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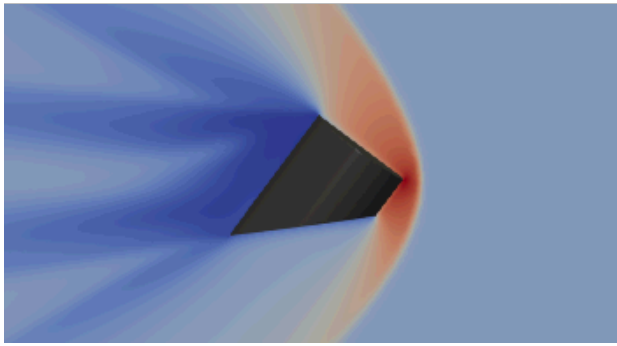

11/24/2017

Simulations of High Speed Fragment Trajectories

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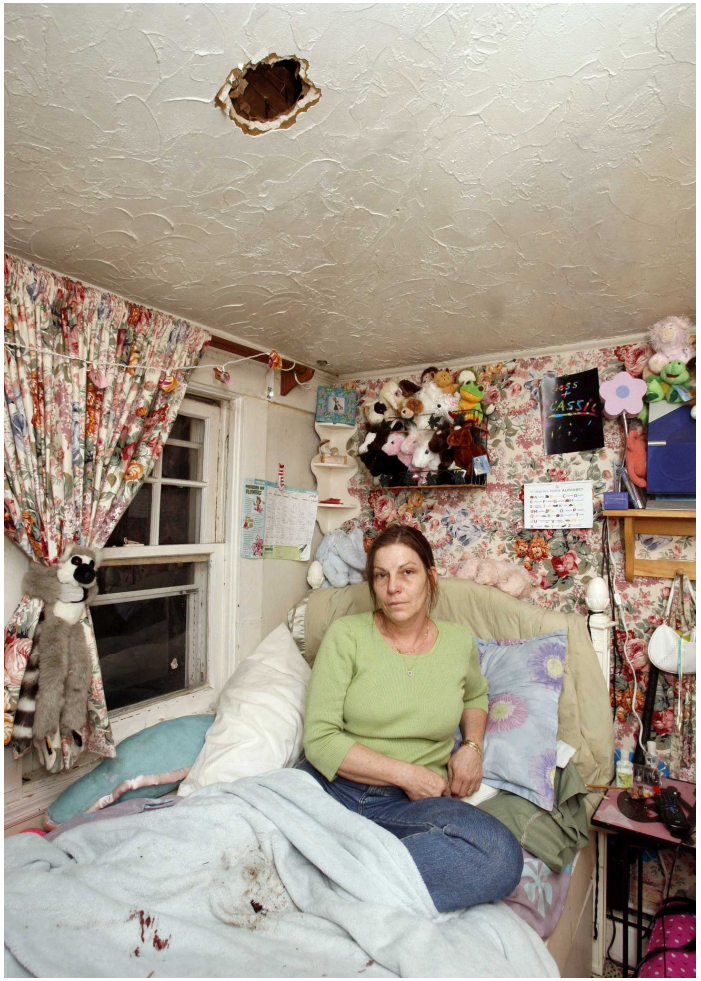
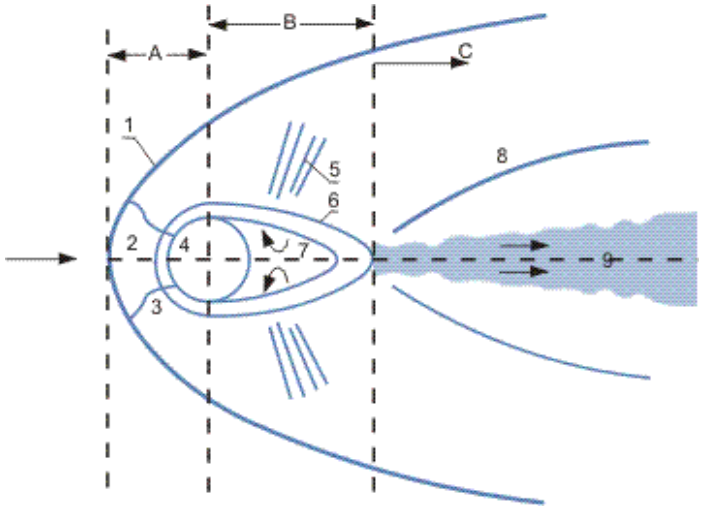
Why is understanding fragment flight important?

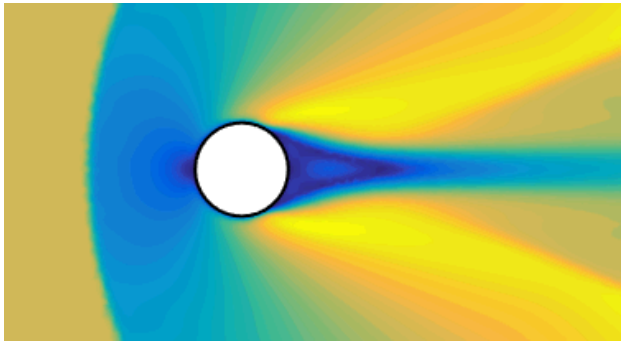
Picatinny Arsenal Accident, 2008



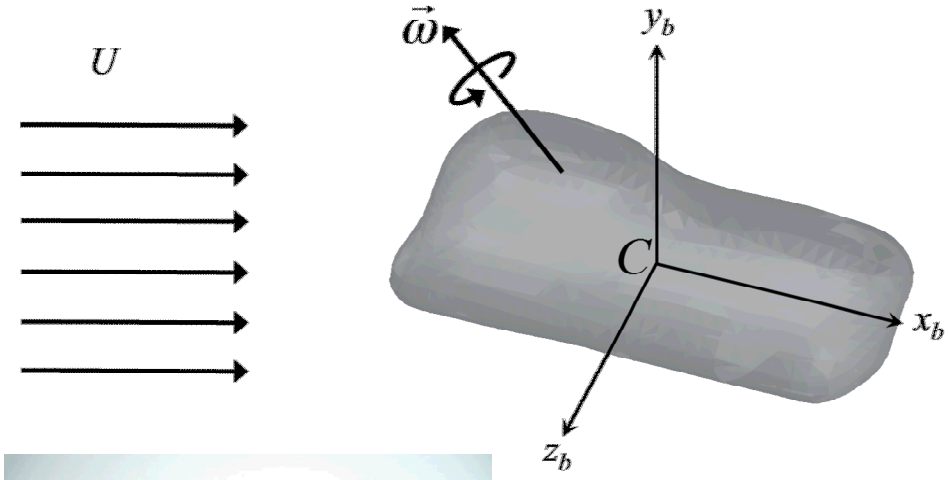
Fragment flight involves complex physics

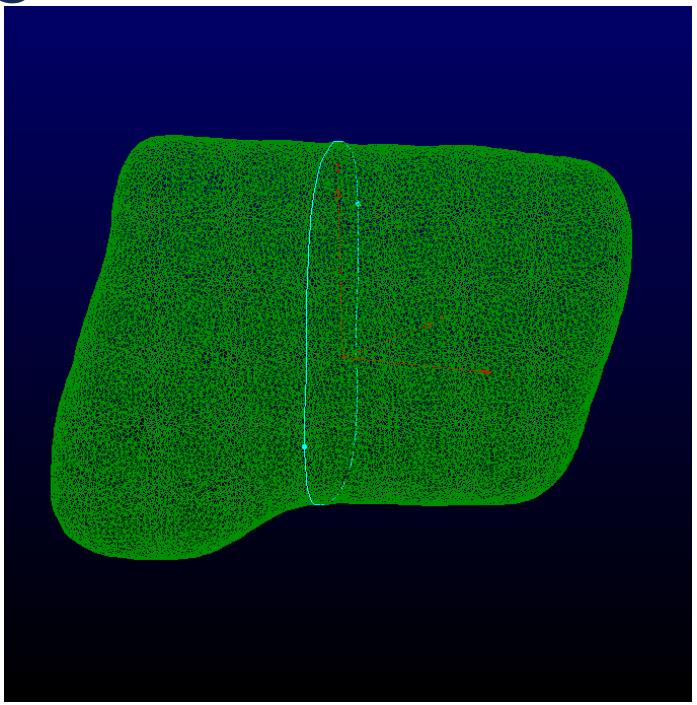
- Fragments fly at supersonic speeds
- Geometry is complicated, high aspect ratio
- Fragment-air interaction creates to tumbling and chaotic motion
- Cylinder flow field has multiple features needed to be captured
- **Approach: Computational modeling with validation by experimental testing**





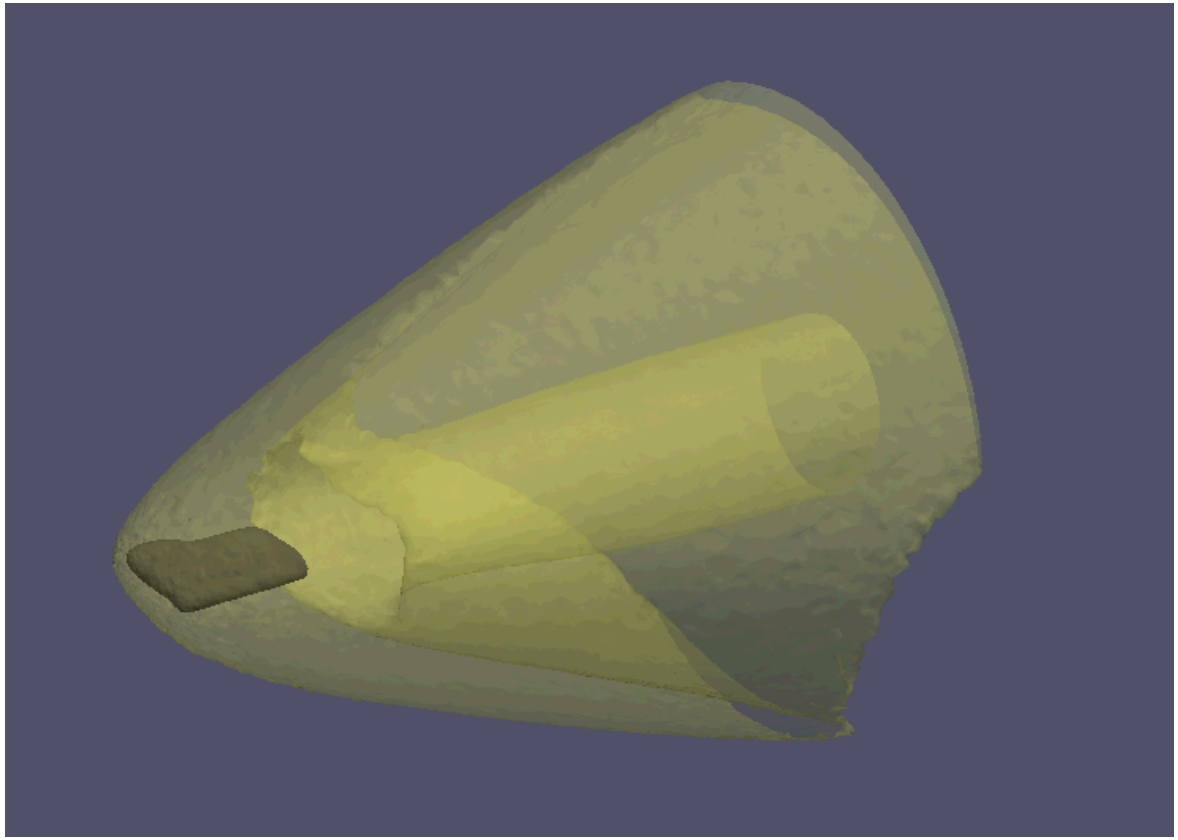
Step 1: Build database of aerodynamic coefficients





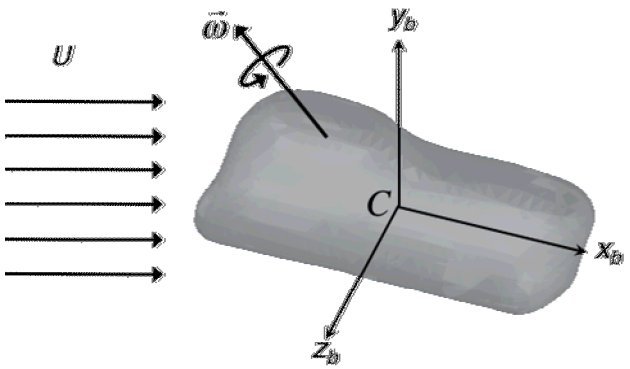
- Example fragment (output from CTH calculation)
- Unstructured tet mesh of fragment surrounded by spherical far-field
- RANS compressible flow solver with SST turbulence model
- Pressure is integrated across surface to determine forces/moments

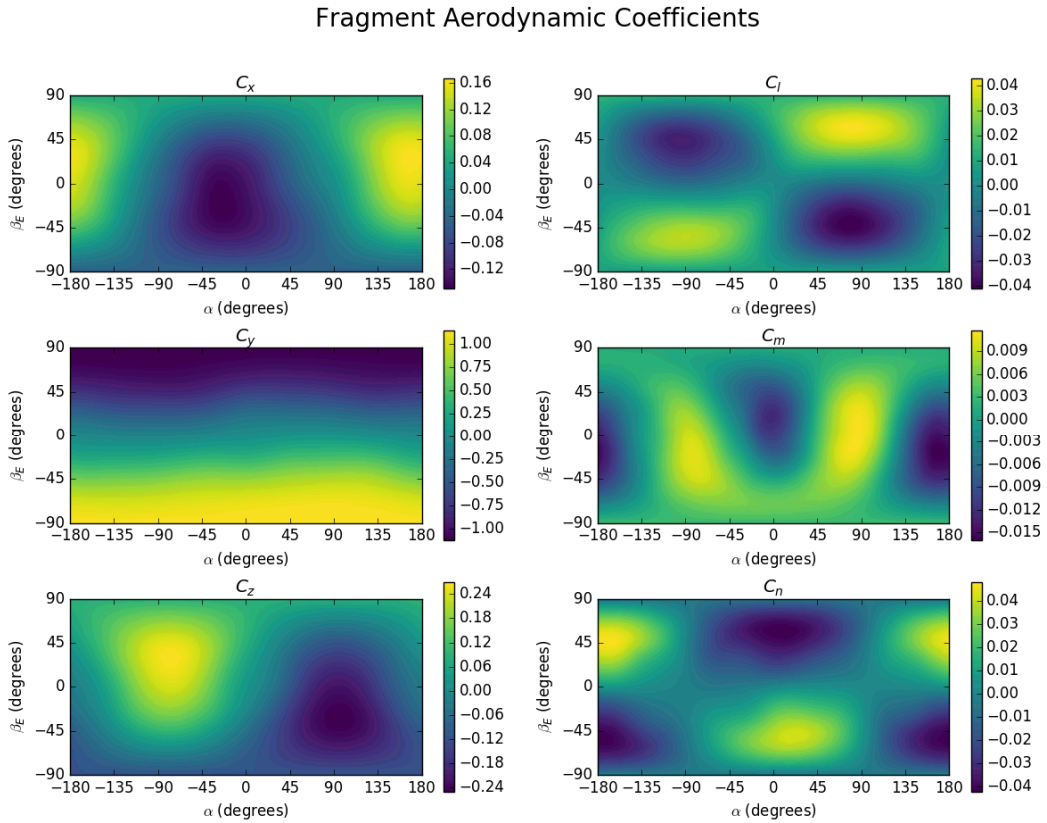
Example flow solution



- Contour of Ma = 1 shows 3D bow shock and rarefaction wave
- Calculated drag matched literature values for simple shapes (cube, sphere)

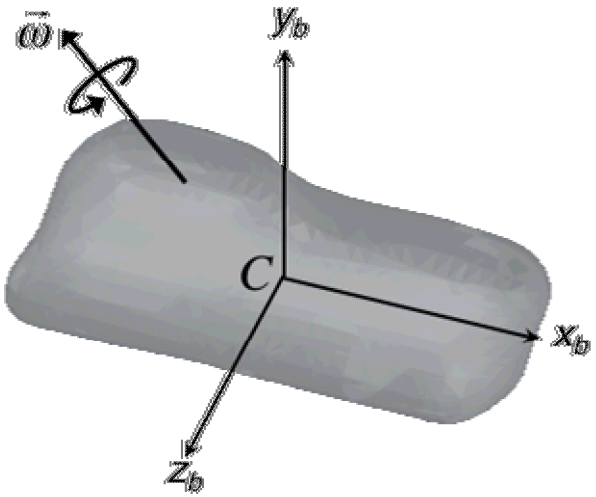
Aerodynamic database





- Orientation characterized by 2 angles
- 6 contour plots of each force/moment coefficient, 1 set per fragment

Step 2: Integrate trajectories



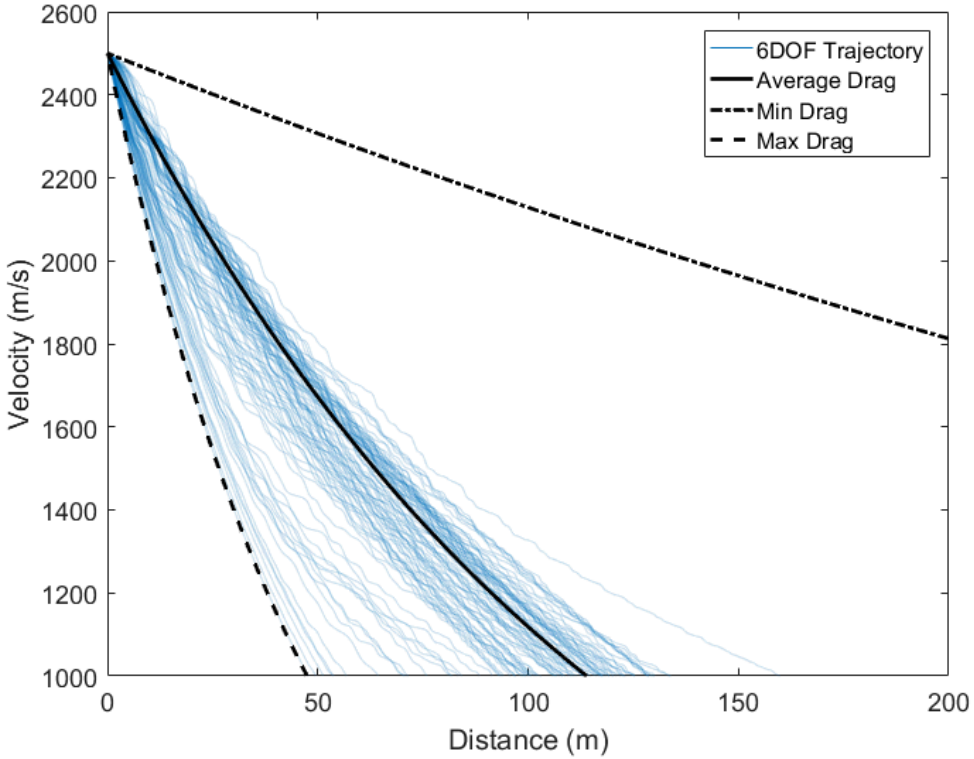
- Trajectory of example fragment
- Newton-Euler equations of motion

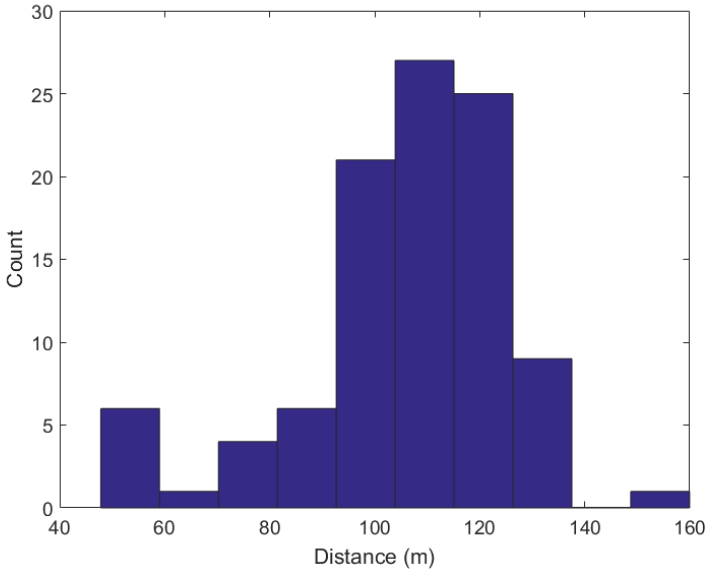
$$\sum \bar{F} = m\bar{a}_C$$

$$\sum \bar{M}_C = \frac{d\bar{L}_C}{dt} \quad \bar{L}_C = \bar{\bar{I}}_C \bullet \bar{\omega}$$

- Forces and moments used from database built by CFD simulations
  - Assume force/moment coefficients not function of Ma (Ma >= 3)
- Steel fragment, initial velocity 2500 m/s, no rotation, ~4.5 cm long

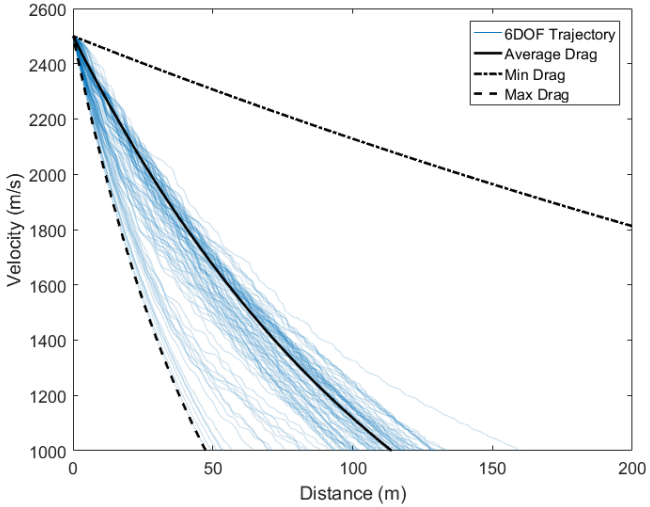
How far can fragments fly?





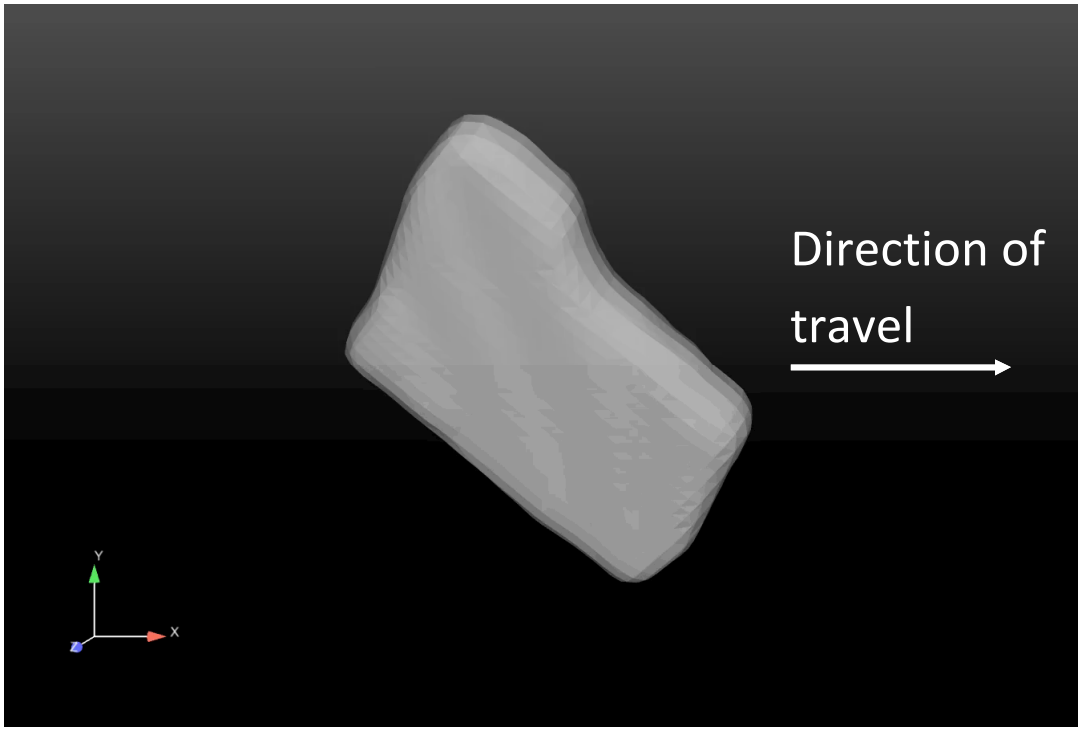
- 100 trajectories sampled with different initial orientations
- Average drag coefficient approximates most likely trajectory
- Distance ranges from 50 to 160 m!

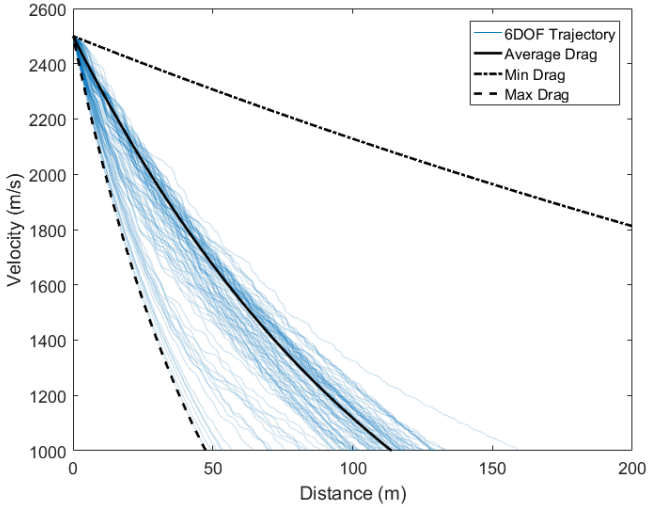
Average trajectory



- Chaotic behavior, although seems to settle on a spin/precession

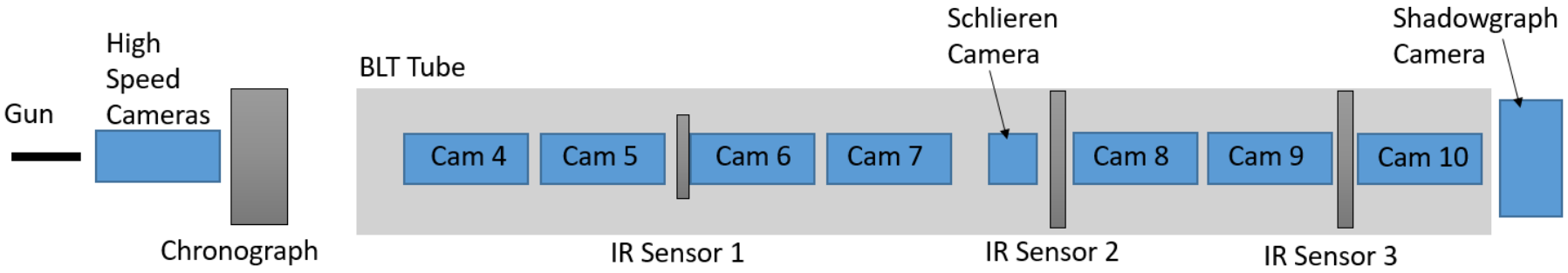
Far flying fragment





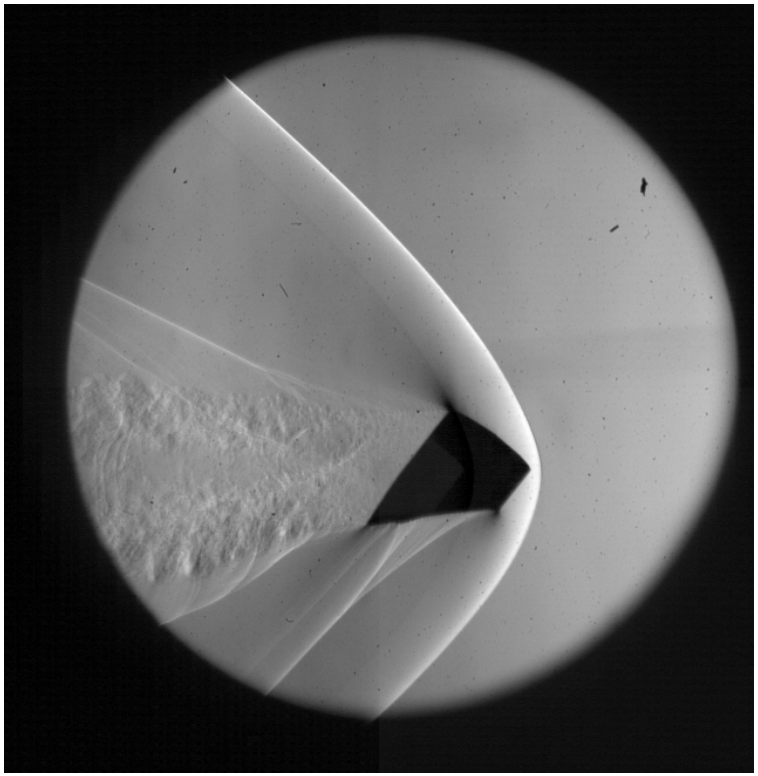
- Settles on a spin with thin edge in direction of travel (like a Frisbee)
- Experiences lower drag for longer portion of trajectory

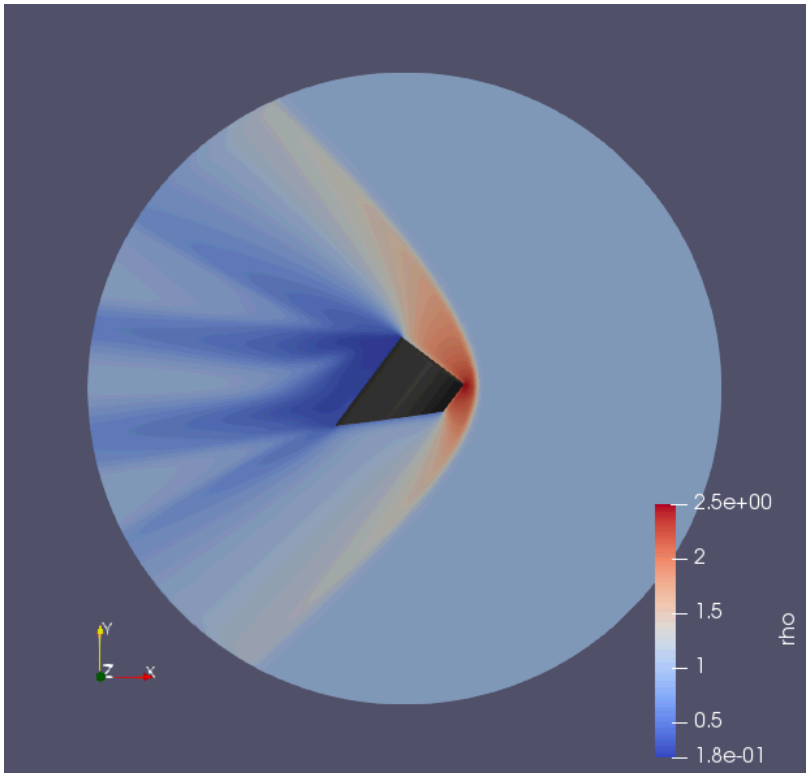
Experimental Setup



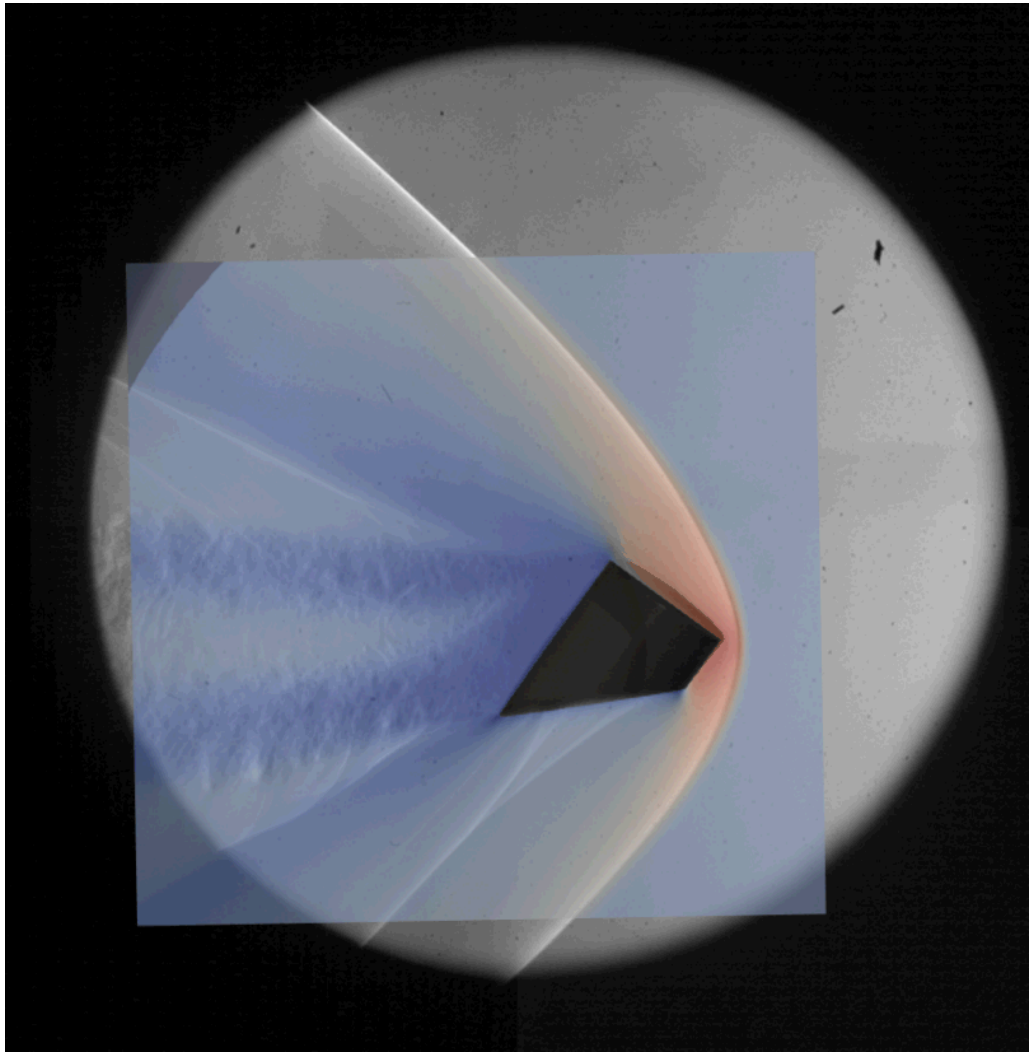
- **Approach: Shoot projectiles in unstable flight and track trajectories using series of camera stations and computer vision algorithms for simulation validation**

Comparison to CFD Simulations



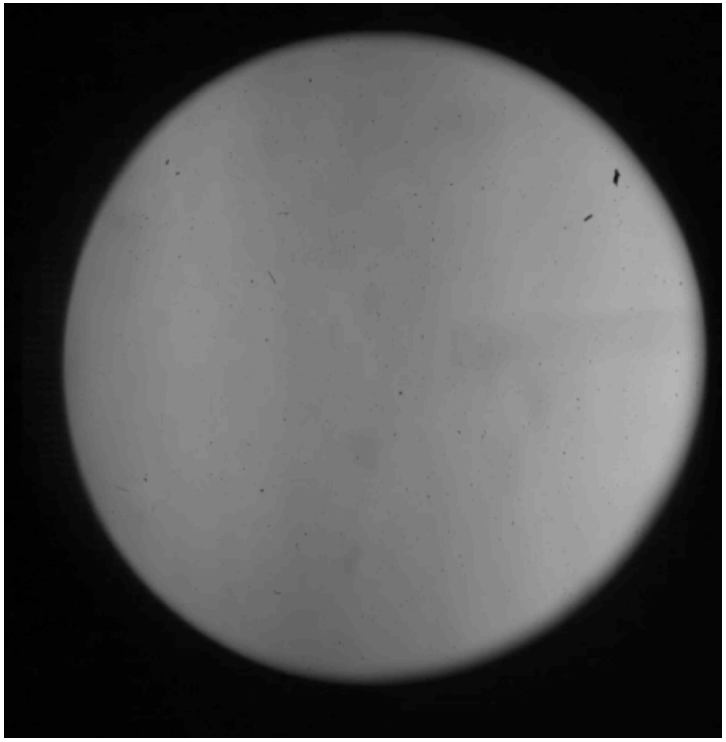


Flow Structures Line Up



Summary/Future Work

- Used simulations to determine trajectory distribution and flight dynamics of example fragment
- Experiments show promise in validating flow field and trajectory
- Future Work
  - Experimental data analysis
  - Effects of fragment shapes and sizes

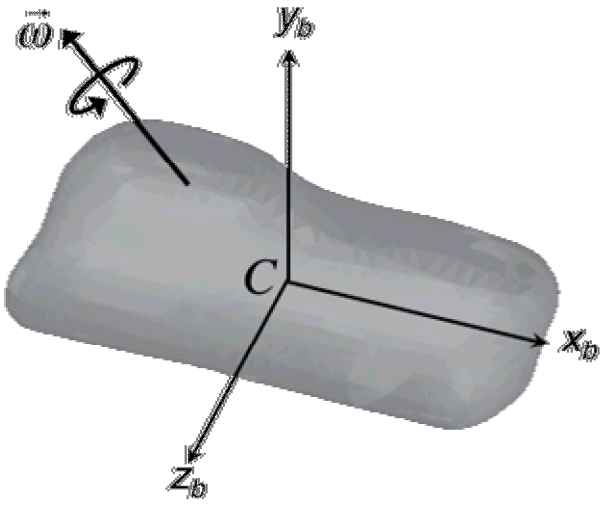


How to characterize tumbling?

- Angular velocity vector

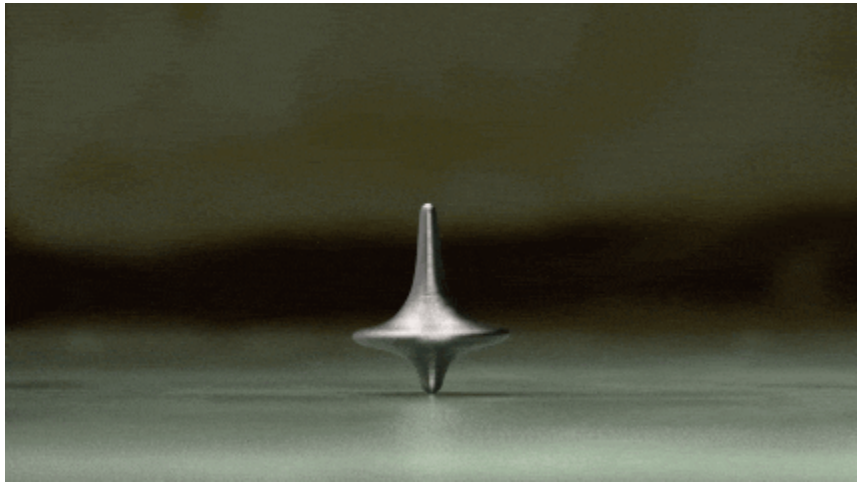
$$\vec{\boldsymbol{\omega}} = p\hat{\mathbf{x}}_b + q\hat{\mathbf{y}}_b + r\hat{\mathbf{z}}_b$$

- Plot (*p*, *q*, *r*) components in 3D *pqr*-space
- "Rotation trajectories"



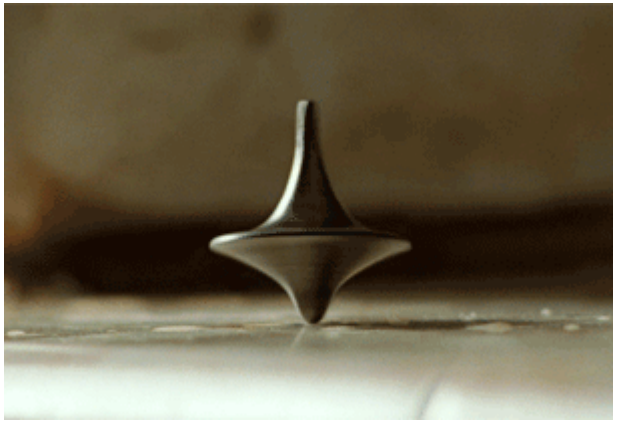
Pure spin

pqr-space : Point



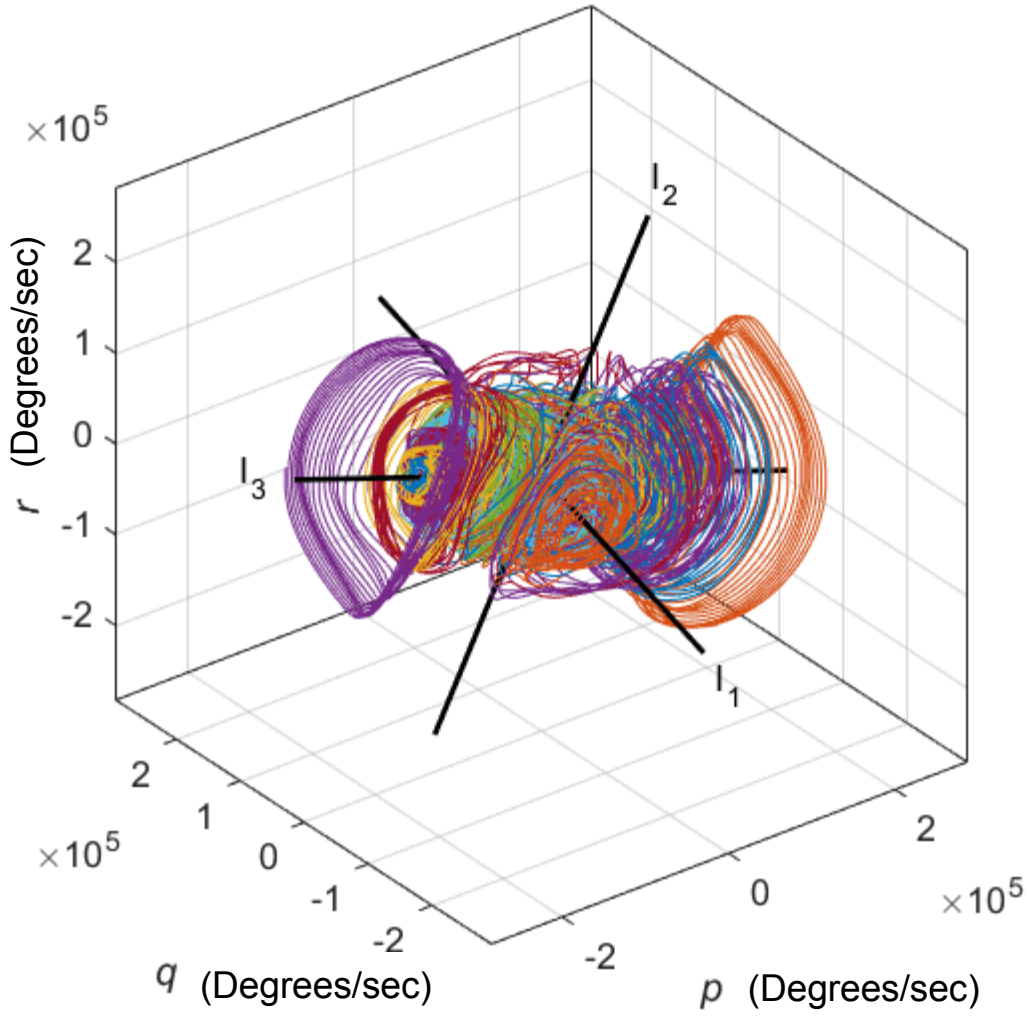
Spin + Precession

pqr-space: Orbit about spin axis



***Inception*. Warner Bros. Pictures, 2010.**

“Rotation Trajectories” for Fragment

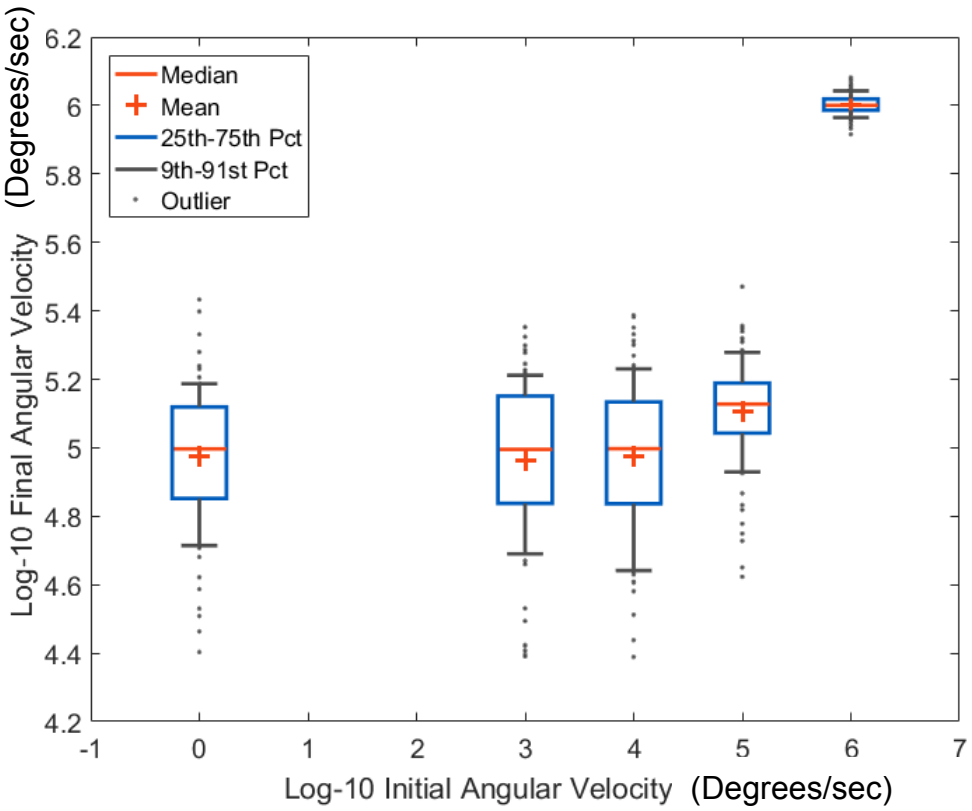


I_1, I_2, I_3: Principal axes of rotation

- Spin + Precession about I_1, I_3
- Rotation about I_2 is unstable
  - “Intermediate Axis Theorem”

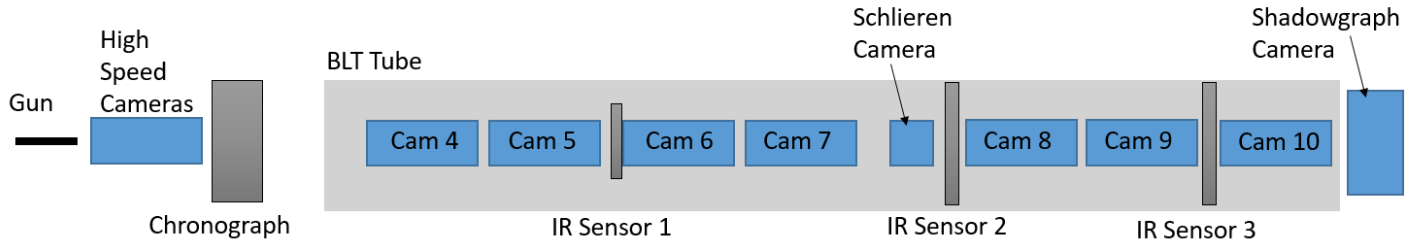
Steady Tumbling Rate

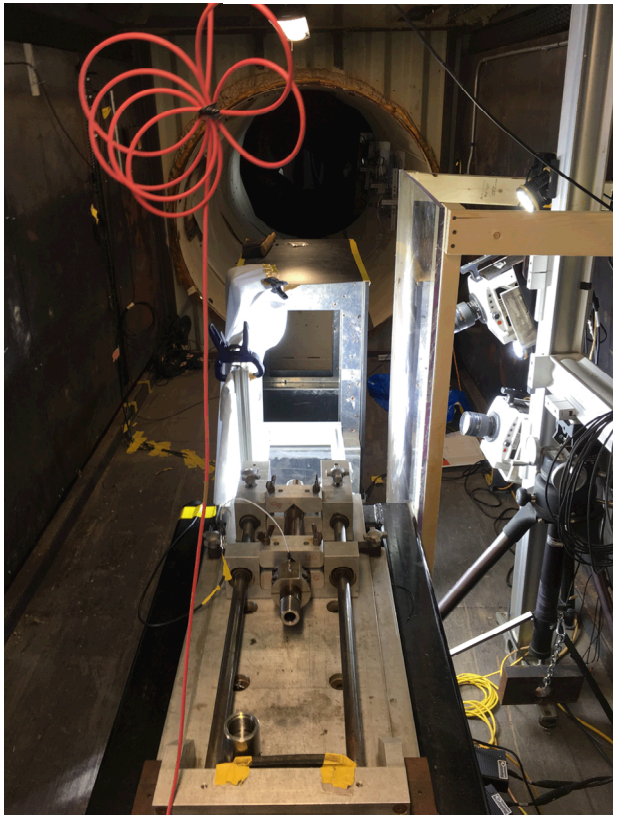
Random initial orientation
Random spin axis
100 samples per angular velocity

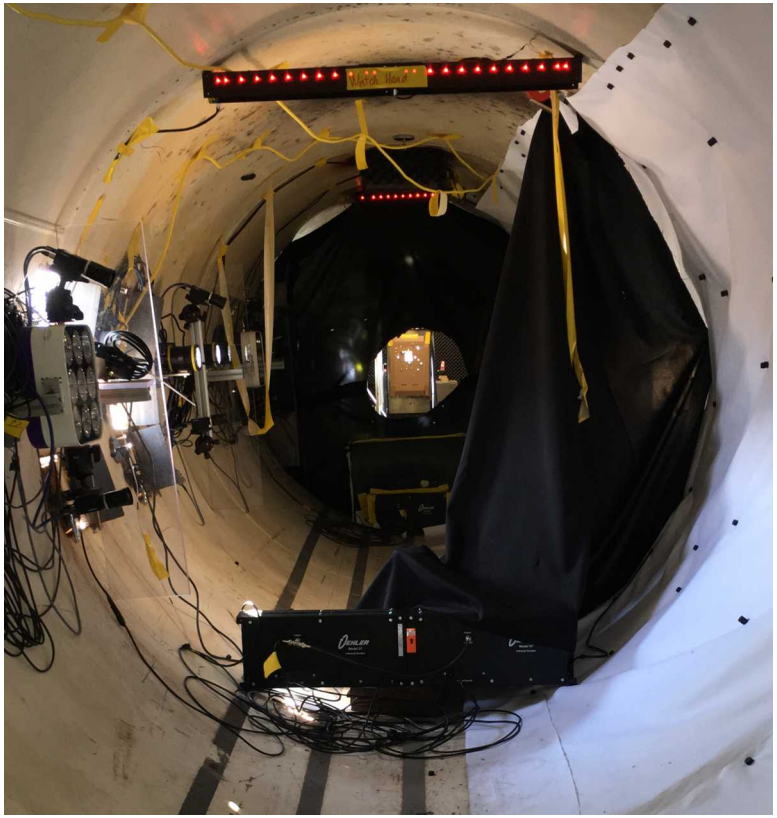


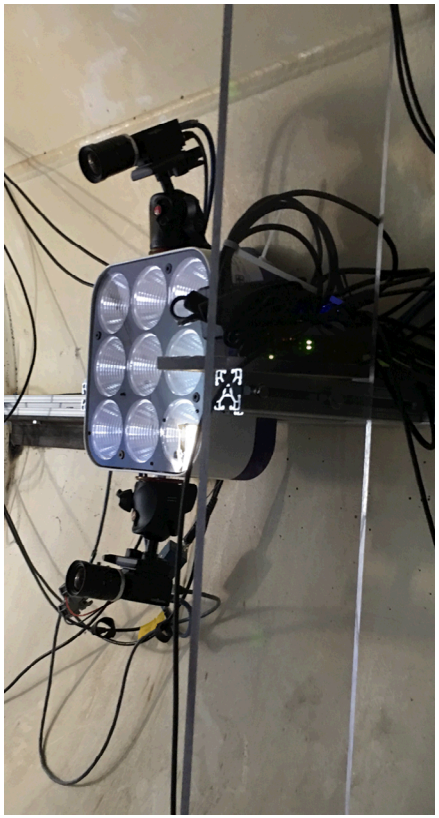
- Fragment reaches steady tumbling rate of ~10^5 deg/s (3.6 ms period)
- Higher initial tumbling rate is not dissipated in time

Stereo Systems

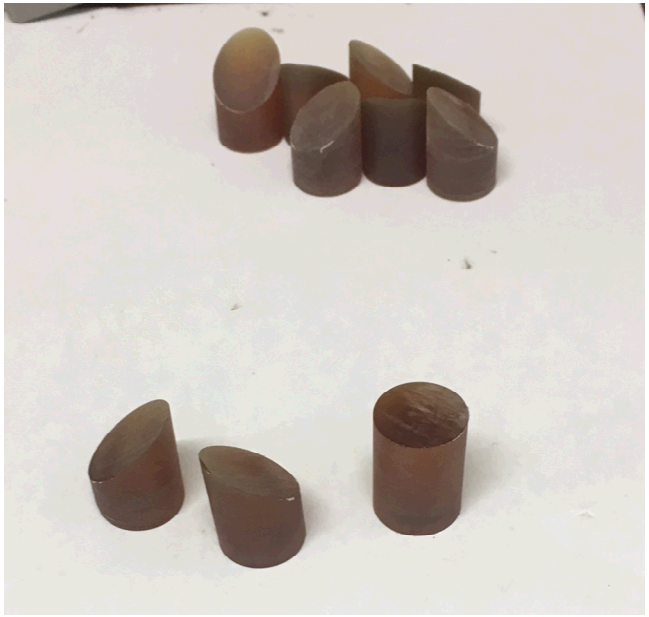




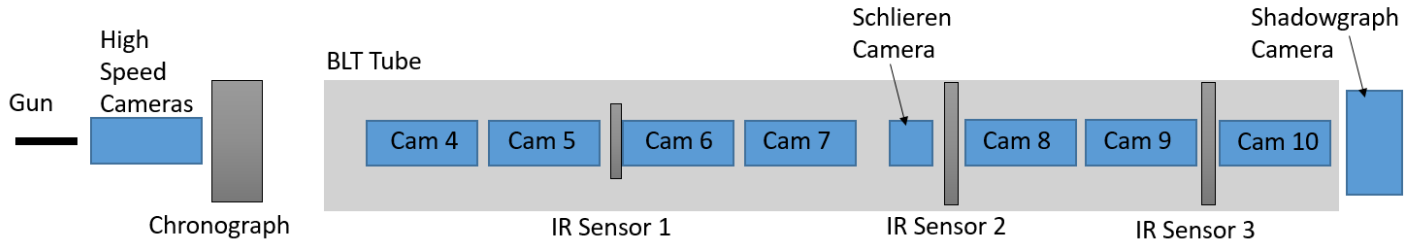




High Speed Stereo System

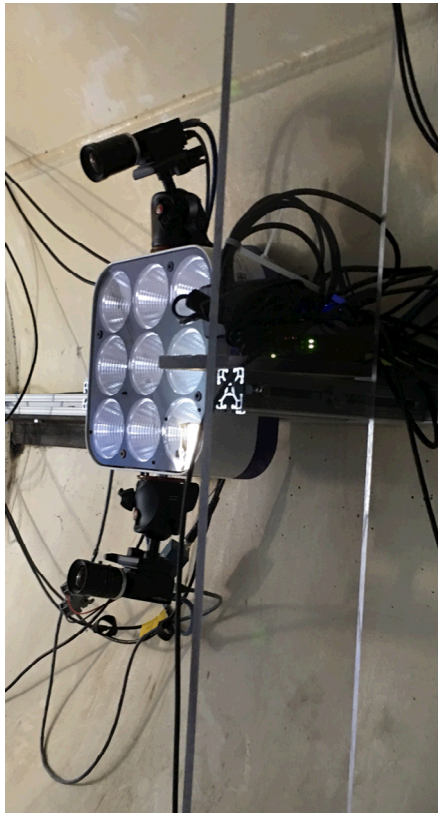


Stroboscopic Camera System



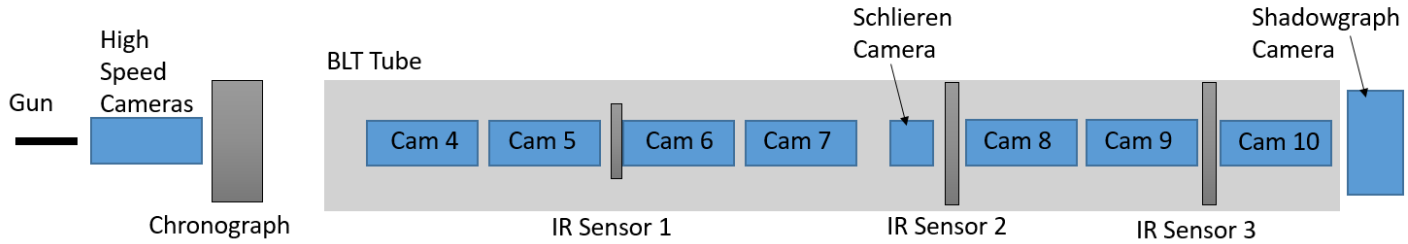
- Open shutter, light pulsed technique
- Need very high frequency light pulses for projectile

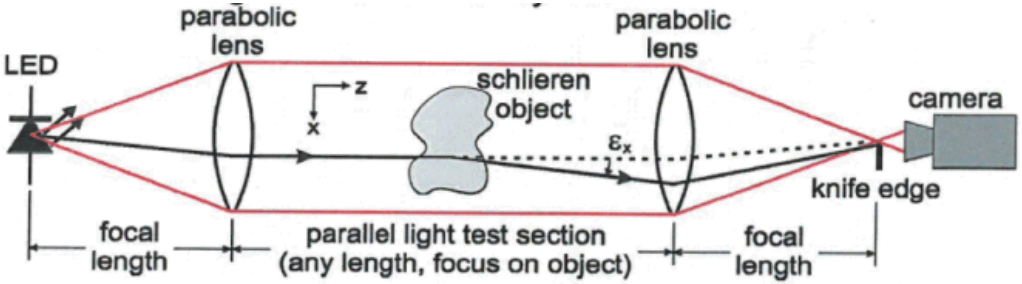
Wikipedia

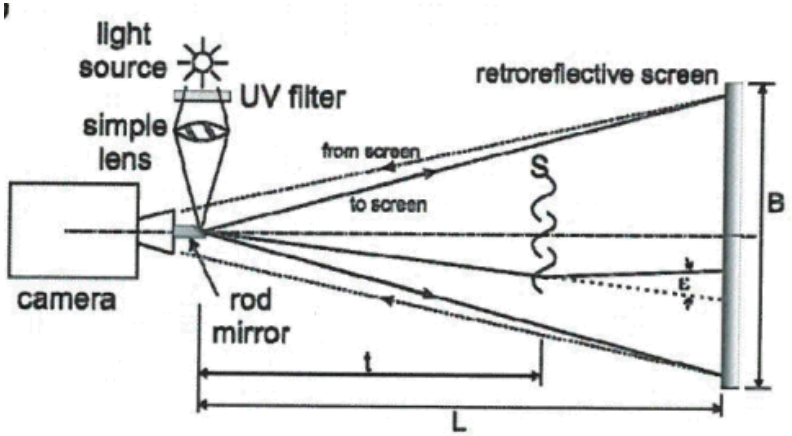


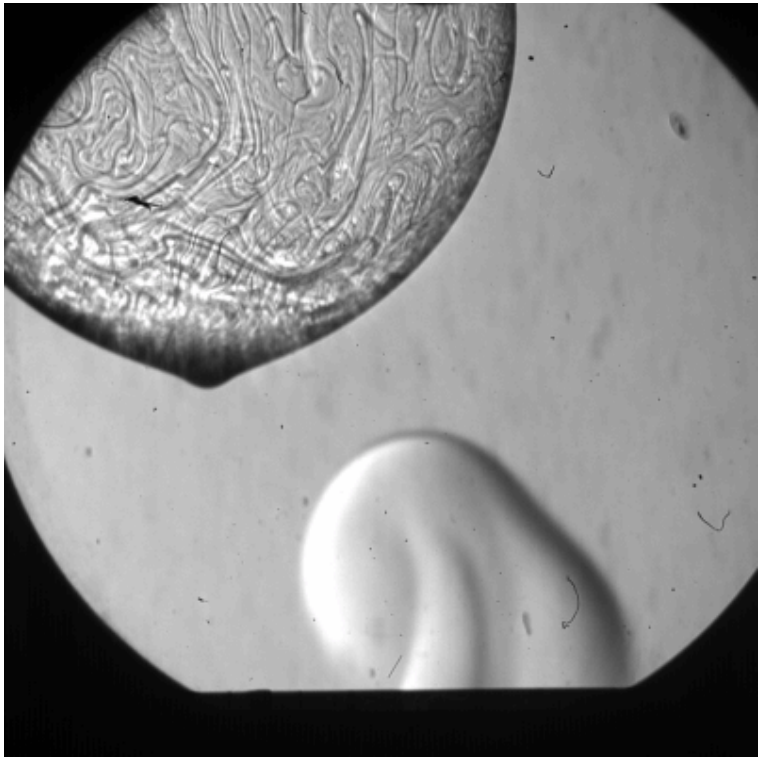
Stroboscopic Images

Schlieren & Shadowgraph Imaging





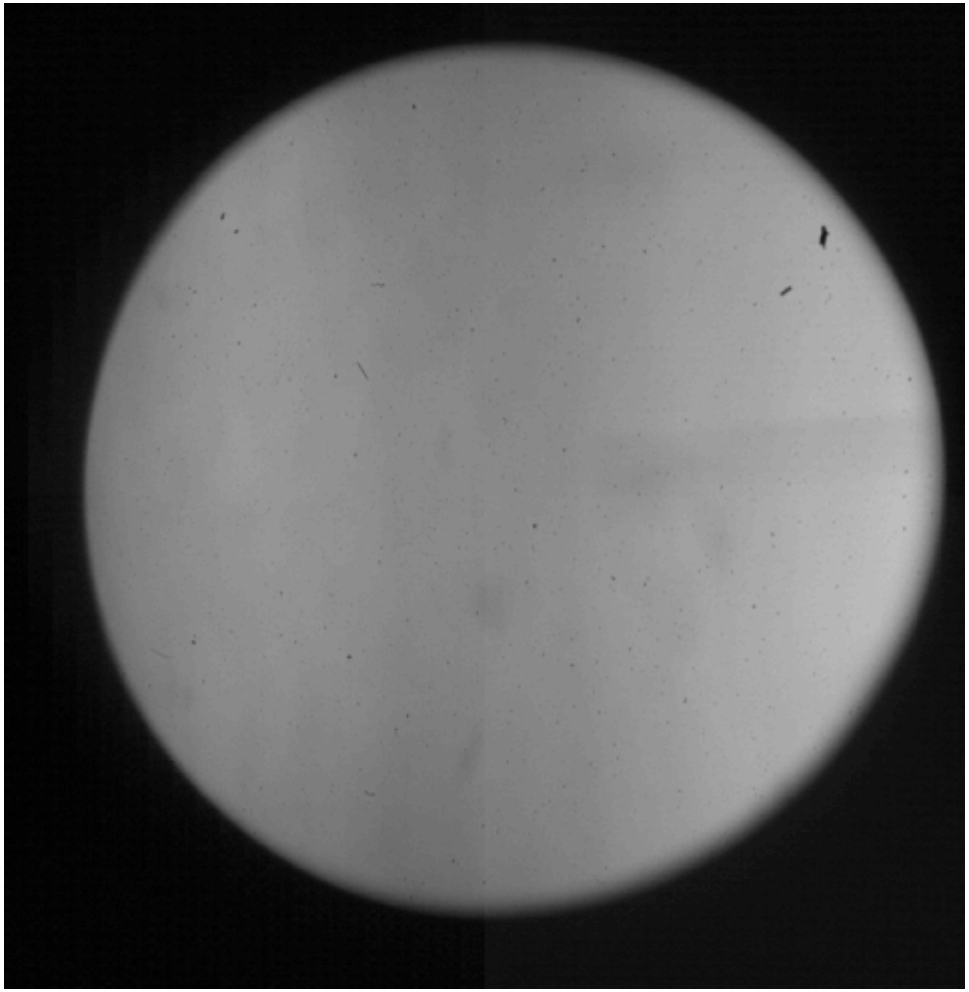




Michael Hargather, New Mexico Tech

Shadowgraph

Schlieren



Questions?