68th Meeting of the Aeroballistic Range Association,
Monterey, CA, USA, September 17 – 23, 2017

Upgrades and Modifications of the NASA Ames HFFAF Ballistic Range

David W. Bogdanoff

AMA Inc., NASA Ames Research Center, Moffett Field, CA, USA

Michael C. Wilder, Charles J. Cornelison

NASA Ames Research Center, Moffett Field, CA, USA

Alfredo J. Perez

Aerodyne Industries, NASA Ames Research Center, Moffett Field, CA, USA

Overview

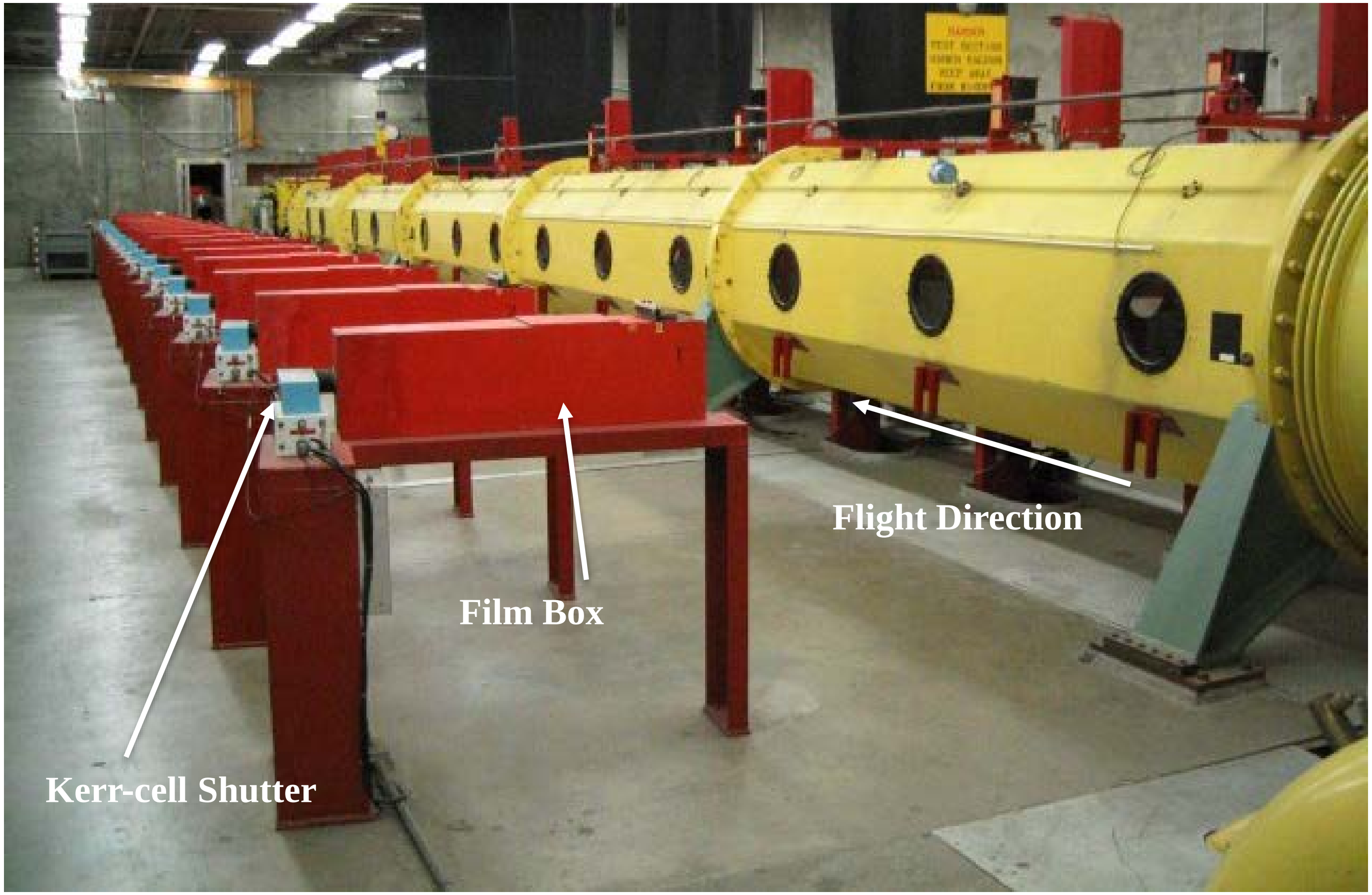
- Introduction
- Shadowgraph imaging
- Model detection
- Replacement gunpowder for light gas gun operation
- New hardware for facility systems checks
- Film reading software developments
- Summary and conclusions

NASA Ames HFFAF Ballistic Range

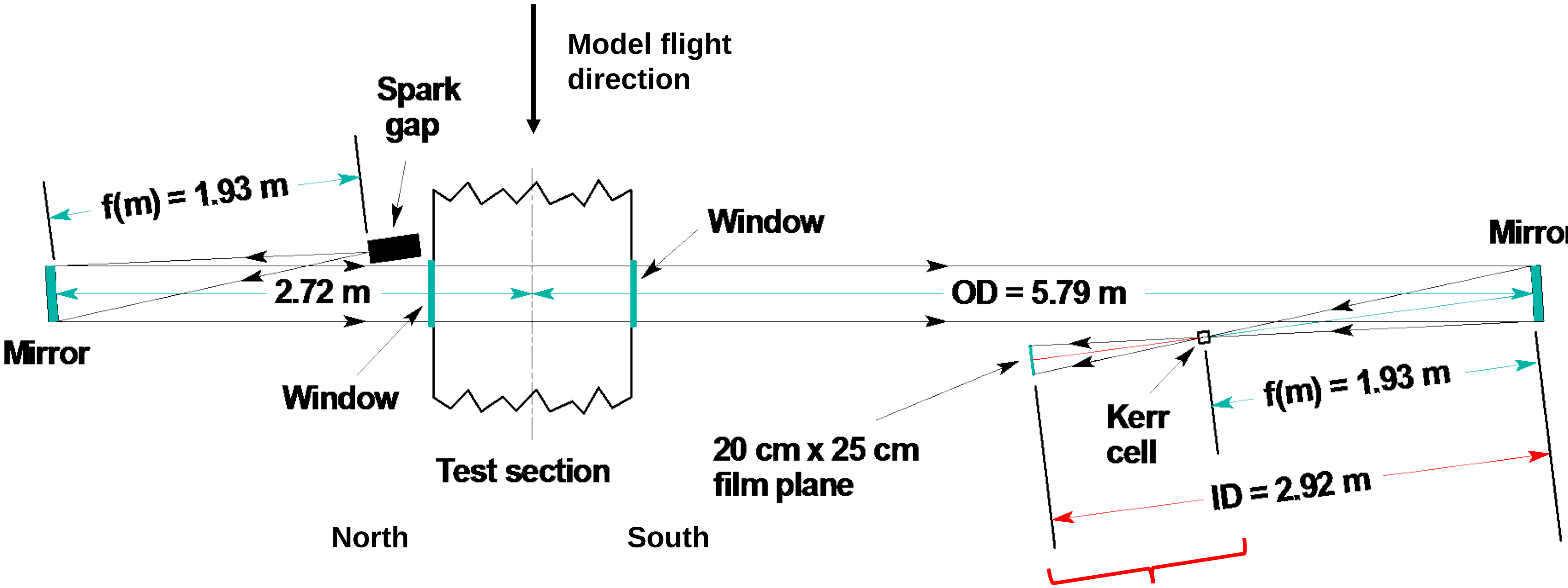
- NASA Ames HFFAF (Hypervelocity Free Flight Aerodynamics Facility)
- 16 orthogonal shadowgraph stations 1.52 m apart, 22.9 m total length
- Windows – 30 and 38 cm
- Record images with sheet film or cameras
- Shuttering – Kerr cells or gated ICCD cameras
- Pressures – 100 μ to 1 atm
- Gases – air, CO_2, N_2, Ar, others
- Launchers - 20 to 61 mm powder guns, 170 m/s to 2.0 km/s
  - 7 to 38 mm two stage light gas guns, 3 to 8 km/s

Shadowgraphs

NASA Ames HFFAF Ballistic Range



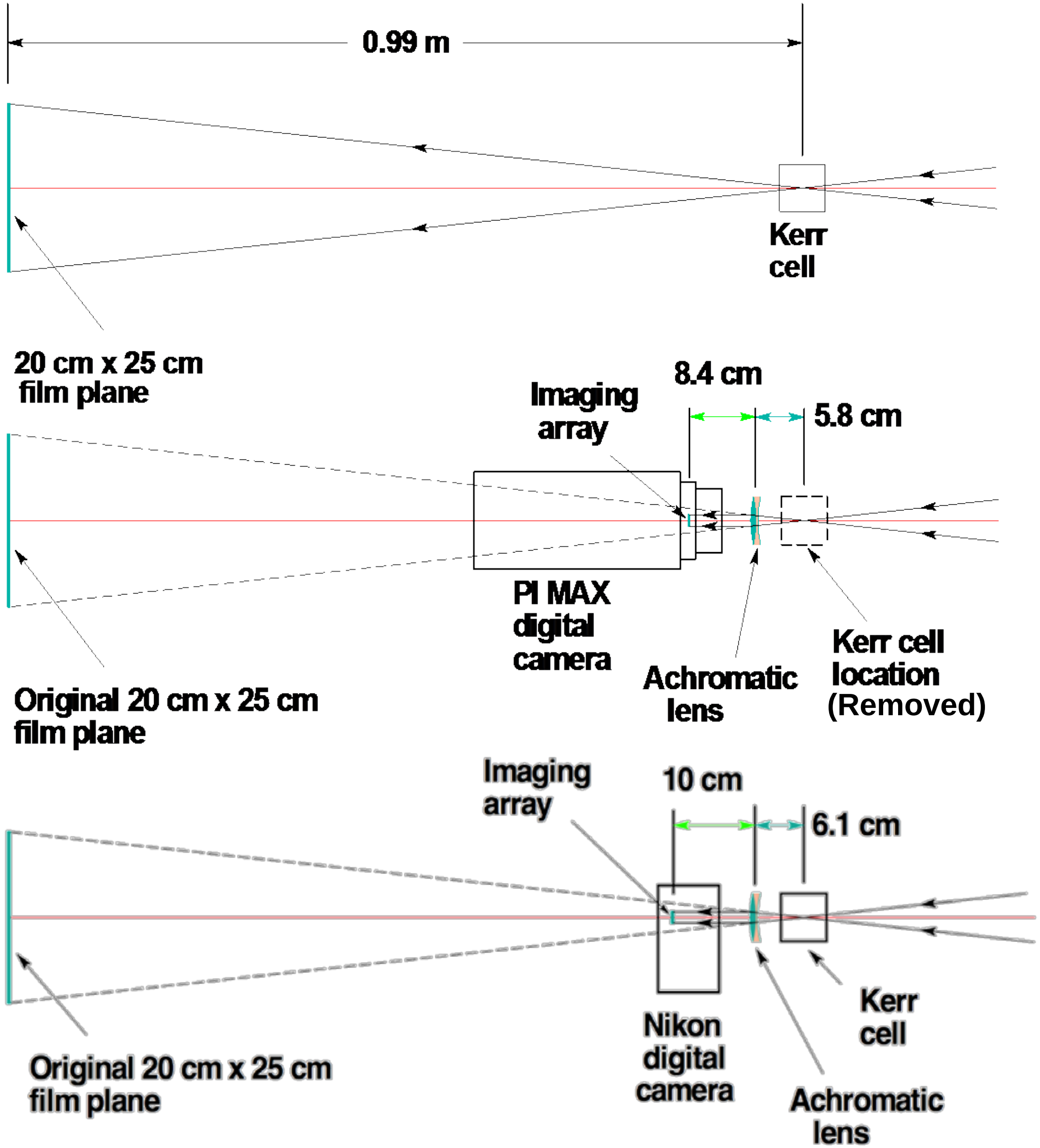
Shadowgraph Optical Set-up



- Only this portion is altered for digital image recording.
- Sheet film camera set-up shown here.

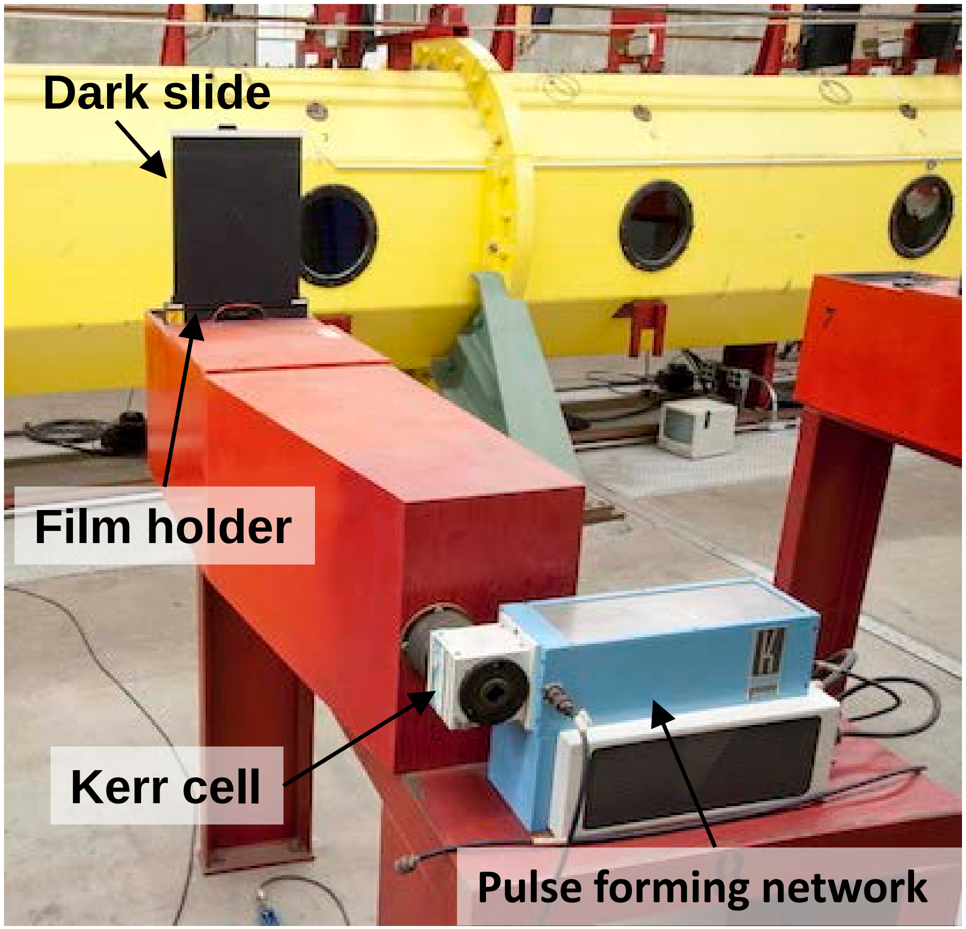
Shadowgraph Imaging: Recording Methods

- Sheet Film
  - High spatial resolution
  - Long turn-around (2-3 hours to develop images)
  - Requires hazardous chemicals
- ICCD Camera
  - Relatively low spatial resolution, high cost
  - High temporal resolution (gated camera) – No Kerr cell shutter required
- Digital SLR Camera
  - High spatial resolution, low cost
  - Kerr cell shutter required



Shadowgraph Imaging: Recording Methods

Sheet Film



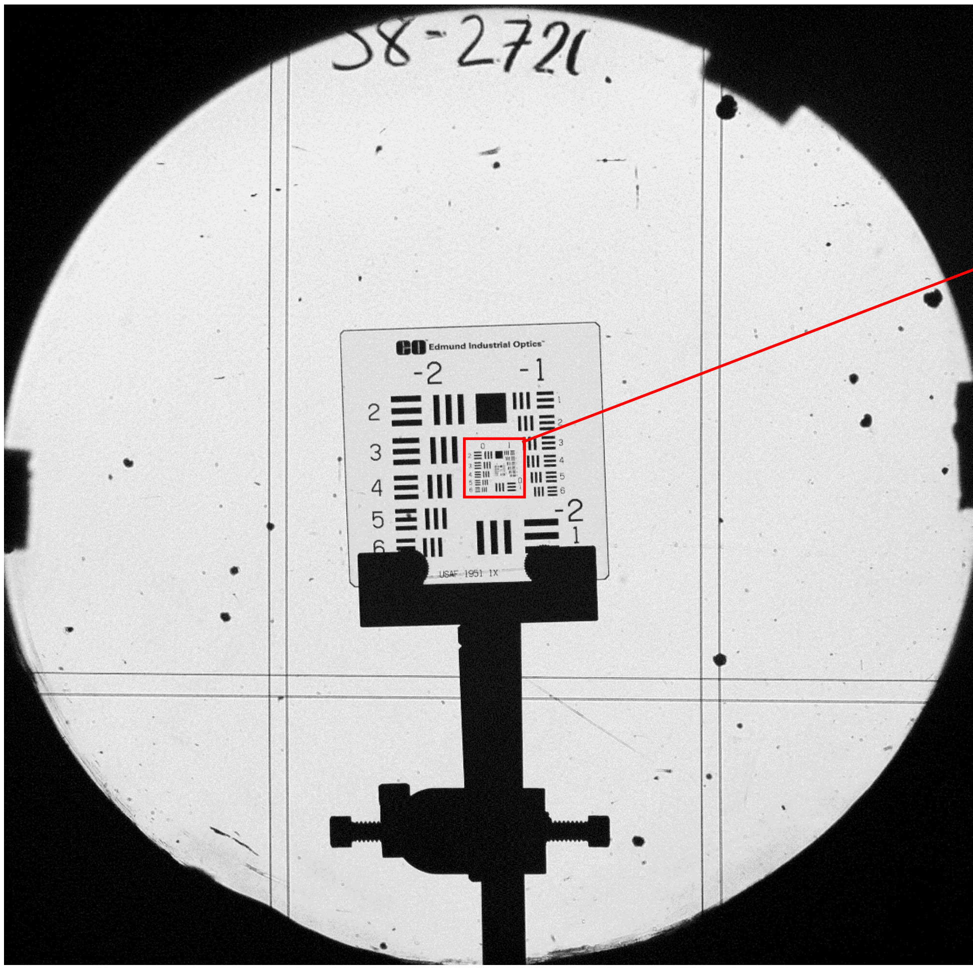
Digital: Gated ICCD

Digital: SLR / Kerr Cell

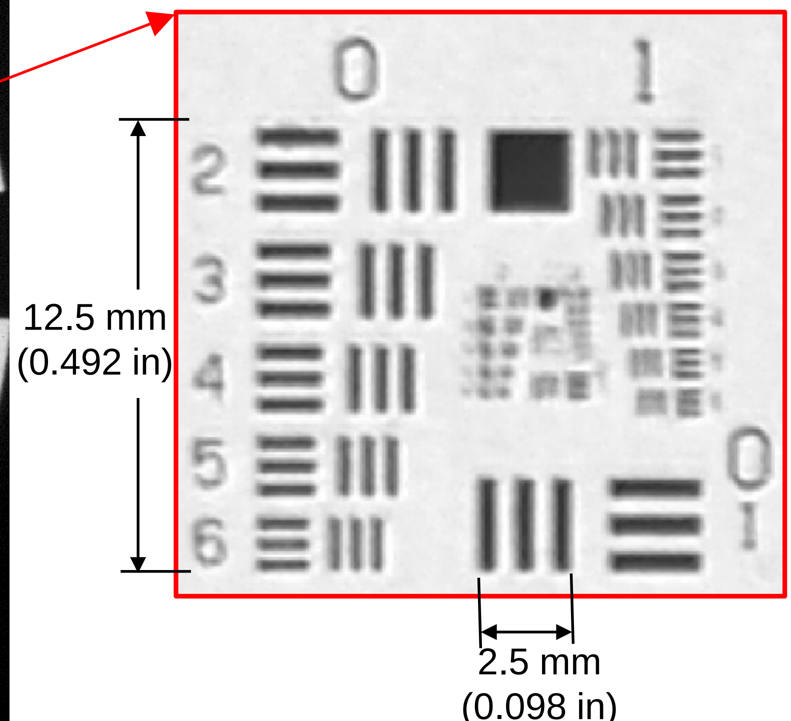
Shadowgraph Imaging: Resolution

Spatial resolution of each shadowgraph camera configuration assessed from images of a USAF 1951 resolution test chart

Shadowgraph Image of Test Chart



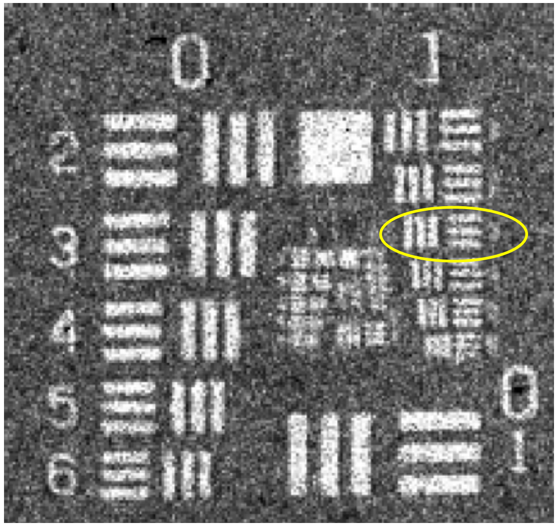
Detail of Resolution Chart
Line Groups 0 and 1



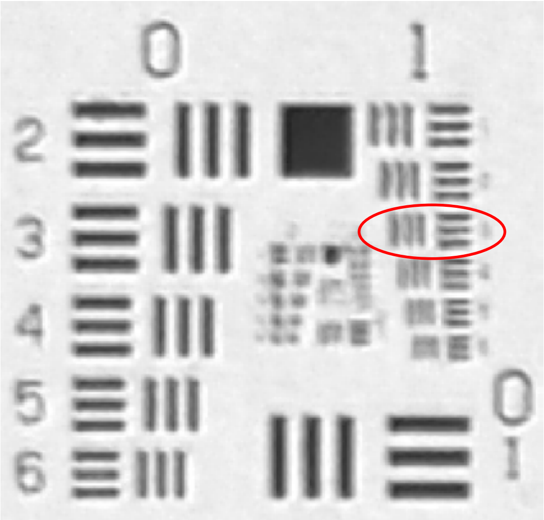
Shadowgraph Imaging: Resolution

- Film, scanned to resolve the film grain, and the digital SLR images all resolve elements in group 1 to at least element 3 (results vary station to station, shot to shot)
  - Line spacing = 2.52 lines/mm
  - Bar width = 0.198 mm
- ICCD images resolve element 4 of group 0
  - Line spacing = 1.41 lines/mm
  - Bar width = 0.355 mm

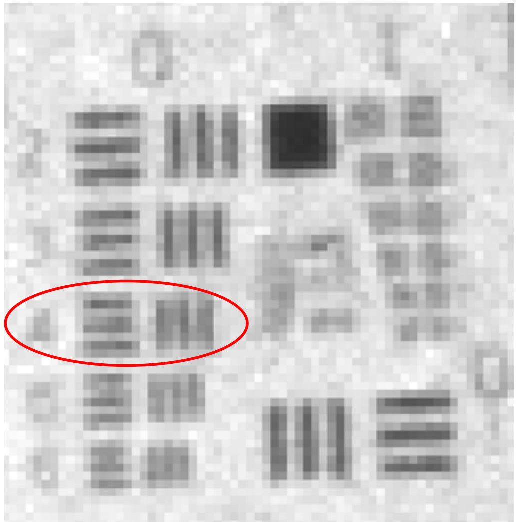
Film Negative Scan
120 pixels/cm



Digital SLR Camera
130 pixels/cm

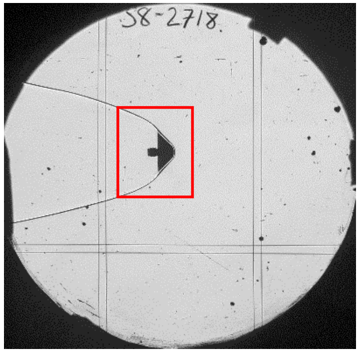


ICCD Camera
38 pixels/cm

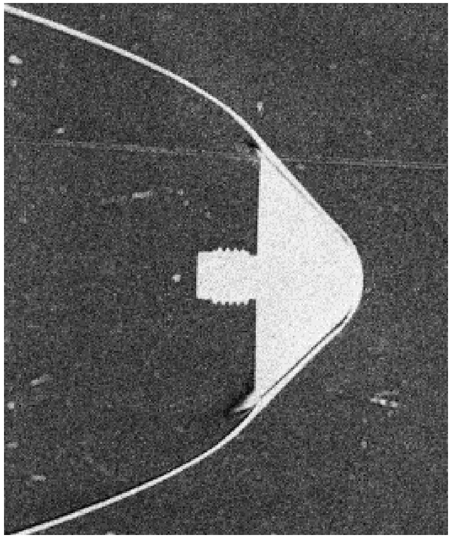


Shadowgraph Imaging: Resolution

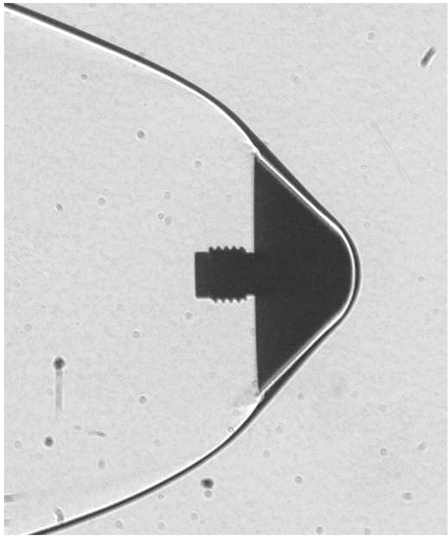
- Example images of a typical HFFAF model in flight
  - 45º half angle cone
  - 3.3 cm base diameter
  - 0.762 cm nose radius
  - Flight speed = 2700 m/s



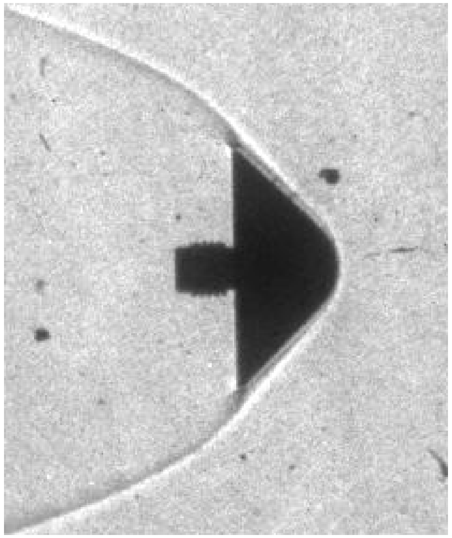
Film Negative Scan
120 pixels/cm



Digital SLR Camera
130 pixels/cm



ICCD Camera
38 pixels/cm



Shadowgraph Imaging

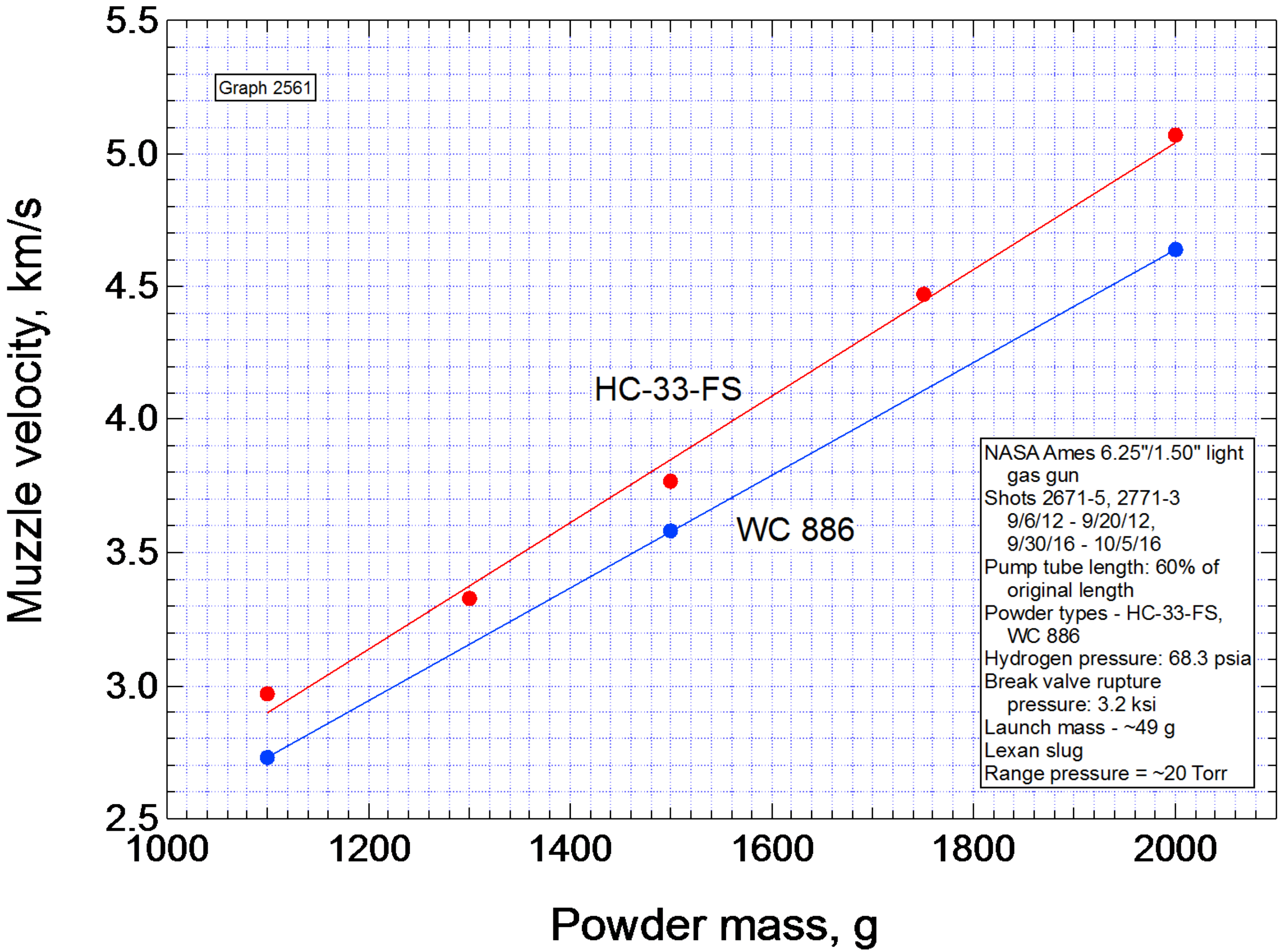
Advantages of new shadowgraph set-up (26 Nikon cameras and 6 PI-MAX cameras):

- Immediate availability of photos versus 2 – 3 hour wait for film development
- No digitizing of sheet film photos required (2 – 3 additional hours of work)
- No film processing equipment with hazardous media to maintain
- 26 out of 32 cameras have high resolution – 6 low resolution cameras acceptable if each is located between two high resolution cameras

Replacement gunpowder for 1.5” light gas gun

- Original powder was Hercules HC-33-FS – no longer available.
- Replacement powder, St. Marks WC 886, found.
- Three proof shots made with new powder – five proof shots had been made with old powder
- Gun operating conditions:
  - Pump tube length – 18.3 m
  - Powder mass – 1.1, 1.5, 2.0 kg
  - Hydrogen pressure - 471 kPa
  - Piston mass – 21.3 kg
  - Break valve rupture pressure – 22.1 MPa
  - Projectile – 49 g Lexan slug
  - Range pressure – 2.67 kPa

Replacement gunpowder for 1.5” light gas gun

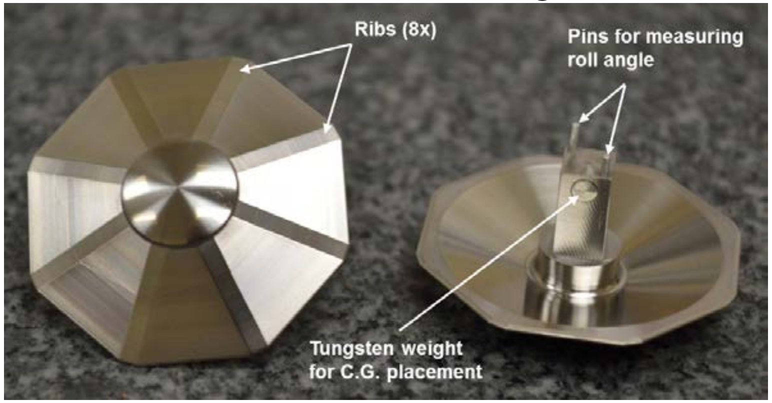


Muzzle velocity versus powder mass for both powders

Image-Reading Software Developments

- A template matching pattern recognition algorithm was developed for determining the position and attitude of a ballistic-range model in shadowgraph images.
- Motivation:
  - A test was recently conducted of a model with a faceted geometry: the Adaptive Deployable Entry and Placement Technology (ADEPT) Sounding Rocket (SR-1) vehicle.
  - Unlike blunt conical models typically tested in HFFAF, the ADEPT SR-1 profile in shadowgraphs appears different vs. roll angle and attitude angle normal to the image plane.
  - Pattern matching using templates generated from the CAD model of the ballistic-range model could potentially yield all attitude angles from a single image.

ADEPT SR-1 Ballistic-Range Model



ADEPT SR-1 Profiles Rotated 18º

Nose Into Page **Nose Out of Page**

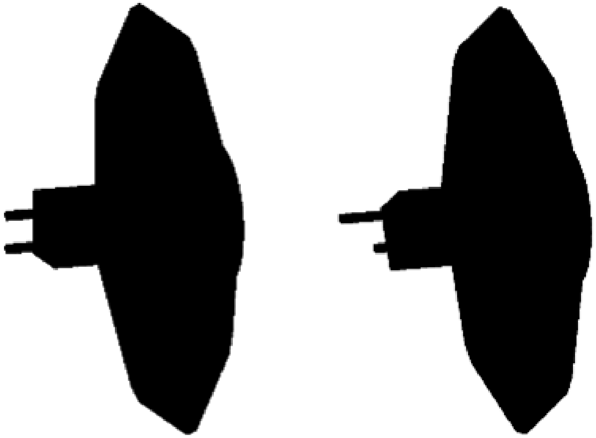
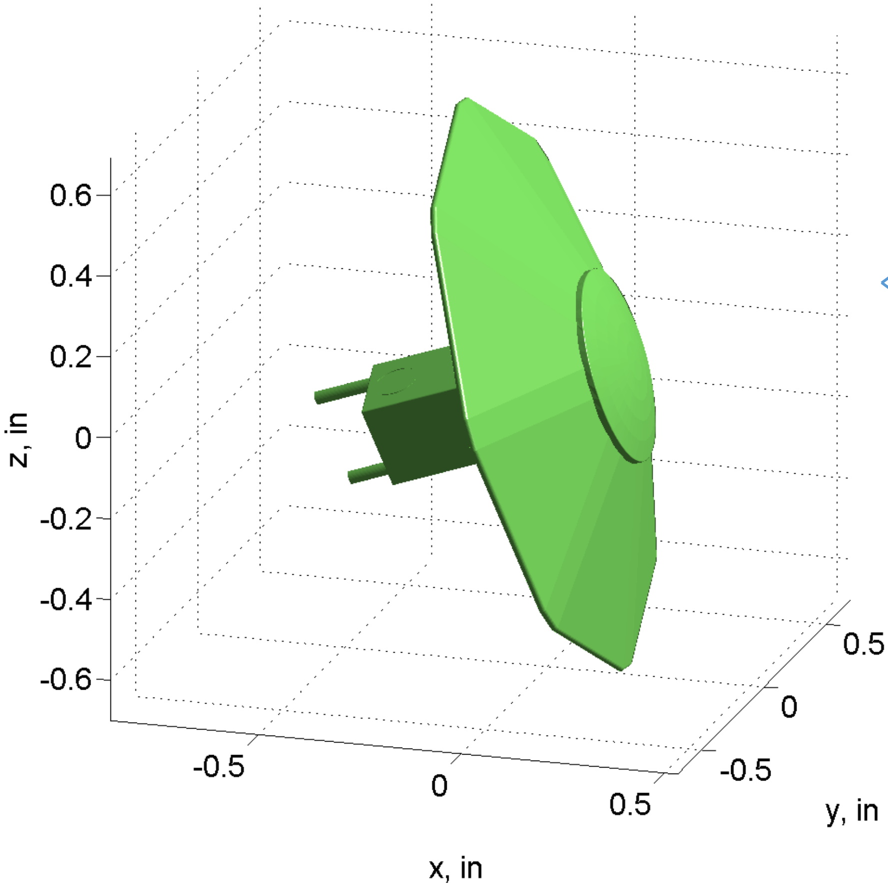


Image Reading: Template Generation

- 3D CAD Model at a Given Attitude
  - Attitude angles (pitch, yaw, and roll) measured about the center of gravity (CG)
  - CG located at the CAD origin



Side-View Template
x-z (Pitch) Plane

Top-View Template
x-y (Yaw) Plane

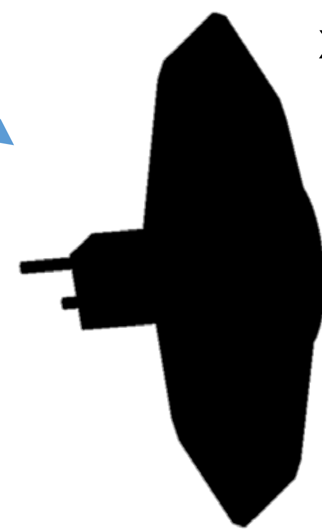


Image Reading: Template Matching

- Cross correlation of image and template
  - The maximum value of the cross-correlation coefficient matrix, C_{max}, is maximized when the template attitude matches the attitude of the model in the shadowgraph image
  - Location of C_{max} determines CG location of the model

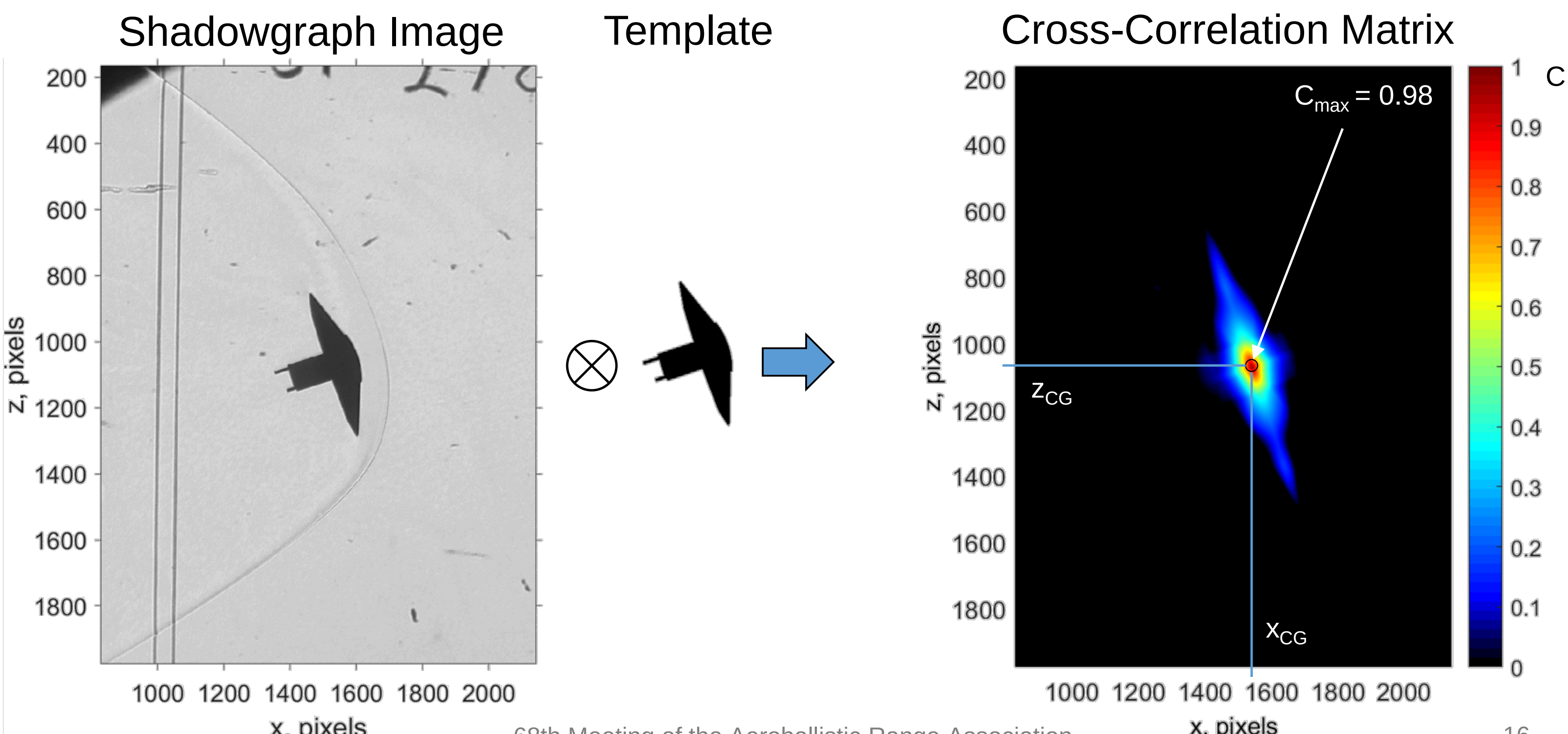


Image Reading: Attitude Determination

- Find in-plane template angle that best matched the image
  - Strongest cross correlation occurs when the template attitude matches the attitude of the model in the shadowgraph image
- Perform search iteratively on both side and top view shadowgraph images

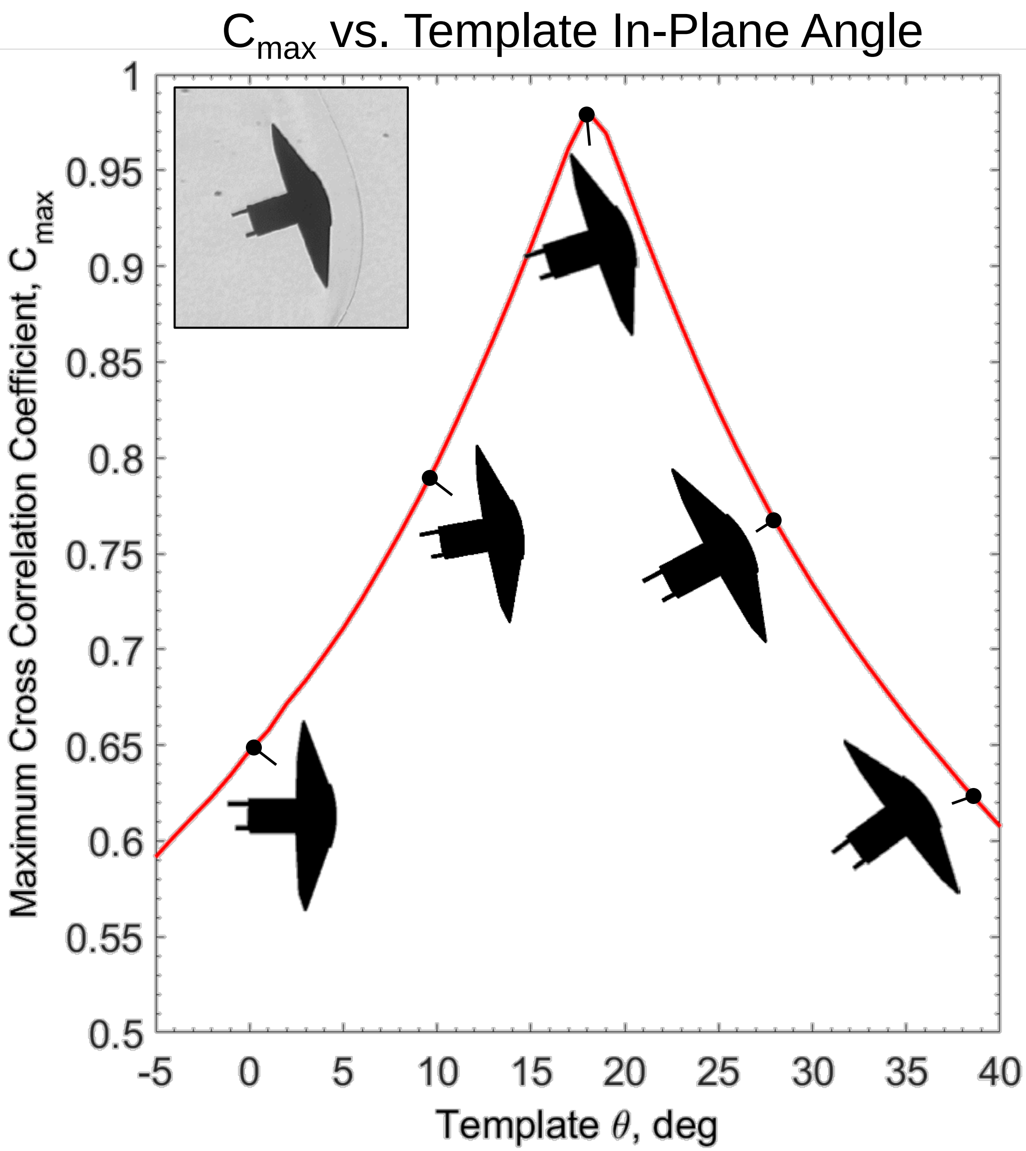


Image Reading: Attitude Determination

- Out-of-plane template angle effects C_{max}, but has small impact on in-plane angle match
  - Consequently, it is possible in this example to determine both in-plane and out-of-plane angles from one image

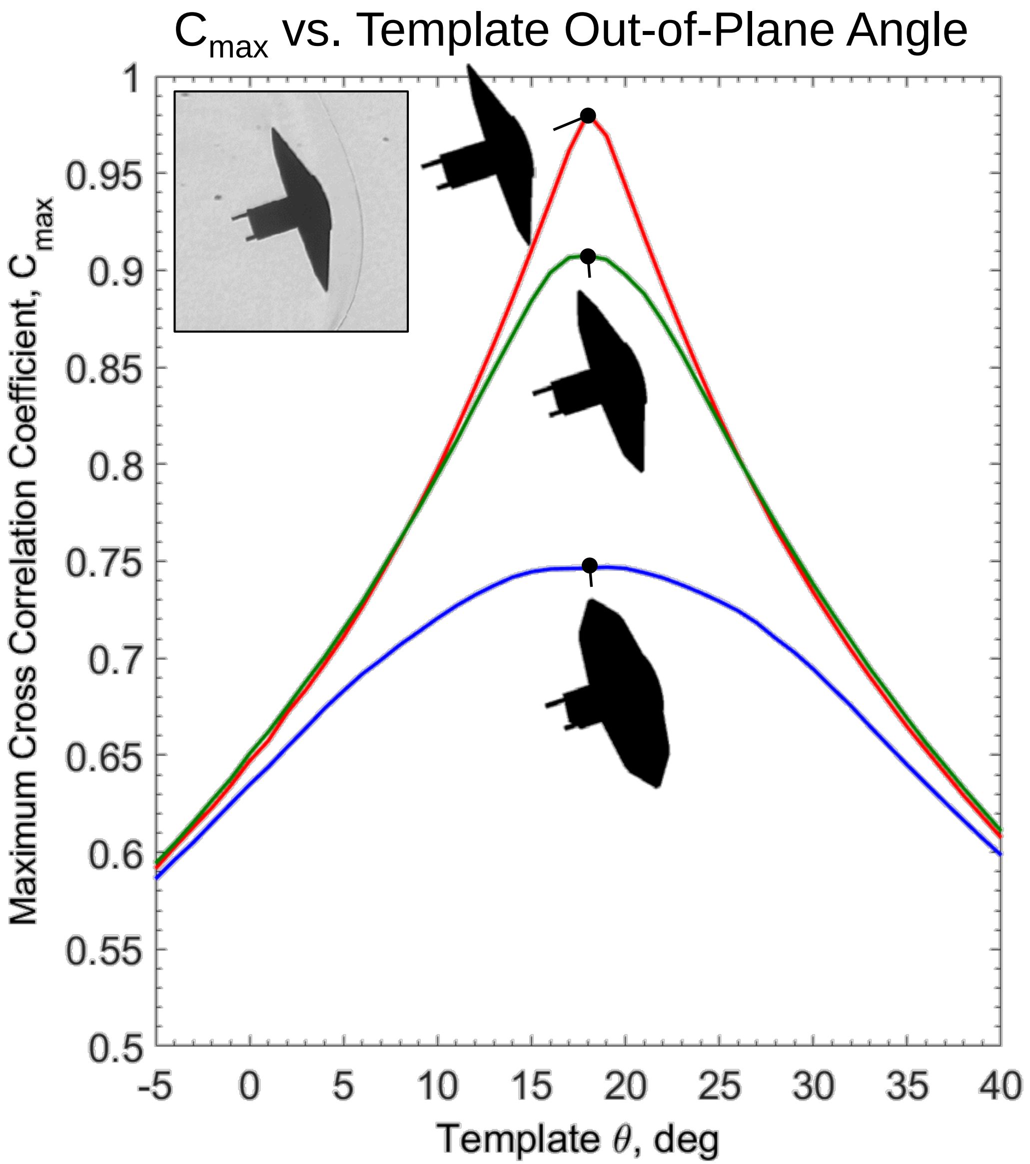


Image Reading: Attitude Determination

- Roll angle can also be determined for certain model geometries, however,
- C_{max} is less sensitive to template roll angle
  - Roll results in small changes to the model profile
- Multiple peaks occur
  - Axial symmetry of this model
- User verification of roll angle is required

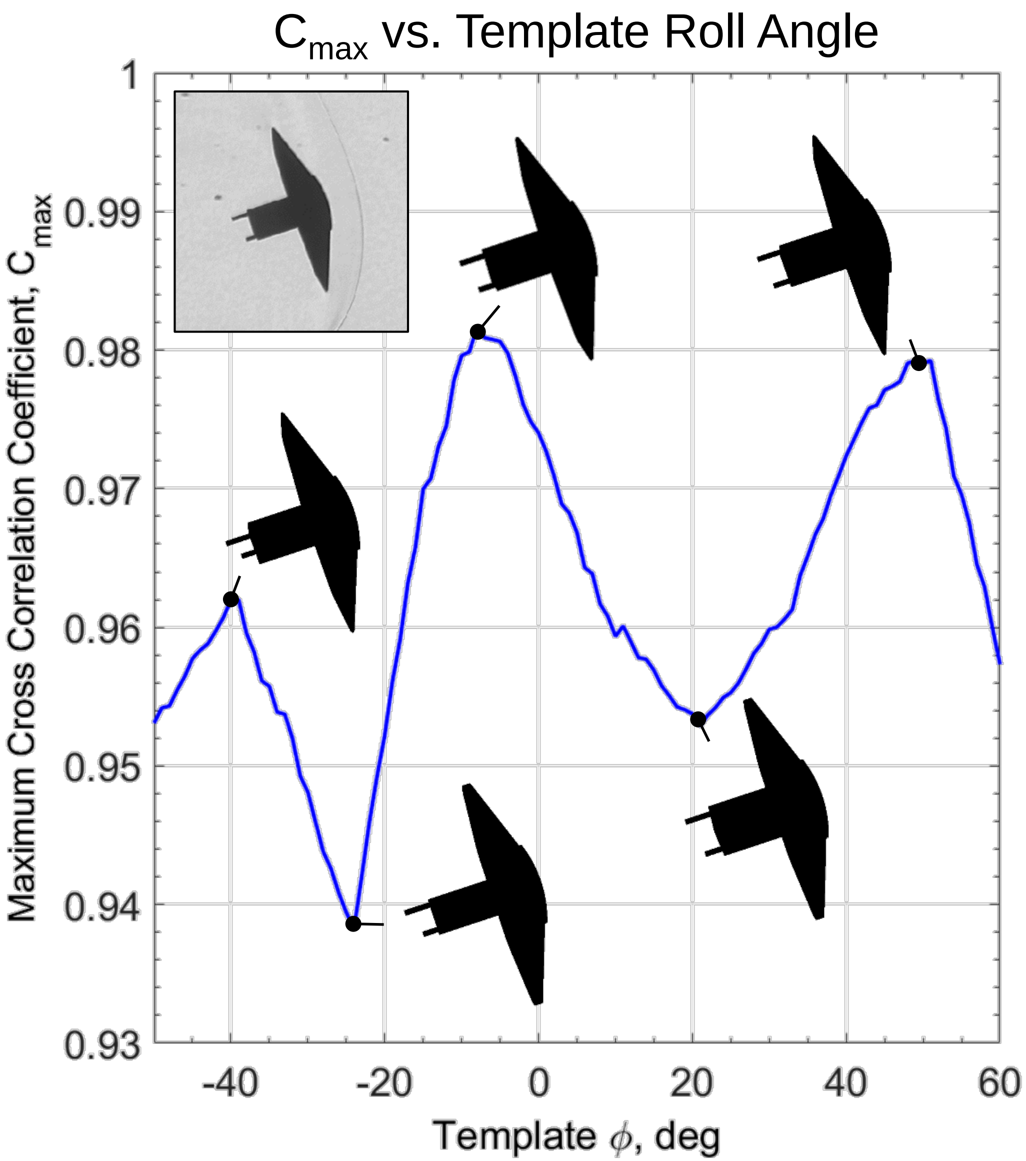
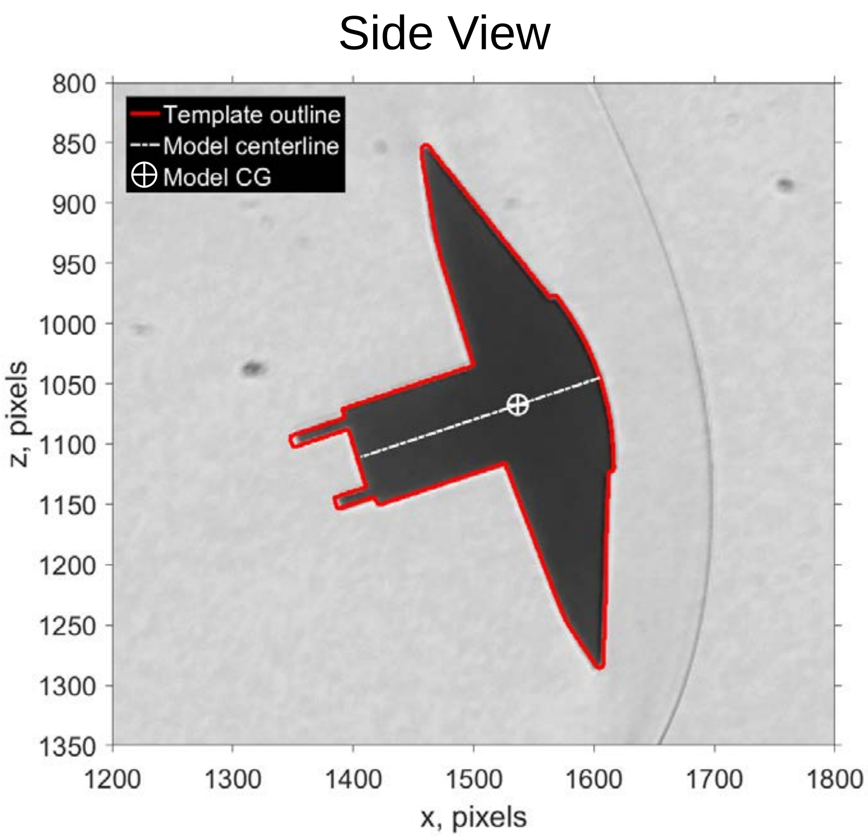


Image Reading: Example Result



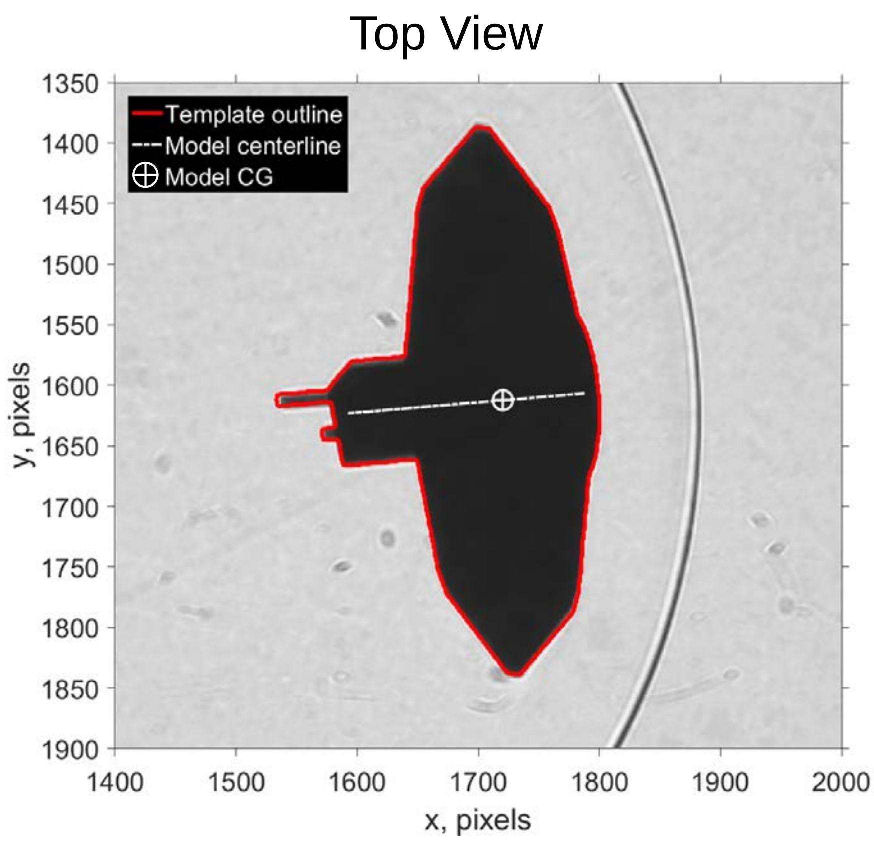
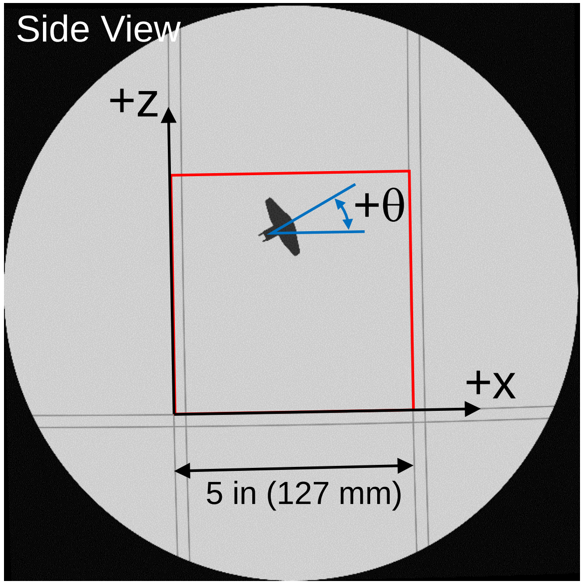


Image Reading: Evaluation

- Computer-generated "shadowgraph" images were used to evaluate the accuracy of the image reading software
  - 160 orthogonal image pairs generated
  - Model position and attitude drawn from uniformly-distributed random numbers
  - CG location rounded to nearest pixel when creating the images (expected accuracy is therefore no better than 1 pixel)



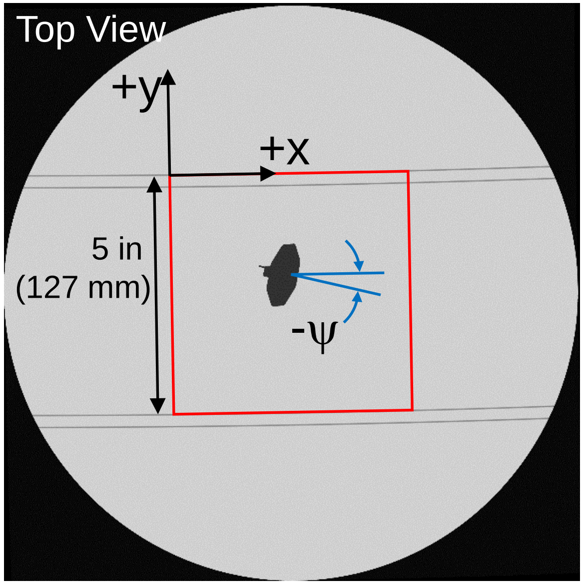


Image Reading: Evaluation

- A second set of images included image distortions representative of HFFAF images
  - A 2nd order curvature
    - Horizontal lines curve down range
    - Vertical lines curve up
  - Images were smoothed to soften the edges of the model and wires
  - Speckle noise was added
  - Images were randomly-rotated between ±2 deg to represent misalignment of sensor-plane axes with tunnel axes
  - The same positions and attitudes were used in both sets

Exaggerated illustration of typical image distortions

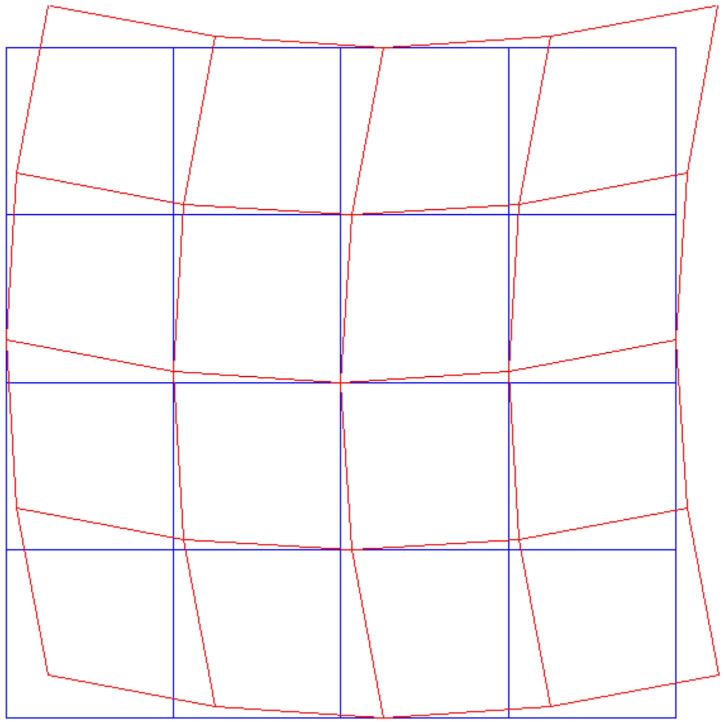


Image Reading: Evaluation

CG location

- Histograms of the difference between measured and actual position is shown for the down-range position
  - Normal distributions for Un-Distorted Images
  - Distribution of errors slightly skewed in direction of distortion for distorted images
  - Larger standard deviation is proportional to degree of distortion
- Similar results were obtained for the cross-range positions, y and z

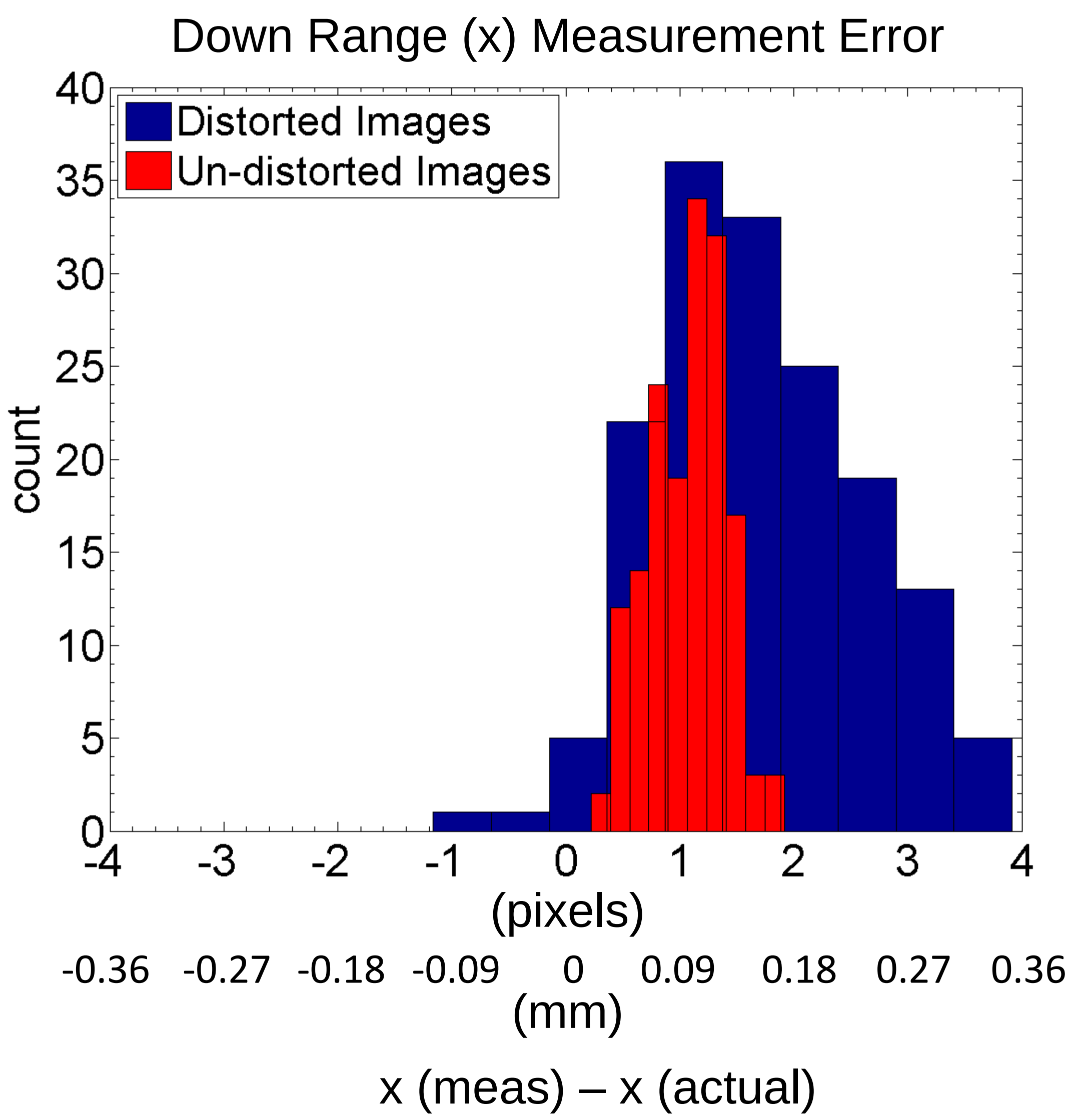


Image Reading: Evaluation

Model Attitude

- Pitch and yaw (not shown) angle measurements were minimally effected by image distortion
  - Mean and standard deviation unaffected by the distortions applied (3σ ~ 0.5 deg)
  - However, more cases deviated from the actual angle with distortions applied

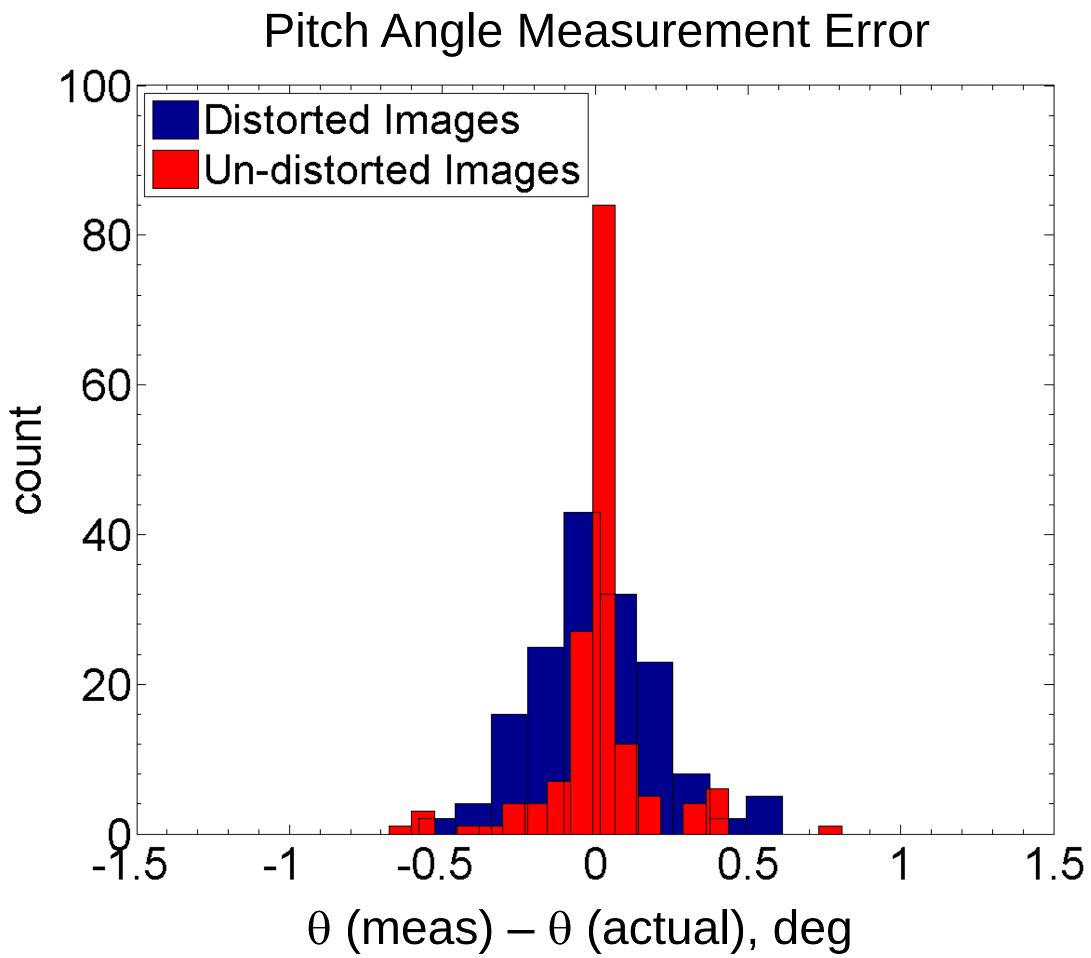
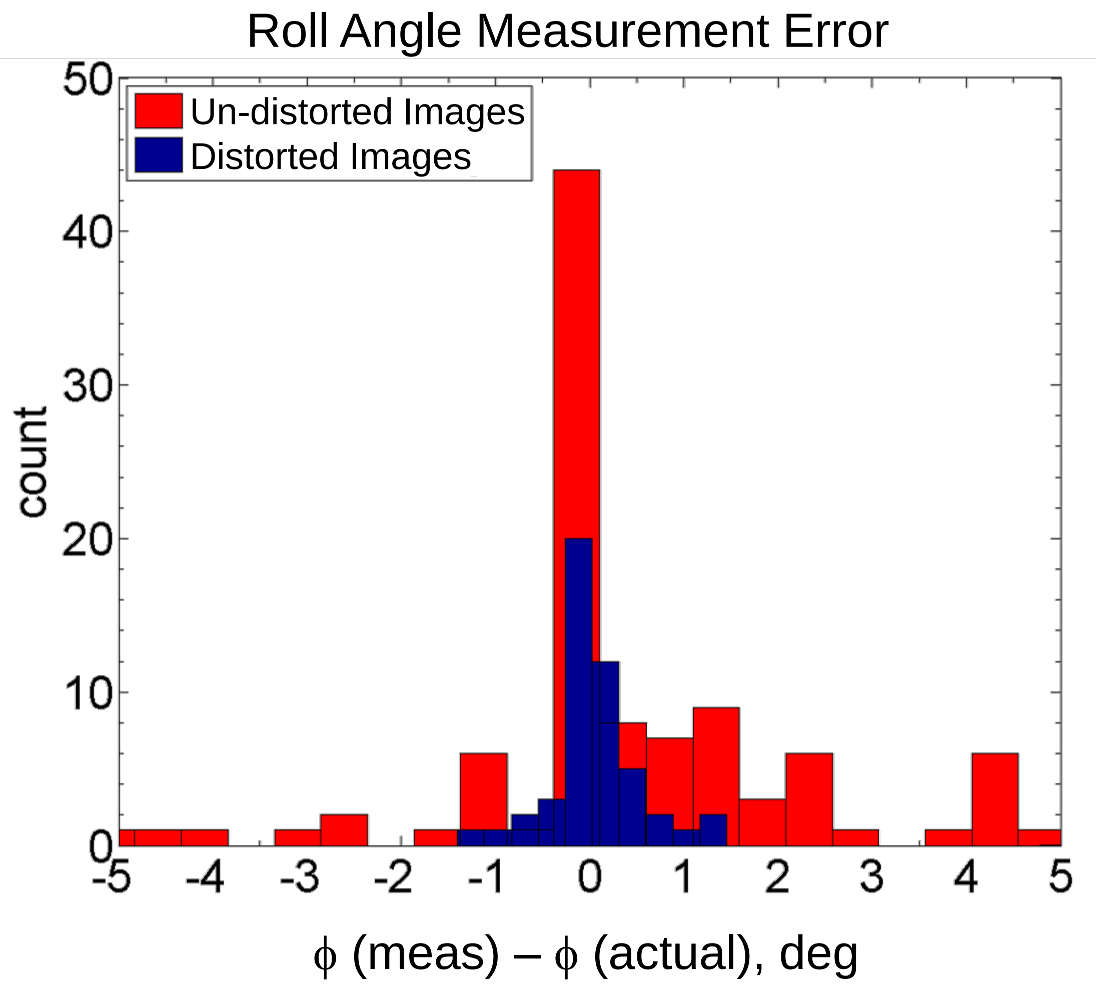


Image Reading: Evaluation

Roll Angle

- The unique geometry of the ADEPT model allows roll-angle identification by this method
- The uncertainty is larger than for pitch or yaw since the model profile variations are small with roll
- The correct angle was more frequently found for un-distorted images, however, the error for misidentified roll angles was much larger
  - Possibly due to pixilation of the un-distorted images



Summary and Conclusions

Several recent upgrades, updates, and hardware evaluations at the NASA Ames HFFAF ballistic range were discussed

Conversion to digital shadowgraph imaging:

- Current configuration:
  - 26 digital SLR cameras equipped with heritage Kerr-cell shutters
    - Resolution approaches the film-grain resolution of the standard sheet film
    - Camera cost is low
  - 6 gated ICCD cameras
    - Lower resolution, but Kerr cell not required
    - Camera cost is high
- Advantages of digital imaging:
  - Immediate availability of images for evaluation (vs ~3 hours for film)
  - No need for film-processing chemicals and equipment
  - No need for film scanning (an additional 2-3 hours)

Summary and Conclusions

Replacement Gun Powder:

- The heritage powder (Hercules HC-33-FS) used in the Ames 1.5” light gas gun is no longer available
- A replacement powder (St. Marks WC 886) was identified
- Proof shots were performed for expected muzzle velocities between 3 km/s and 5 km/s
  - Muzzle velocities were 5 – 9% lower (for the same powder mass) for the replacement powder
  - Difference in performance of the powders easily compensated for by increasing powder load of new powder ~10%
  - Additional evaluations are planned

Summary and Conclusions

Shadowgraph-reading software:

- Shadowgraph-reading software that employs template-matching pattern recognition was developed
  - For the case studied, 3σ measurement accuracy was

    ±0.3 mm in position

    ±0.6° for pitch and yaw

    ±1.8°, for roll angle, however user verification of roll angle was required

Summary and Conclusions

(Discussed in the full paper, but not presented here)

Model detection:

- An off-the-shelf, solid-state, model detection system was retro-fitted to the HFFAF at 3 stations to evaluate as a potential replacement for the heritage vacuum-tube technology
  - New system is more susceptible to spurious triggers (early and/or late detection) when the projectile is self-luminous (typical for speed > 3 km/s)
  - New system functions well for lower-speed shots
  - No further evaluations currently planned

System check hardware:

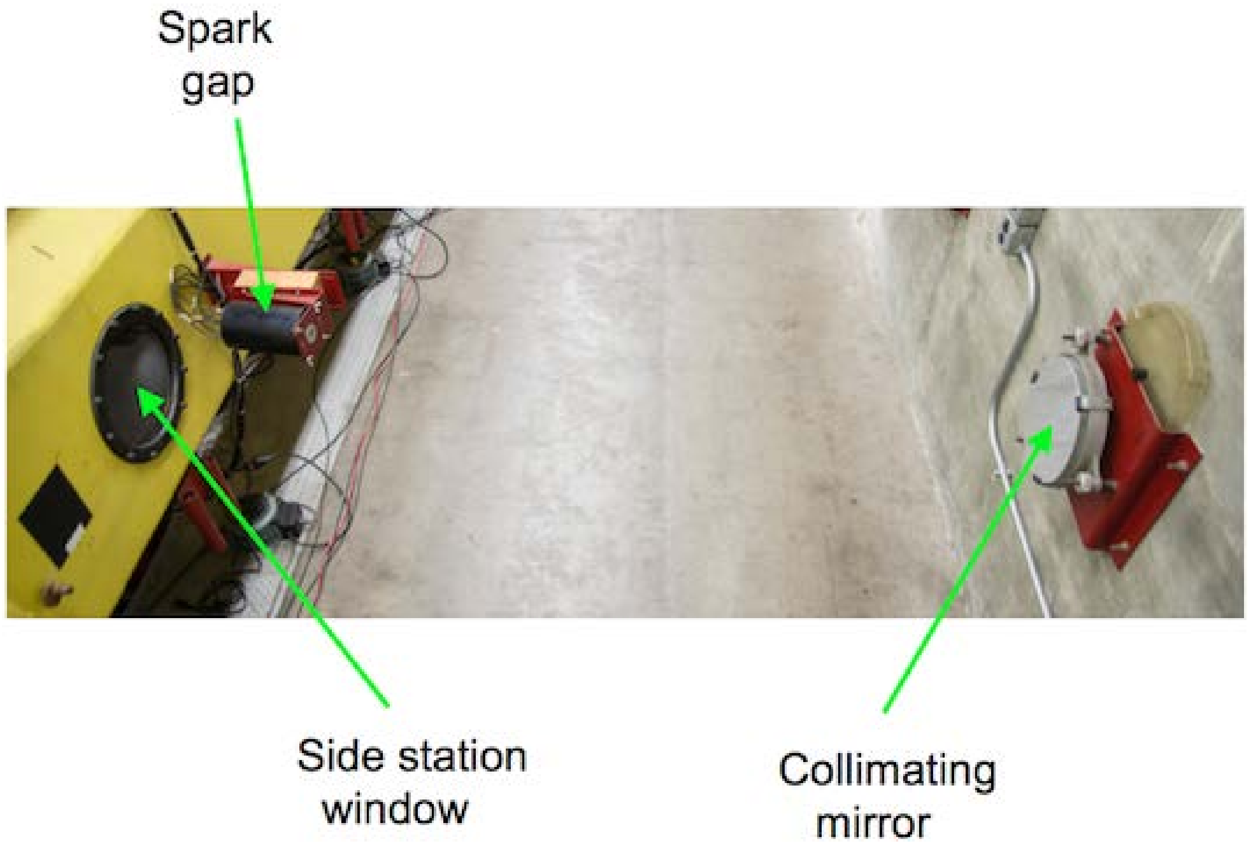
- A high-velocity rifle is used to check model-detection and shadowgraph imaging systems
- Updated from 0.220” Swift rifle to a 0.204” Ruger
  - Ammunition for the heritage rifle became difficult to obtain
  - No impact to facility operations have been found

National Aeronautics and
Space Administration

Ames Research Center
Entry Systems and Technology Division

Backup

Shadowgraphs



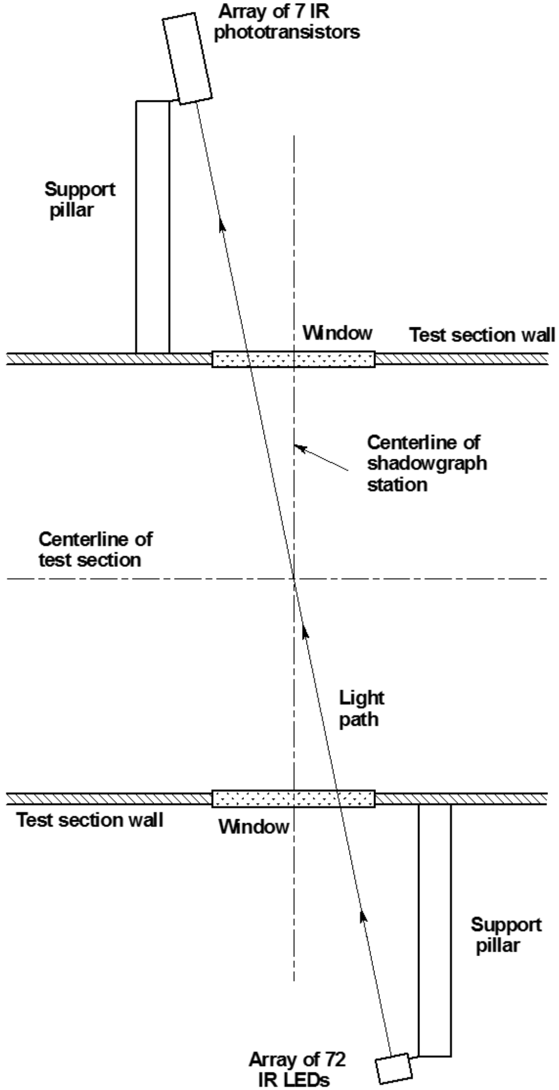
Shadowgraph optical set-up – spark gap, collimating mirror and side station window – this portion of set-up always remains unchanged

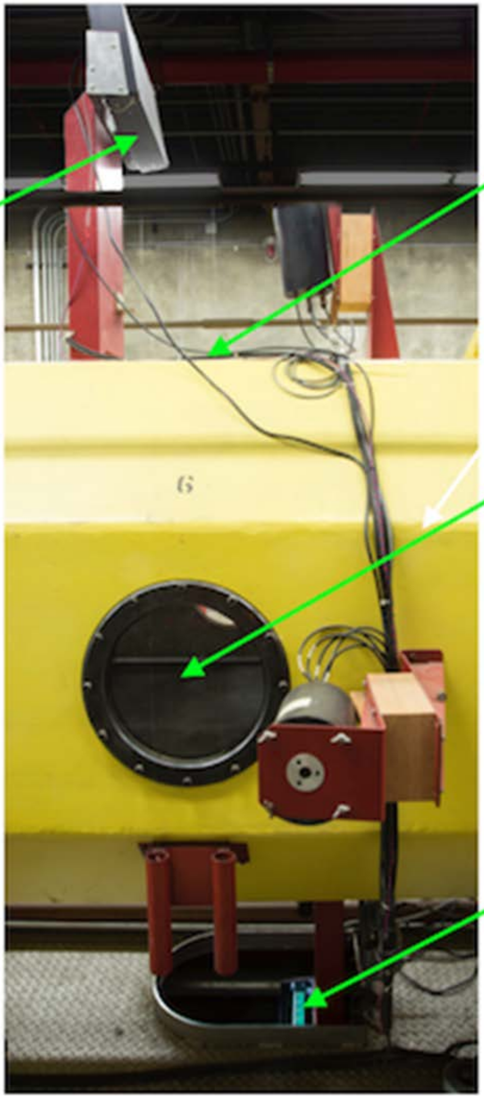
Shadowgraphs

Shadowgraph optical set-up – focussing mirror and film box. Kerr cell is behind film box.

Model Detection

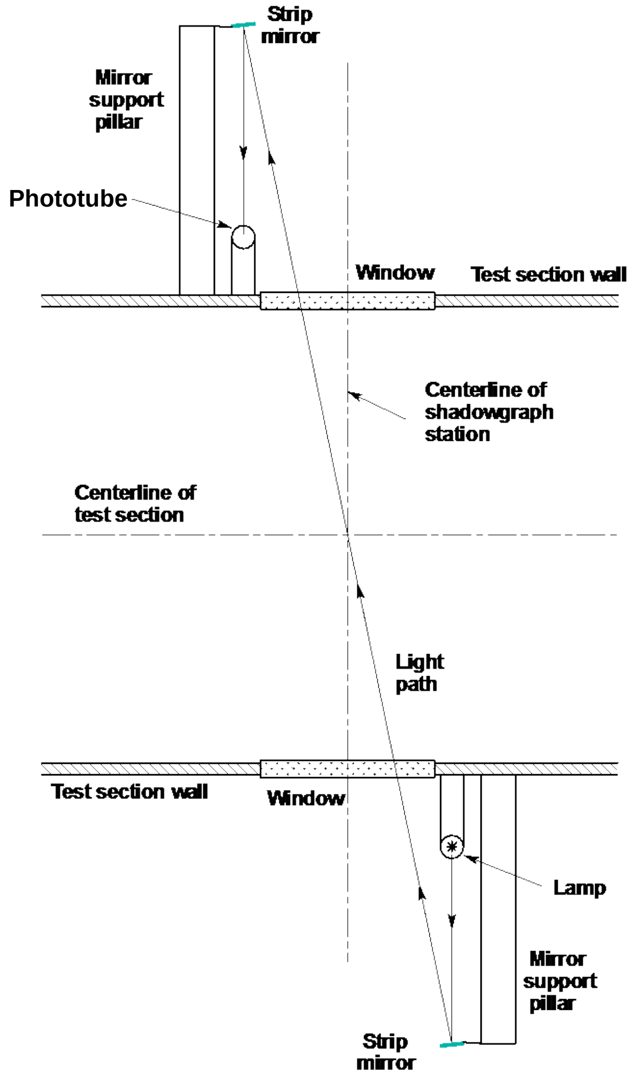
Off-the-Shelf Infrared Model Detection System

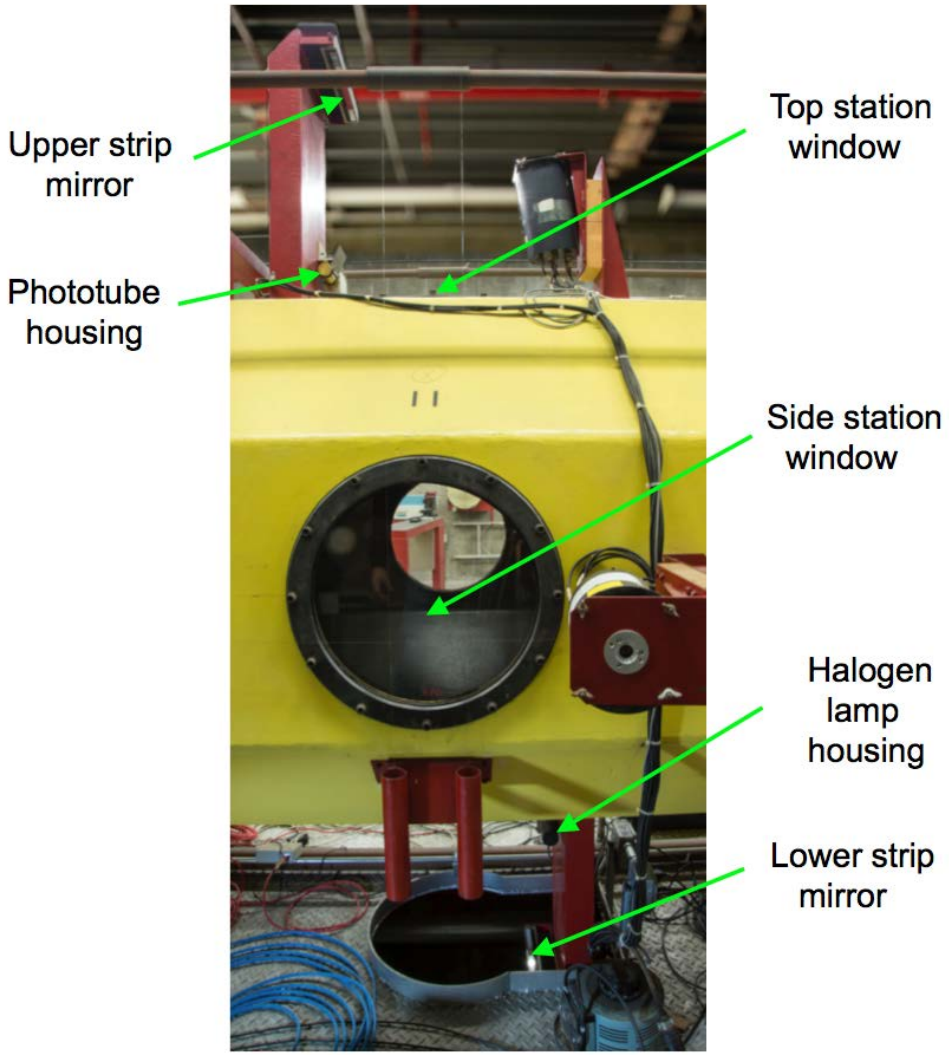




Model Detection

Standard Custom Visible Light Model Detection System





Model Detection

Tests are underway to investigate the use of a commercially-available infrared (IR) model detection system as a replacement for the custom-designed and built visible-light photobeam system

- Standard system
  - Light sheet source: Visible light from halogen lamp collimated by strip mirror
  - Light detection: Phototube
- Off-the-Shelf system
  - Light sheet source: Row of IR LEDs
  - Light detection: Row of IR phototransistors
- Results:
  - IR system found to be more likely to trigger at erroneous times with self luminous models (e.g. hypersonic tests with radiating bow shock)
  - Three IR systems implemented; on account of above issue, no more planned at this time

Shadowgraph Imaging

Sheet film/camera comparisons

Film/camera	Camera cost	Resolution	Needs Kerr cell	Wait time to view photos
Sheet film	0	High	Yes	2 - 3 hours
PI-MAX	High	Lower	No	0
Nikon	Low	High	Yes	0

Replacement gunpowder for 1.5” light gas gun

- Original powder was Hercules HC-33-FS – no longer available.
- Replacement powder, St. Marks WC 886, found.

Powder type		Hercules HC-33FS	St. Marks WC 886
Composition (%)			
	Nitrocellulose (NC)	Remainder	Remainder
	Nitrogen in NC	13.0	
	Nitroglycerin	7.0	13.0
	Diphenylamine	1.0	
	Potassium nitrate	1.0	
	Graphite (added)	0.3	
	Deterrent	2.0	6.5*
Dimensions (cm)			
	Length	0.33	0.0686
	Diameter	0.279	0.127
	Web	0.0635	0.0686†
	Perforations	7	0

*Added as an outer coating

†Taken equal to length (grain is a flattened ball)

Replacement gunpowder / New hardware

Replacement gunpowder

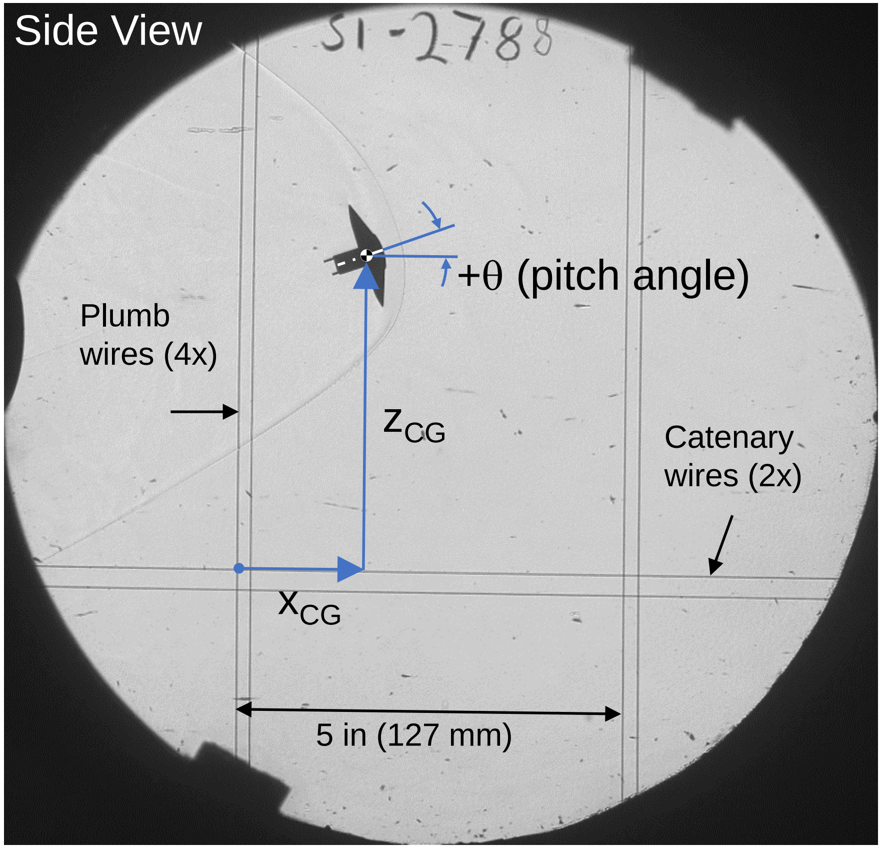
- Muzzle velocities were 5 – 9% lower with the new powder than with the old powder
- This can easily be compensated for by increasing the powder load with the new powder by ~10%

New hardware

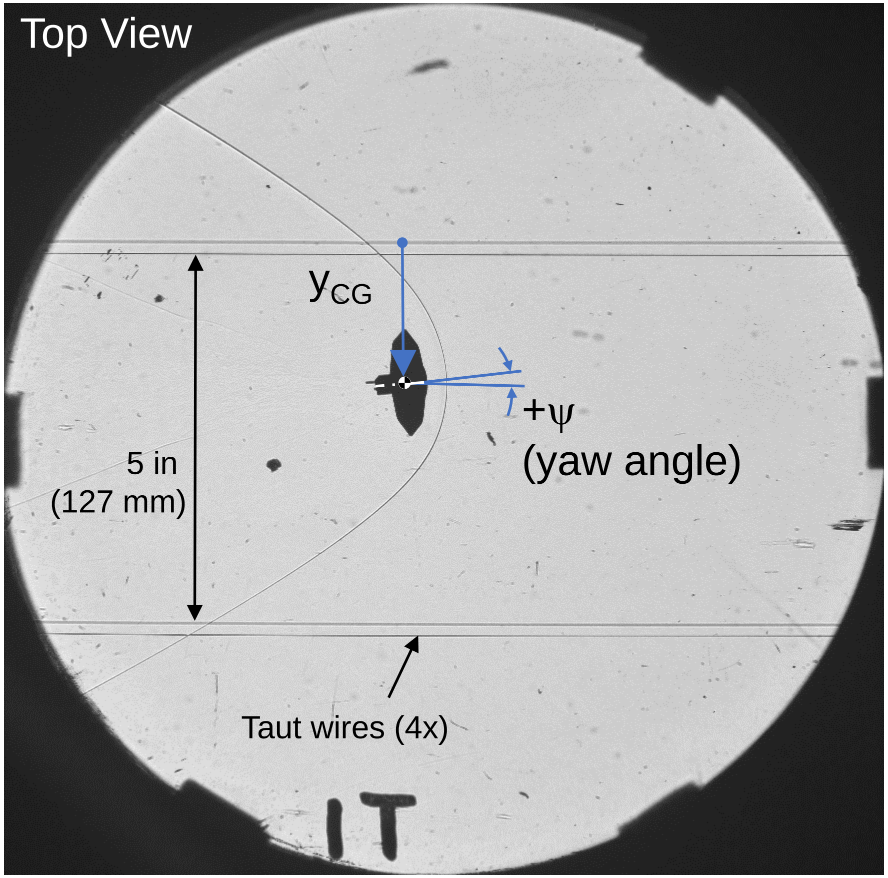
- To check out the shadowgraph stations, in the past a 0.220” rifle with 0.220” Swift ammunition was used.

- It was becoming harder to obtain the Swift ammunition, so a switch to a 0.204” Ruger rifle was made.

Image Reading: Coordinate System



- Position of the center of gravity (CG) of the model measured relative to the reference wire origin

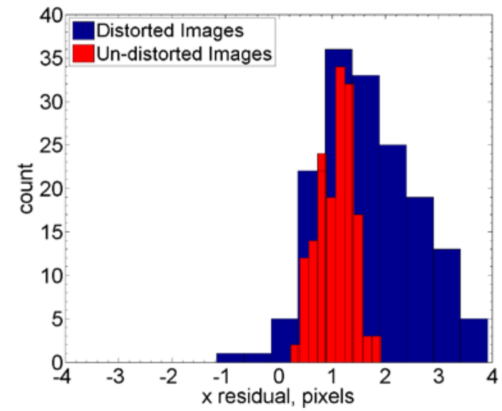


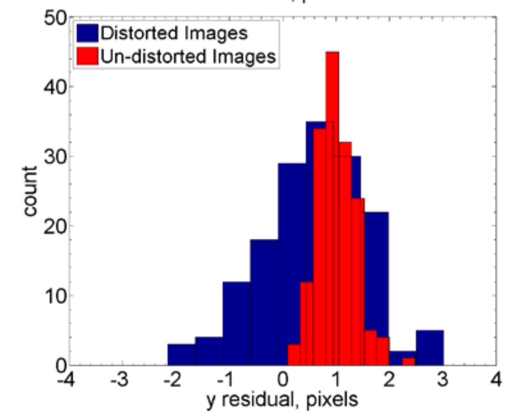
- The in-plane attitude measured relative to the reference wires
- Roll angle typically determined with reference pins on the model

CG location

- Residual error (i.e., difference between measured and the actual position) plotted as histograms for the 160 image pairs
- Normal distributions for Un-Distorted Images
- Distribution of errors slightly skewed in direction of distortion for distorted images

Un-Distorted Images			
	x	y	z
Mean error	1.07 pix 0.10 mm	1.00 pix 0.09 mm	-1.04 pix -0.10 mm
3σ	1.01 pix 0.09 mm	1.06 pix 0.10 mm	1.16 pix 0.11 mm
Distorted Images			
Mean error	**1.68 pix 0.16 mm**	**0.60 pix 0.05 mm**	**-0.53 pix -0.05 mm**
3σ	**2.79 pix 0.27 mm**	**2.93 pix 0.27 mm**	**3.28 pix 0.30 mm**





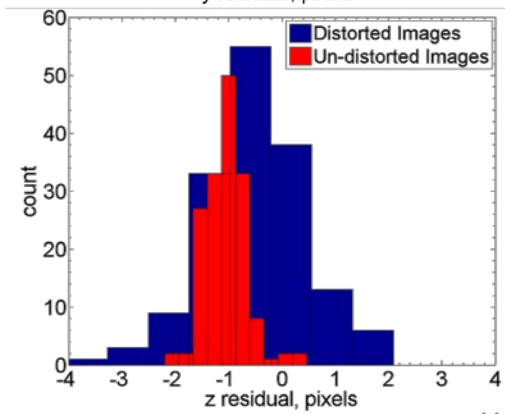


Image Reading: Evaluation

Model Attitude

- Pitch and yaw angle measurements were minimally effected by image distortion
- For roll angle (automated results without user verification), the correct angle was more frequently found for un-distorted images, however, the error for misidentified roll angles was much larger (reason TBD)

Un-Distorted Images			
	Pitch (θ)	Yaw (ψ)	Roll (ϕ)
Mean error	0.004°	0.002°	0.69°
3σ	0.51°	0.31°	11.34°
Distorted Images			
Mean error	**0.003°**	**0.009°**	**-0.04°**
3σ	**0.64°**	**0.59°**	**1.79°**