimate of the velocities.

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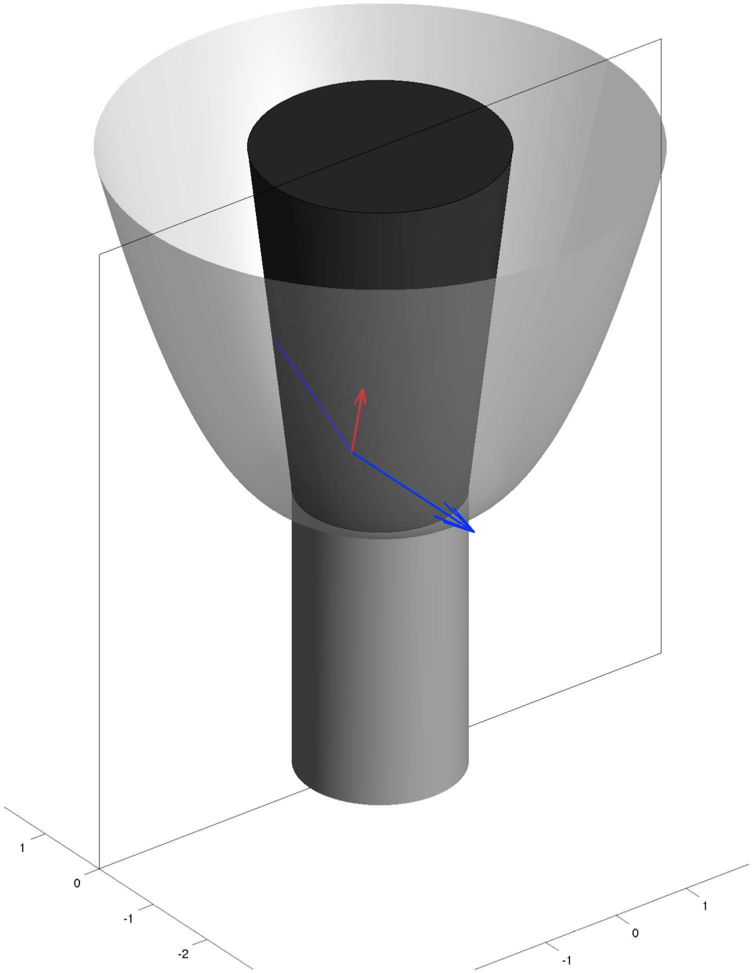
# Correcting for Refraction of Light in the Shock

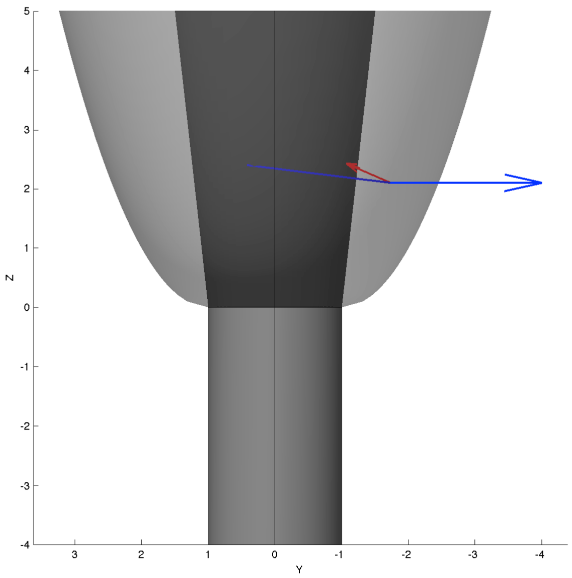
- The profile as seen in the 2D fast-frame image is distorted in all three dimensions due to the light passing through the 3D shock surface.
- The diagram to the right shows a ray of light (shown in blue) emitted from the back face of the product gas surface will be bent as it comes into contact with the shock surface to give a false impression of both the axial and radial positions of the profile.
- This explains the apparent sudden expansion of product gases near the detonation front in the fast-frame images.
- The relative angle between the ray and the surface normal vector (shown in red) will follow Snell's law:

$$n_1 sin(\theta_1) = n_2 sin(\theta_2)$$

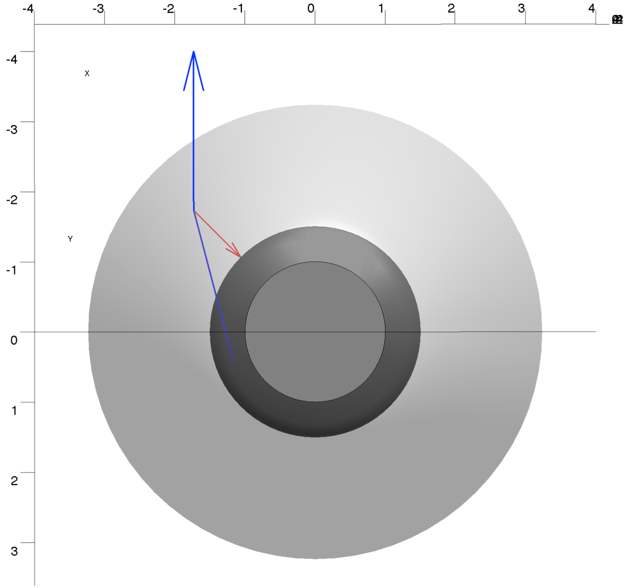


# 3D Nature of Refraction

Side View




Bottom View




Position of any point in the product gas profile is distorted in z, r, and θ.

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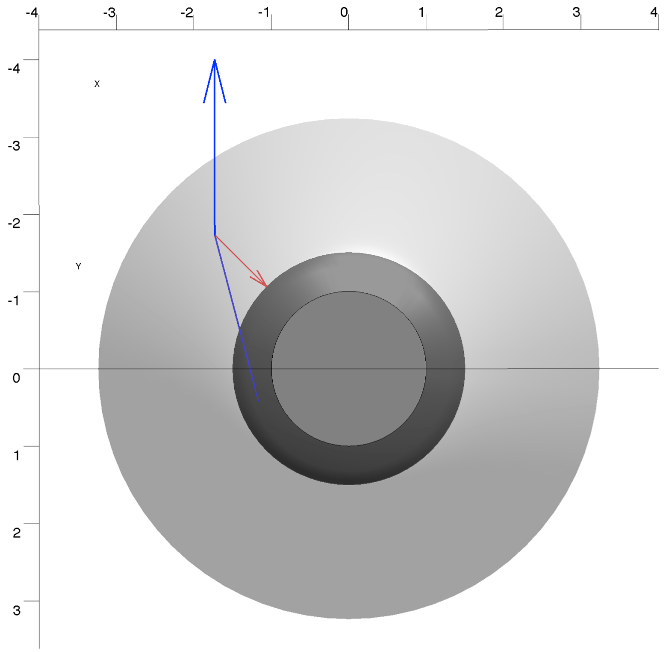
# Procedure for Correcting for Refraction

- Find the angle θ where the point on the profile intersects the shock surface:

$$\theta = \arccos\left(\frac{r_p(z)}{r(z)}\right)$$

- Now to simplify the calculation, convert the surface normal unit vector in the plane of the image into Cartesian coordinates and rotate it around the cylinder axis to find the local surface normal unit vector at the point of intersection.
- To simplify the refraction correction we also assume that the light is effectively parallel when it arrives at the camera, i.e., that it leaves the shock surface in a direction normal to the plane of the image.
- We then employ Heckbert's 3D refraction method to find the direction where the ray originated.



# Heckbert's 3D Refraction Method

- Glassner, A. S. (Editor), 1989: An Introduction to Ray Tracing. Morgan Kaufmann, San Francisco, CA, USA, 327p.
- N is 3D surface normal unit vector.
- I is the 3D unit vector of the incident ray.
- T is the 3D unit vector of the transmitted ray.
- The indices of refraction are $n_1$ and $n_2$.

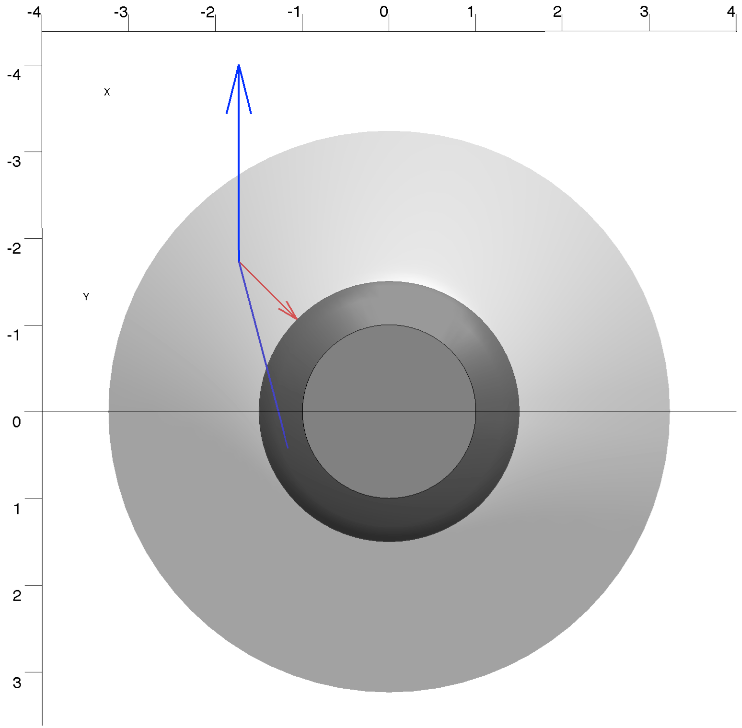
$$\eta = \frac{n_1}{n_2} \qquad C_1 = -\vec{I} \bullet \vec{N} \qquad C_{S2} = 1 - \eta^2 \left(1 - C_1^2\right)$$

- If $C_{s2}$ is less than 0 then there is total internal reflection. Otherwise a portion of the ray will be reflected and the rest will be refracted and transmitted into the material. We are only interested in the direction of refraction.

$$\vec{T} = \frac{\eta\vec{I} + \left(\eta C_1 - \sqrt{C_{s2}}\right)\vec{N}}{\left|\eta\vec{I} + \left(\eta C_1 - \sqrt{C_{s2}}\right)\vec{N}\right|}$$

# Procedure for Correcting for Refraction

- Note 1: While the diagrams show the direction that the light travels in reality (out toward the observer), the algorithm solves the problem in reverse starting with an incident ray perpendicular to the image and an outward surface normal vector.
- Note 2: In order to reduce the computational cost of this procedure we only correct the user defined product gas data points. The rest of the analyses on the product gases are performed using the corrected user data.
- Once we have the direction of the transmitted vector we can solve for the radial component by determining the minimum distance between two lines: the transmitted ray and the cylinder axis.



# Finding the Minimum Distance between Two Lines

- T is the transmitted ray direction unit vector.
- Z is the z axis unit vector.
- P is the point of incidence position vector.
- O is the origin position vector.
- First find the common perpendicular direction vector (C) by taking the cross product of T and Z:

$$\vec{C} = \frac{\vec{T} \times \vec{Z}}{\left|\vec{T} \times \vec{Z}\right|}$$

- Then determine the direction vector (D) between the two reference points:

$$\vec{D} = \vec{P} - \vec{O}$$

- Finally the minimum distance (r) between the lines is simply:

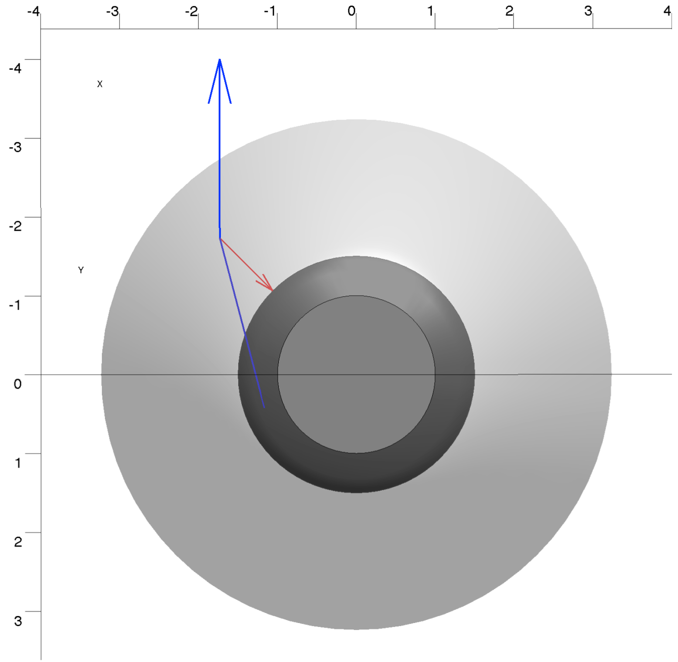
$$r = \vec{C} \bullet \vec{D}$$

# Procedure for Correcting for Refraction

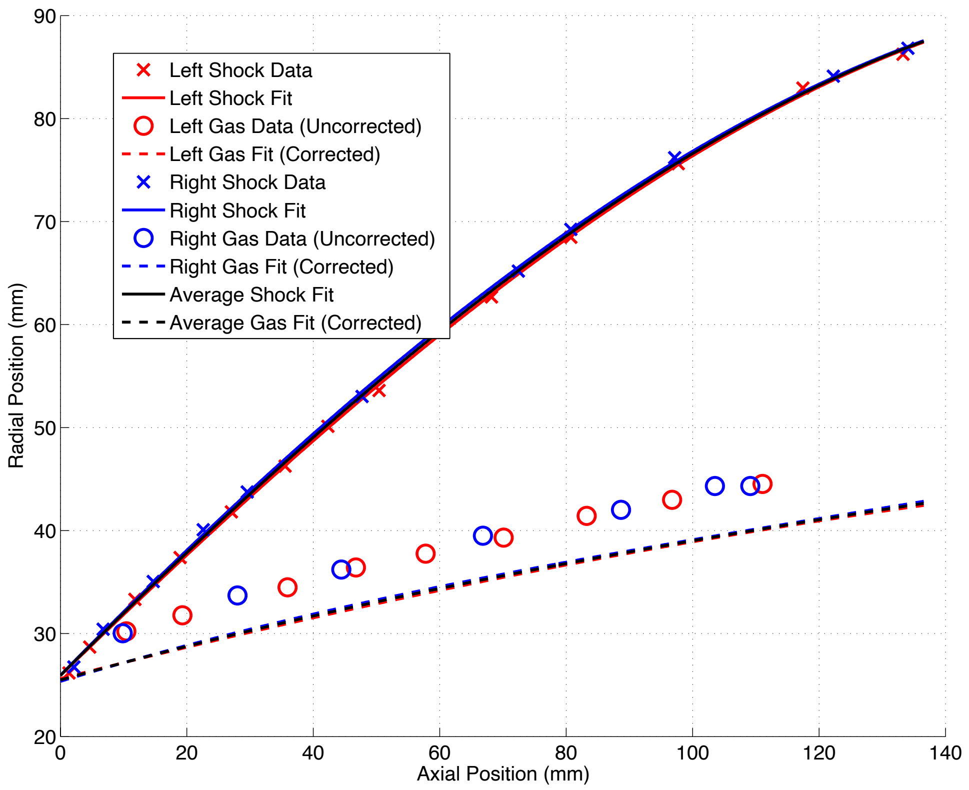
- Finally, once the corrected radial position of the point is known, we can solve for the corrected axial position of the point of interest.
- Start with the vector definition of the transmitted line (L) starting at the point of incidence:

$$\vec{L} = \vec{P} + S\vec{T}$$

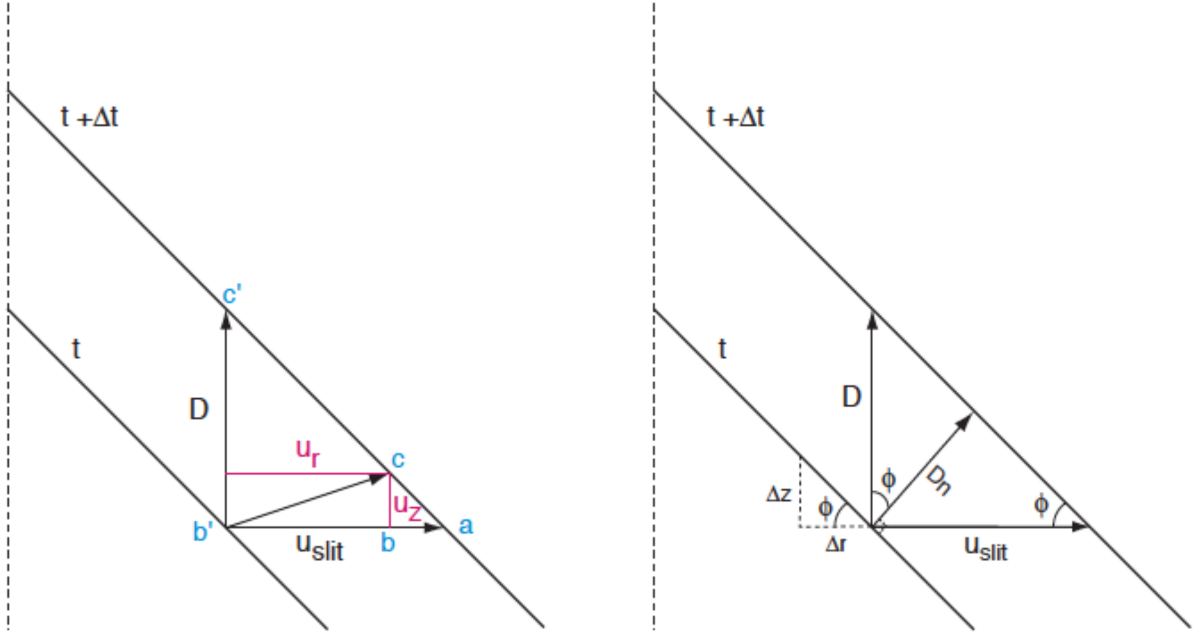
- The axial position is found iteratively by solving for the distance (S) along the line that will produce a radial position equal to the minimum distance (r).
- Once we have found S then we can solve for the corrected axial position (z) by using the axial component of L.



# Shock and Product Gas Profile Results



# Slit Velocity Calculation




Menikoff, R., Scovel, C. A., and Shaw, M. S., 2013: Cylinder Test Wall Velocity: Experimental and Simulated Data

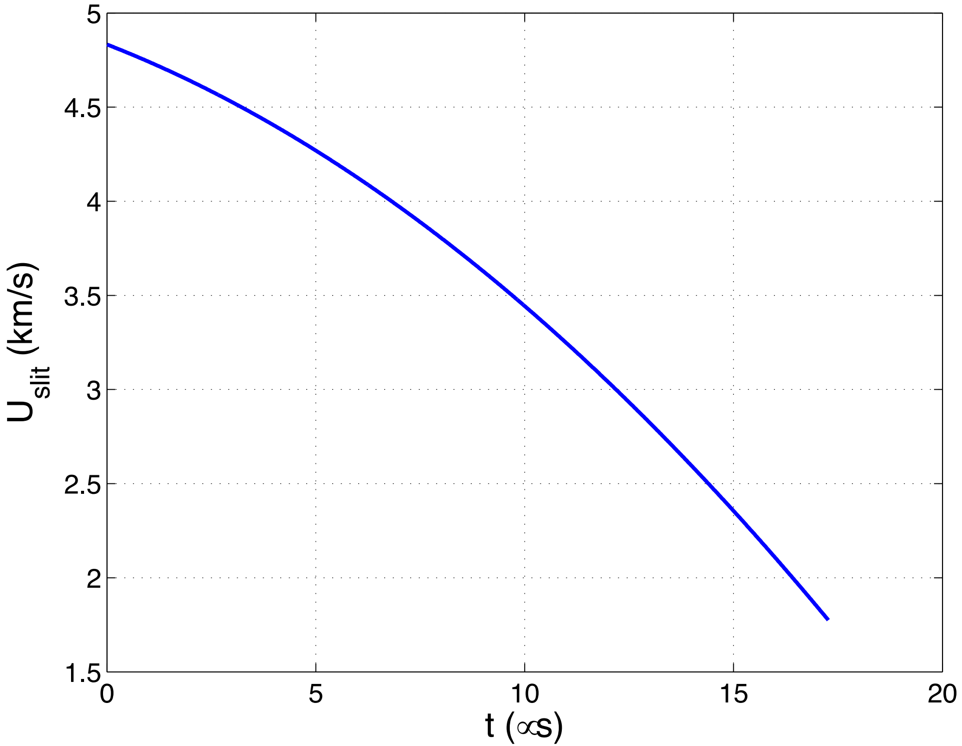
# Slit Velocity Calculation

- From Menikoff et al. 2013 the slit velocity (i.e., the rate of radial expansion of the wall of a cylinder at a given axial position) can be calculated by using the detonation velocity (D) in the following relation:

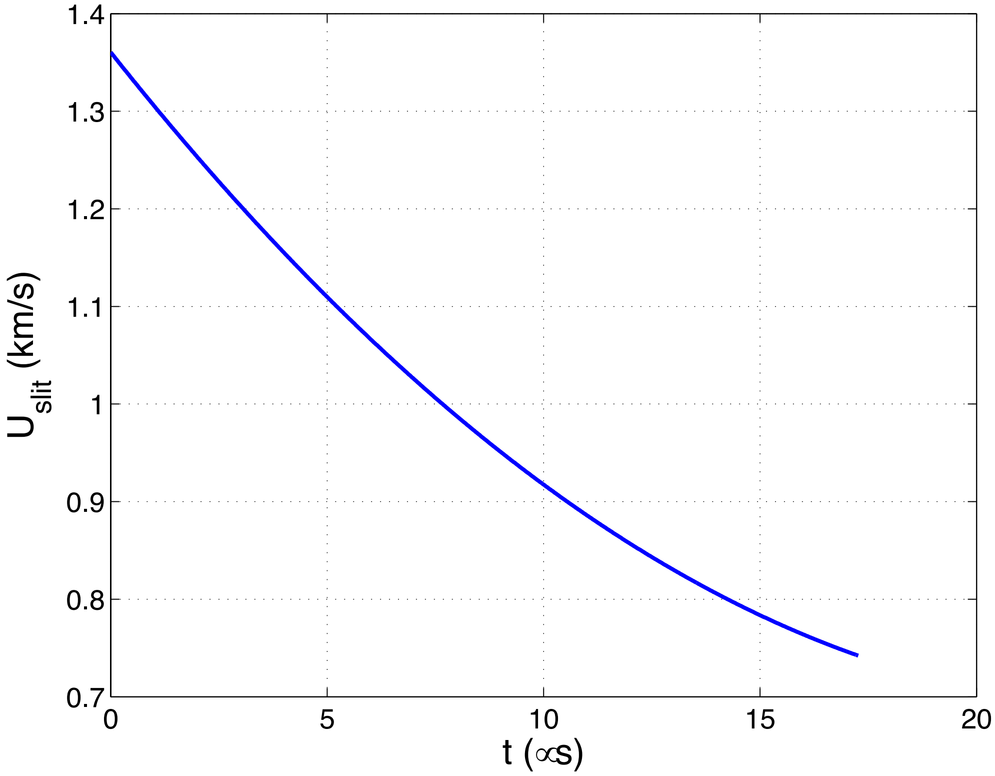
$$u_{slit} = \left| \frac{dr_{wall}}{dz_{wall}} \right| D$$

- We find r(z) using a third order polynomial fit to the user defined data. The derivative of r with respect to z is found by taking the derivative of the polynomial fit.
- This allows us to find $u_{slit}$ as a function of axial distance from the detonation front.
- We then use the assumption of steady state reaction to determine $u_{slit}$ as a function of time by dividing the axial distance by D.

# Slit Velocity Results for Shock Profile



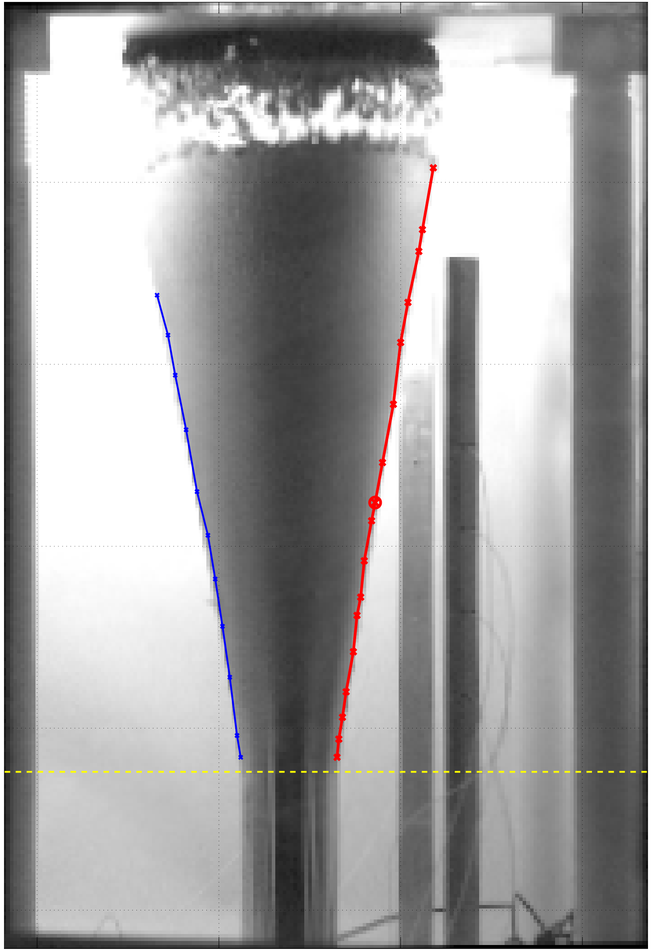
# Slit Velocity Results for Gas Profile



# Cylinder Test

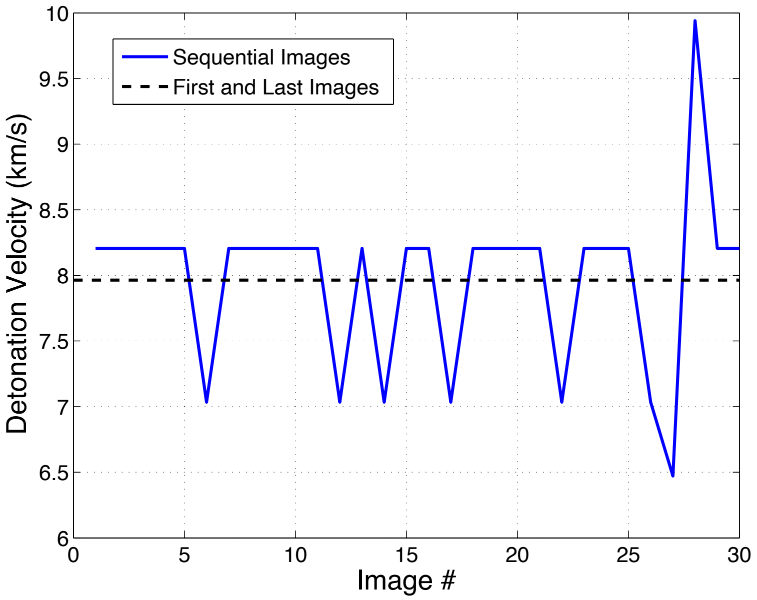
# Cylinder Test Shock Profiles

- Performed using a 1” diameter HE stick contained within a copper tube with a 0.1” wall thickness.
- Camera Resolution is much more coarse than aquarium test causing more relative error in graphical position estimates.

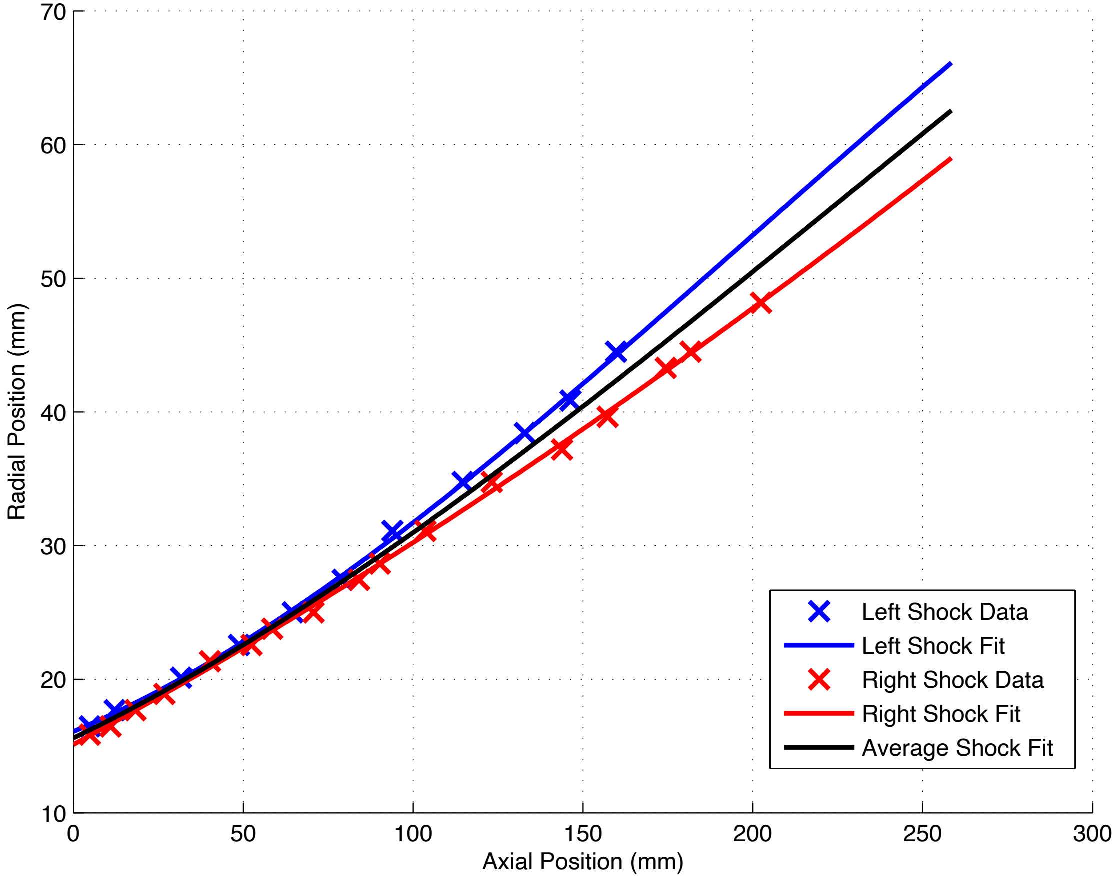


# Detonation Velocity – Cylinder Test

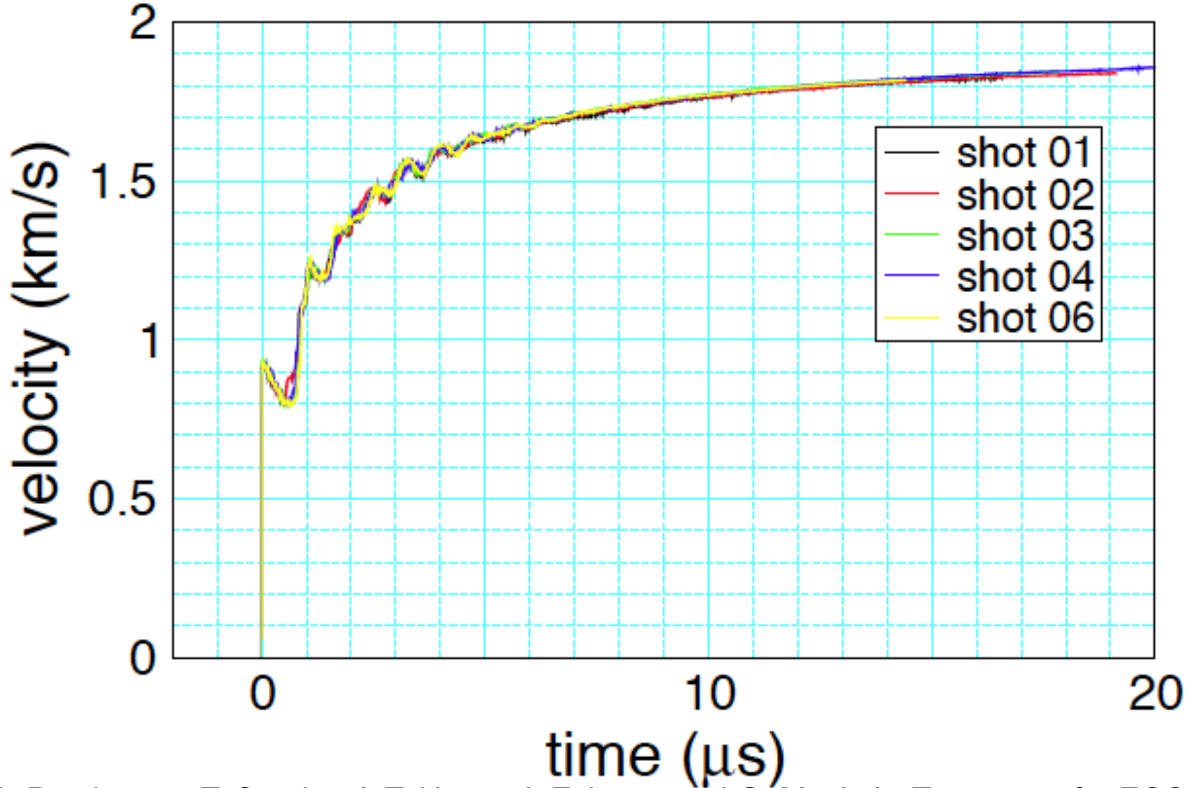
- Using a simple difference in undetonated length of the HE cylinder between sequential images we get the blue line in the plot of detonation velocity to the right.
- The variation of detonation velocity using this method is non-physical (if it were otherwise there would be evidence of it in the shape of the shock wave). It is instead due to errors in the measurement of the length of undetonated material and possibly the elapsed time between sequential images.
- Since the detonation process ideally occurs at a constant rate, measuring the detonation velocity over the entire shot will provide a much more accurate value of 7.964 km/s.



# Cylinder Shock Profile Results

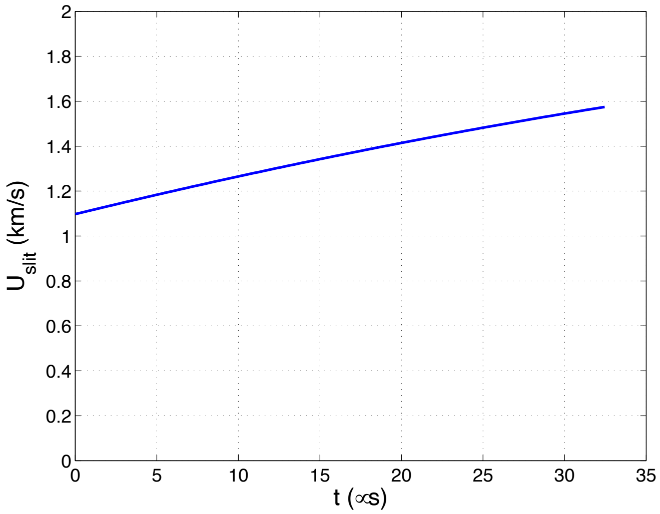


# Slit Velocity Results for Shock Profile

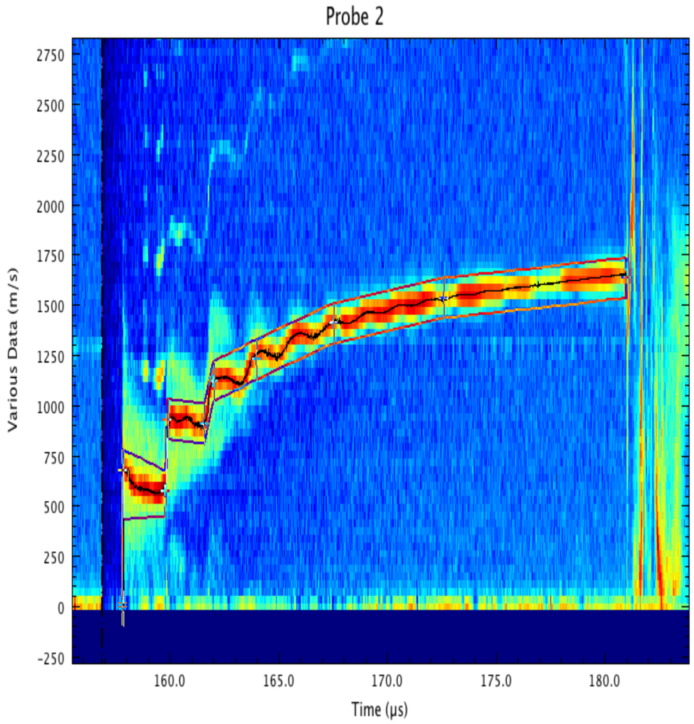



S. Pemberton, T. Sandoval, T. Herra, J. Echave, and G. Maskaly. Test report for EOS measurement of PBX 9501. Technical Report LA-UR-11-04999, LANL, 2011. 4, 7

# Slit Velocity Results for Shock Profile

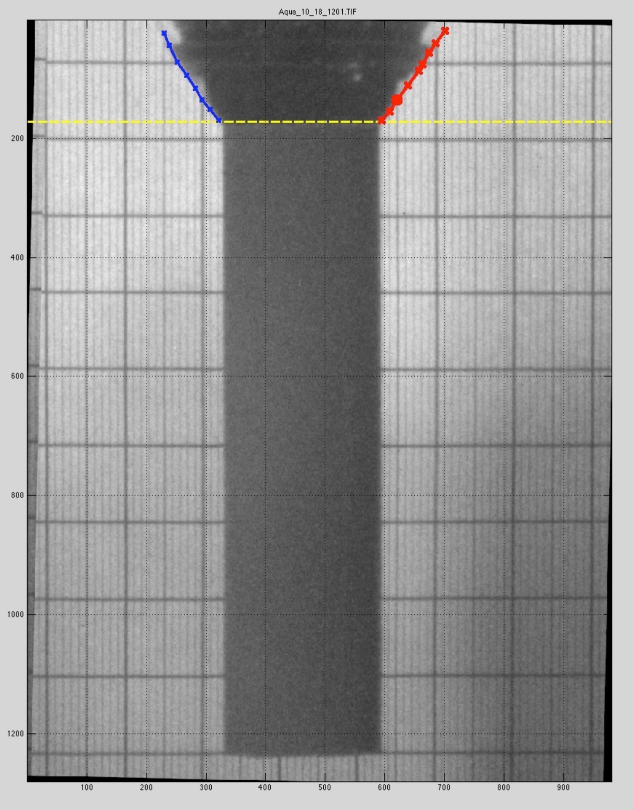


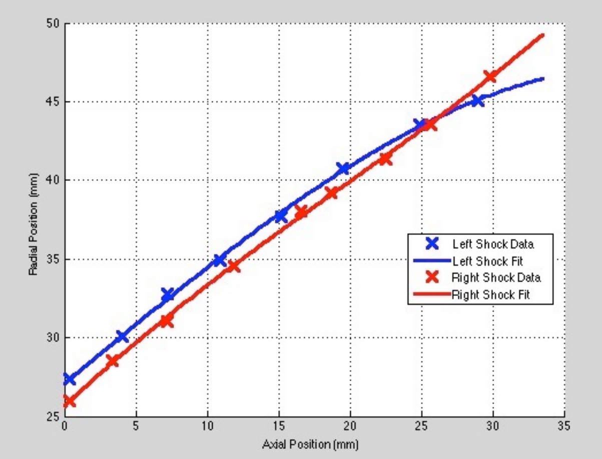

Cylinder Shot Image Analysis

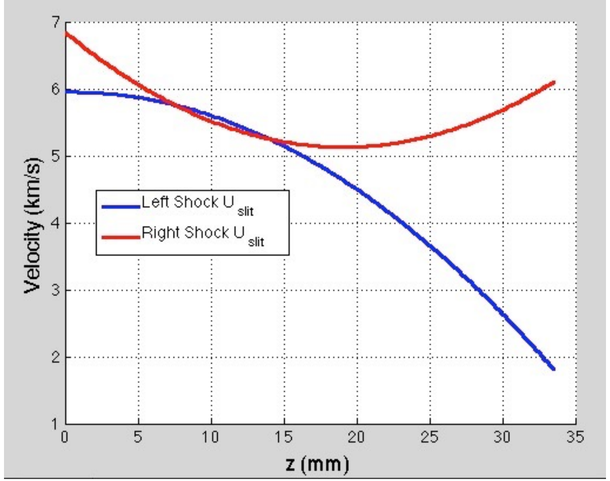



3/14/2013 CSM cylinder shot PDV data

# Sensitivity to User Defined Data



# Automating Edge Detection

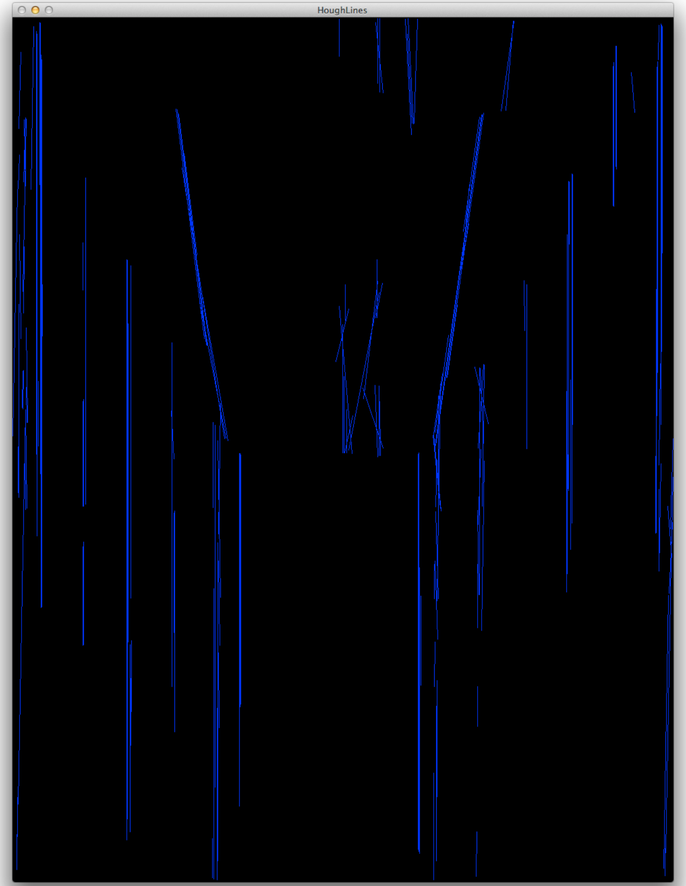
Canny Edge Detection Algorithm used to find points and contours of interest in original image

- Original image blurred slightly to remove unwanted effects from single pixels
- Pixels with sharp color intensity gradients are marked as points of interest
- Canny Points are grouped into sets of adjacent contours

# Automating Image Rotation

Using Hough Transforms to correct image rotation

- Using output from Canny Edge Detection, find sets of points that match a linear equation
- Group lines by angle of rotationCalculate slope of lines, ignoring lines more than some threshold off vertical
- Weight lines by distance from centerline and distance from image’s bottom edge
- Calculate weighted average angle of rotation and negate for image correction



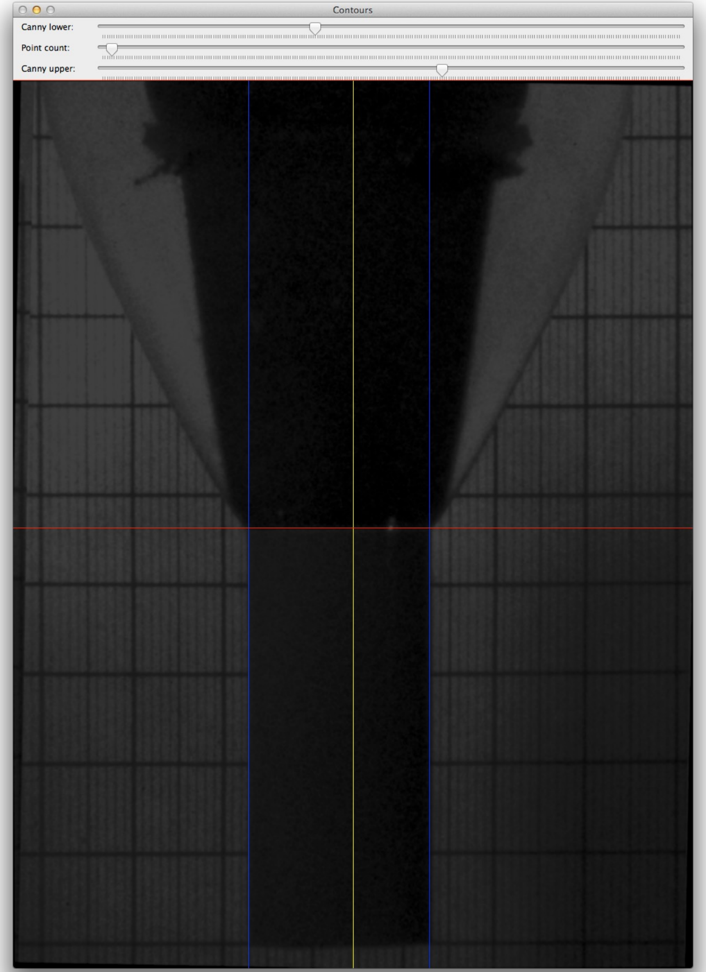
# Automating Line Detection

Detecting HE vertical edges (blue)

- Define image centerline (yellow)
- Find first vertical line (in +/- directions from centerline) on which the number of Canny points is above a threshold
- Progress until the next vertical line contains fewer Canny points than the last (blue)

Detecting Explosive Front (red)

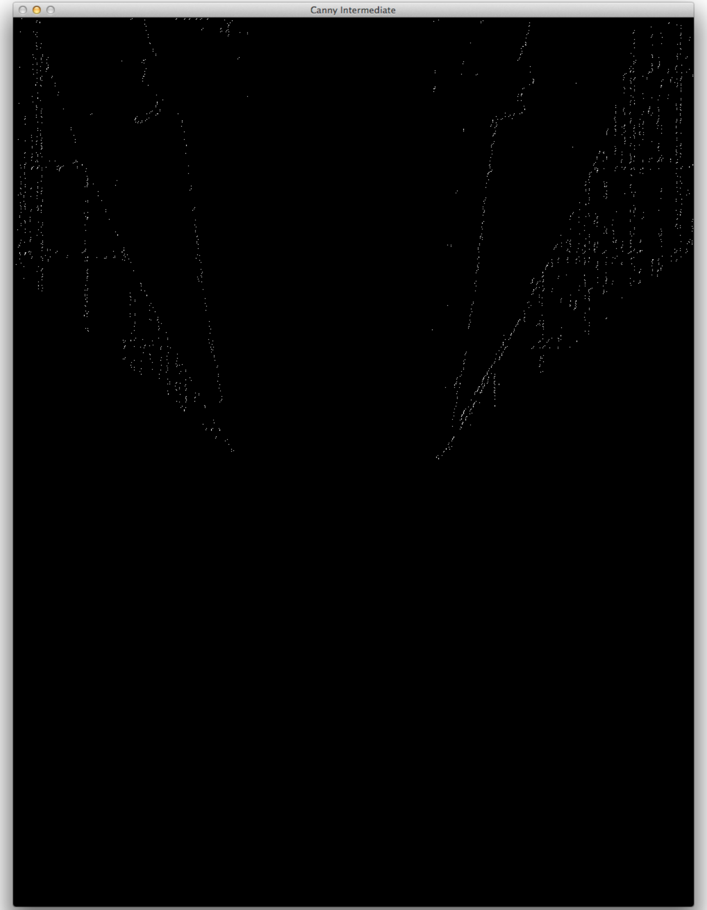
- Weight canny points by inverse of distance from centerline (yellow)
- Score horizontal lines as sum of weighted Canny points on line
- Find horizontal line with highest weighted score (red)



# Automating Curve Detection

Filtering Canny Points

- The points of interest reside in specific regions of the image
  - Above the explosive front
  - To the left of the left HE vertical edge and right of right HE
  - To the right of the right HE vertical edge
- Points of interest are more likely to lie on regions of contours with a mostly vertical slope
- Points of interest are likely to lie above a line with a non-zero slope (~40° above the horizon in the image to the right)



# Automating Curve Detection

Hough Transforms are a class of equation fitting algorithms

- Define an equation for fitting data with two or more unknown parameters
- Define ranges for unknown parameters
- For N unknown parameters and each data point, iterate over the possible ranges for the first N-1 parameters, and solve for the last unknown
- Bin results into N dimensional space
- Locate regions of high concentration in N dimensional space to find sets of parameters that best match the data

# Automating Curve Detection

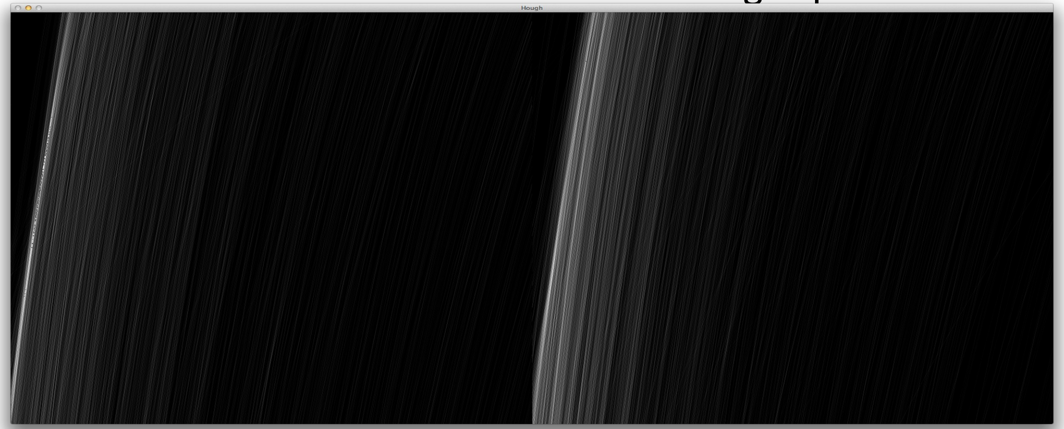
Hough Transform in 2 dimensions

- Attempt to fit x,y pairs to the function $y=m*x^z$
- Define range and granularity for m and z

For each point x,y:

- For each possible value of m:
  - Solve for z
  - Increment counter at point m,z in Hough space

Find points of highest concentration in Hough space




2D Hough transform for left and right shockwaves
m is displayed on the horizontal axis and z on the vertical

# Automating Curve Detection

Hough Transform in 4 Dimensions

Attempt to fit pairs x,y to the function

$y=ax^3+bx^2+cx+d$

Define range and granularity for a,b,c and d

For each point x,y:

For each possible value of a:

For each possible value of b:

For each possible value of c:

Solve for d

Increment counter at point a,b,c,d in Hough space

Find points of highest concentration in Hough space

Having 4 unknowns requires a tradeoff when compared to 2 unknowns:

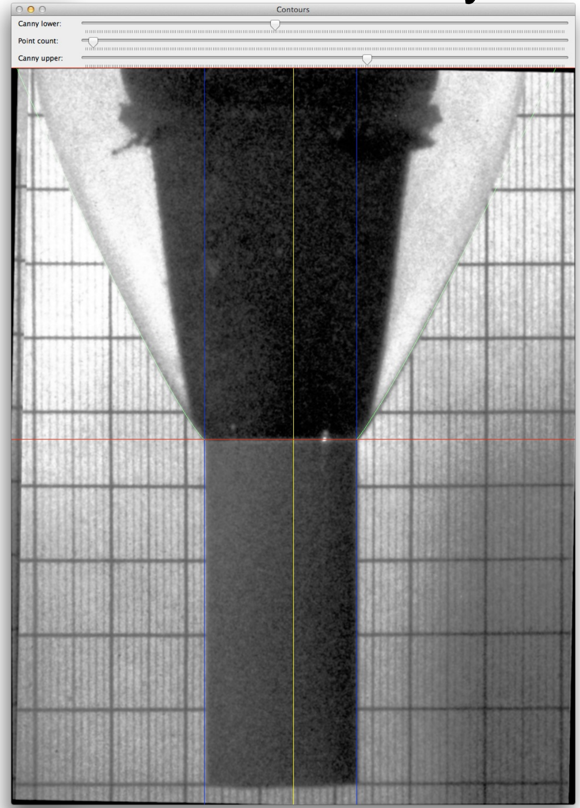
Significantly larger granularity,

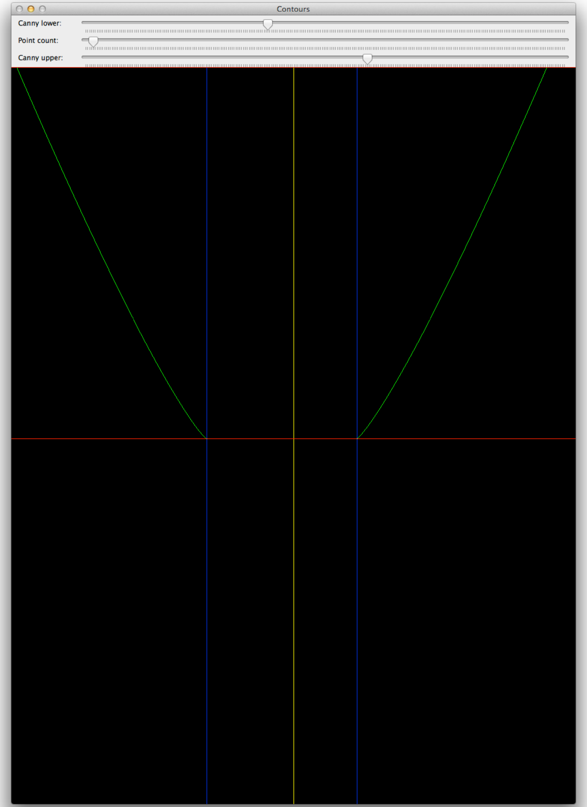
Significantly smaller range,

Or significantly longer runtime and higher memory requirements

# Automating Curve Detection

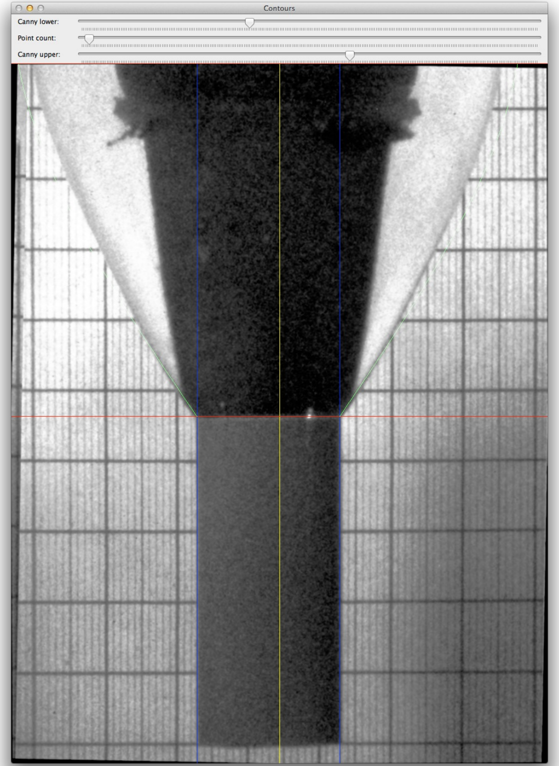
Best fit for $y=m*x^z$ (2D Hough space)

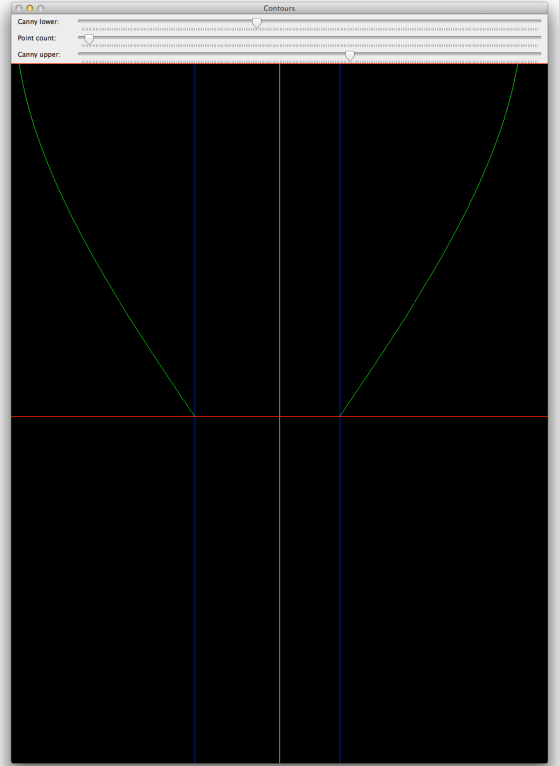


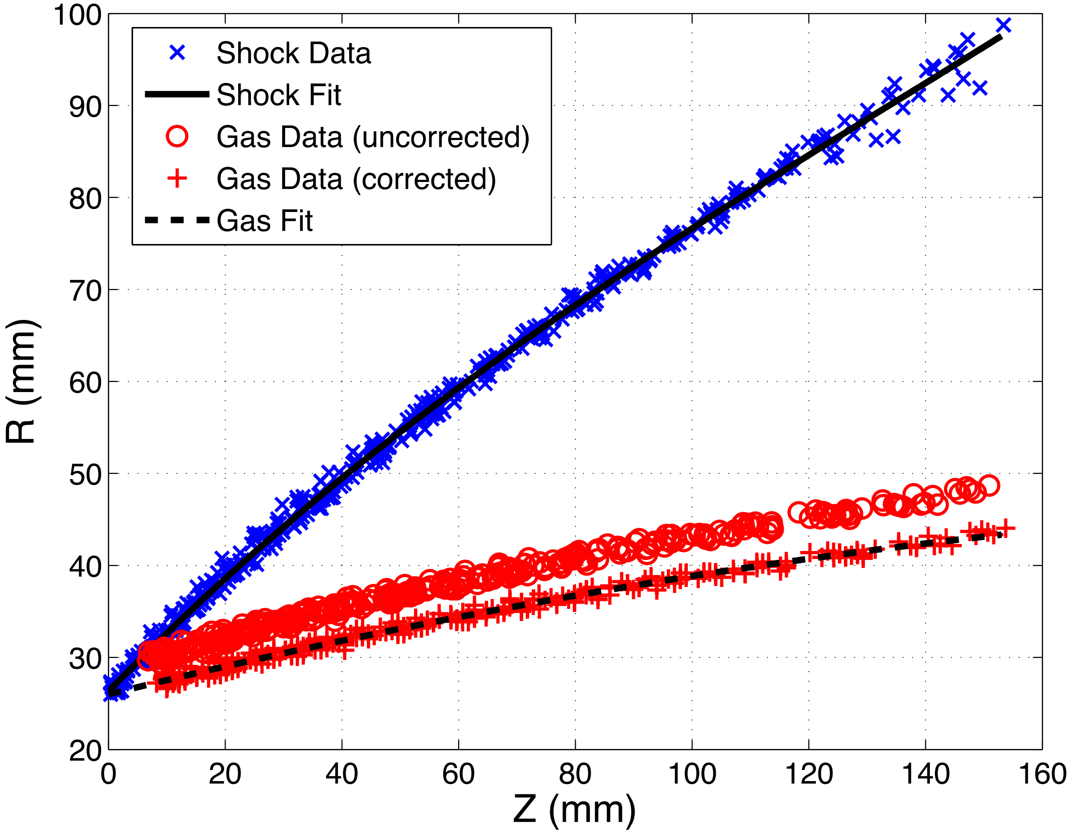
# Automating Curve Detection

Best fit for $y=ax^3+bx^2+cx+d$ (4D Hough space)



# All Images from 10/18/2012

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# Conclusions

- Refraction at the shock surface distorts the apparent location of the product gas profile in all three dimensions.
- This distortion must be corrected in order to accurately measure the velocity of the water along the streamline adjacent to the contact discontinuity.
- The velocities derived from the images are very sensitive to inconsistencies from user input.
- The detection of edges and curves of interest should therefor be automated to remove these inconsistencies as much as possible.
- Edge detection of the cylinder geometry is fairly straight forward but the shock and product gas profiles are non-trivial.
- We may need to investigate other functional forms for the fits to the shock and product gas profiles.