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Prediction of High Speed Rigid Body Manoeuvring in Air-Water-Sediment

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Sponsored by
ONR Coastal Engineering

Sixth International Conference Advances in Fluid Mechanics, Skiathos, Greece, May 8-10, 2006

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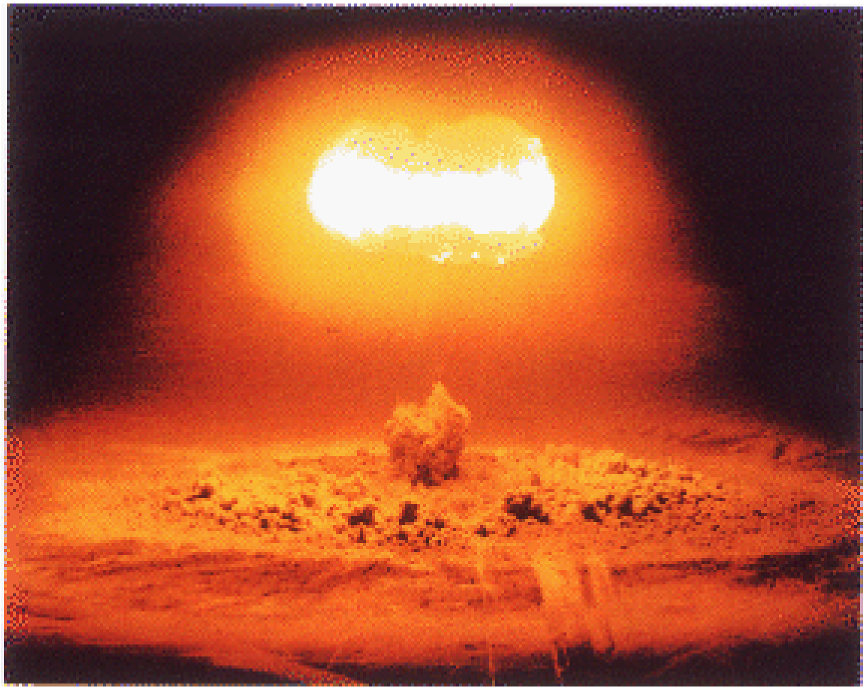
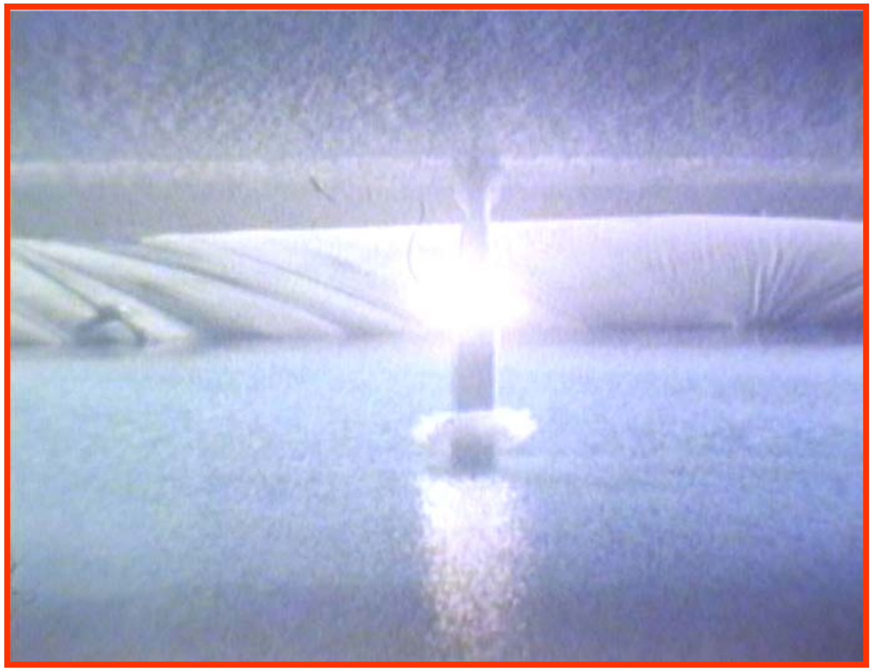
- Chu, P.C., 2006: Mine impact burial prediction from one to three dimensions. **IEEE Journal of Oceanic Engineering**, in revision.

Scientific Problems

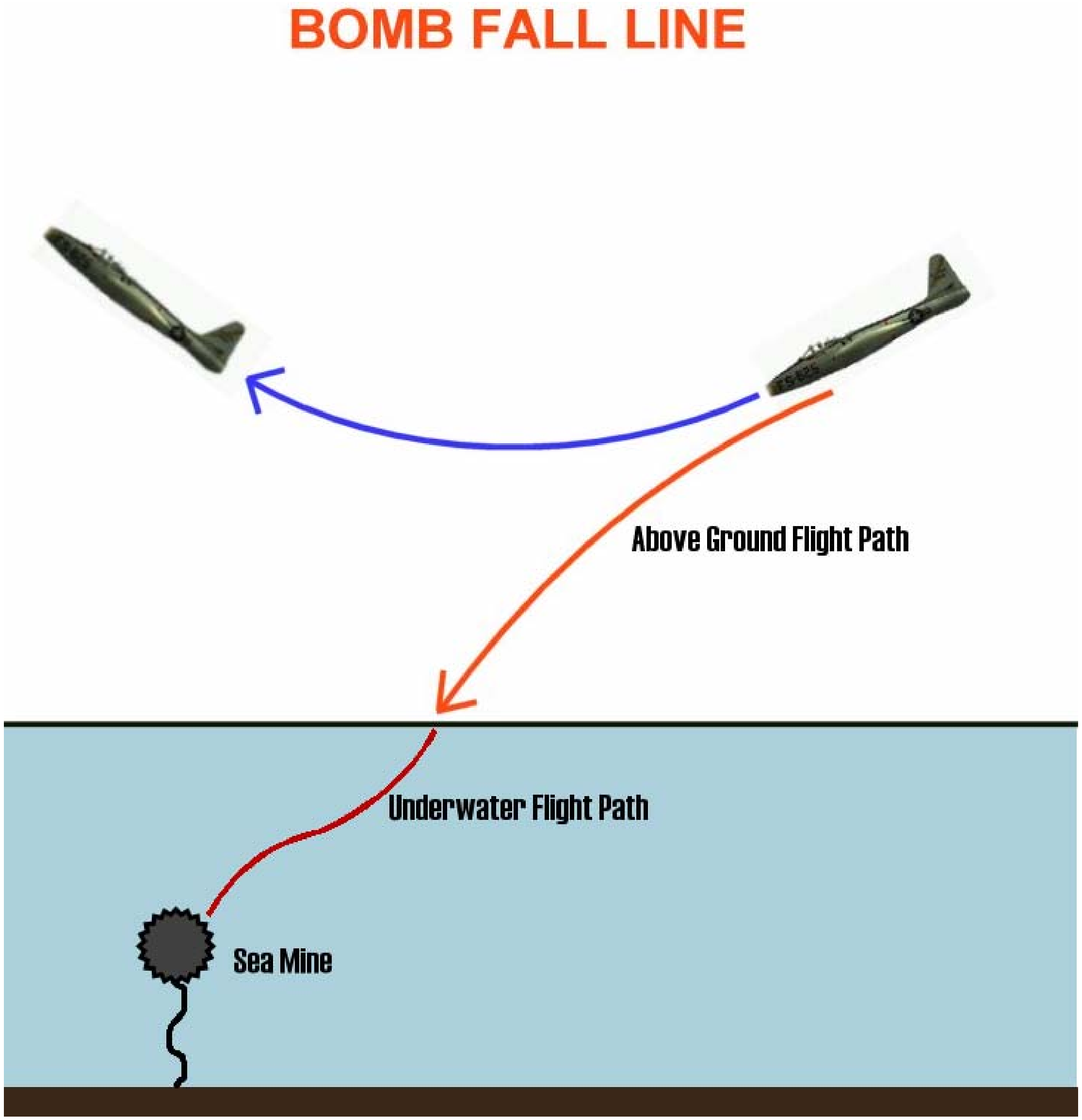
- Supercavitation
- Bubble Dynamics
- Nonlinear System

Military Application
Bomb Strike for Mine Clearance





Prediction of Bomb Maneuvering Trajectory



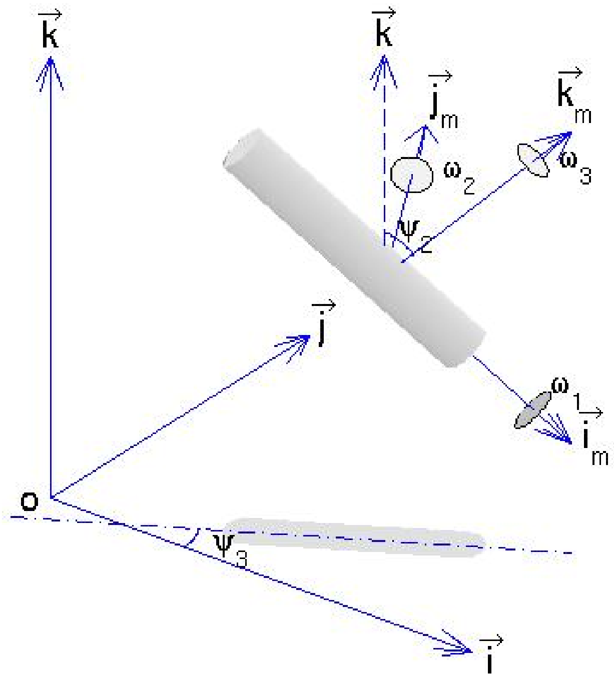
3D Model Development

- Triple Coordinate Systems
- Momentum Equations
- Moment of Momentum Equations
- Supercavitaion
- Bubble Dynamics

Triple Coordinate Transform

- Earth-fixed coordinate (E-coordinate)
- Bomb’s main-axis following coordinate (M-coordinate)
- Hydrodynamic force following coordinate (F-coordinate).

E and M Coordinate Systems



$$\mathbf{j}_M = \mathbf{k} \times \mathbf{i}_M, \qquad \mathbf{k}_M = \mathbf{i}_M \times \mathbf{j}_M$$

E-Coordinate, $F_E(O, \mathbf{i}, \mathbf{j}, \mathbf{k})$

- COM Position: $\mathbf{X} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$,

- Translation velocity:

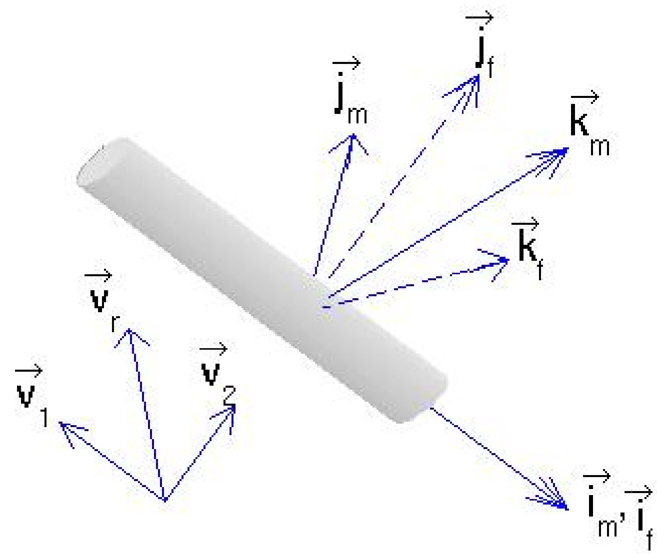
$$d\mathbf{X}/dt = \mathbf{V}, \quad \mathbf{V} = (u, v, w)$$

Transform Between E- and M-Coordinate Systems

$${}^{E}_{M}\mathbf{R}(\psi_2,\psi_3) \equiv \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}:$$

$$= \begin{bmatrix} \cos\psi_3 & -\sin\psi_3 & 0 \\ \sin\psi_3 & \cos\psi_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\psi_2 & 0 & \sin\psi_2 \\ 0 & 1 & 0 \\ -\sin\psi_2 & 0 & \cos\psi_2 \end{bmatrix},$$

F-Coordinate System



E- and F-Coordinate Transform

$$\mathbf{i}_F = \mathbf{i}_M = \begin{bmatrix} r_{11} \\ r_{21} \\ r_{31} \end{bmatrix}, \qquad \mathbf{j}_F = \mathbf{V}_2 / |\mathbf{V}_2|, \qquad \mathbf{k}_F = \mathbf{i}_F \times \mathbf{j}_F.$$

$${}^{E}_{F}\mathbf{R}(\psi_2, \psi_3, \phi_{MF}) \equiv \begin{bmatrix} r_{11} & r'_{12} & r'_{13} \\ r_{21} & r'_{22} & r'_{23} \\ r_{31} & r'_{32} & r'_{33} \end{bmatrix},$$

Momentum Equation in E-Coordinate System

$$\frac{d}{dt}\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ g(\rho_w / \rho - 1) \end{bmatrix} + \frac{\rho_w}{\rho}\frac{D\mathbf{V}_w}{Dt} + \frac{1}{\rho\Pi}(\mathbf{F}_h + \mathbf{F}_v),$$

$\mathbf{F}_h$ is hydrodynamic force (drag, lift)

$\mathbf{F}_v$ is the bubble force

Moment of Momentum Equation in M-Coordinate System

$$\mathbf{J} \cdot \frac{d\omega}{dt} = \mathbf{M}_w + \mathbf{M}_b + \mathbf{M}_h + \mathbf{M}_v,$$

Inertial terms are small

M-Coordinate

The moment of gyration tensor for the axially Symmetric cylinder is a diagonal matrix

$$\mathbf{J} = \begin{bmatrix} J_1 & 0 & 0 \\ 0 & J_2 & 0 \\ 0 & 0 & J_3 \end{bmatrix},$$

Supercavitation

- (1) Cavity Radius (Dare et al., 2004)

$$r_{cav} = \frac{d}{2}\sqrt{\frac{kx_M}{d} + 1},$$

k = 2, d is nose diameter

- (2) Cavity Number

$$\sigma = \frac{p - p_v}{\frac{1}{2}\rho_w V_w^2},$$

Drag Coefficient in Supercavitation

$$C_d = \left(\frac{2r_{cav}}{d} \right)^2 (\sigma - 0.132\sigma^{8/7})$$

Bubble Dynamics

$$\mathbf{F}_V = 2\pi r_b^2 \rho_w (\mathbf{V}_w - \mathbf{V}) \frac{dr_b}{dt}$$

$$r_b \frac{d^2 r_b}{dt^2} + \frac{3}{2}\left(\frac{dr_b}{dt}\right)^2 = \frac{1}{\rho_w}\left(p_v - p_g \frac{\Pi_{b0}}{\Pi_b} - p - \frac{2\tau}{r_b} - \frac{4\mu}{r_b}\frac{dr_b}{dt}\right),$$

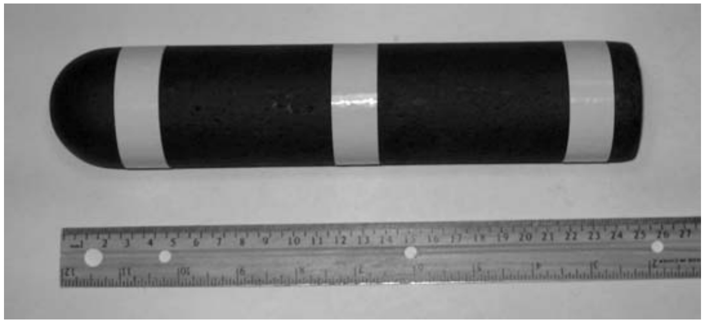
r_b is the bubble radius

Bomb Strike Experiment

- Improve warhead lethality for use in quick, precise and accurate strikes on known enemy naval minefields in the littoral combat environment.

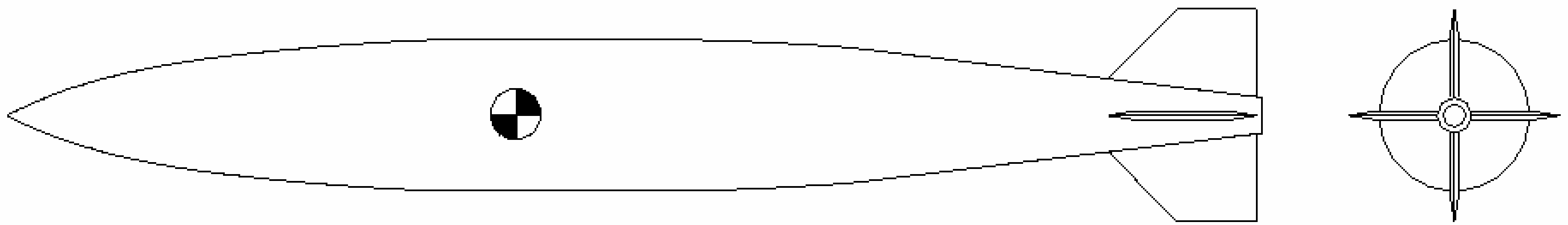
- Collect data for model development and validation

1/12 the Scale Bomb Models



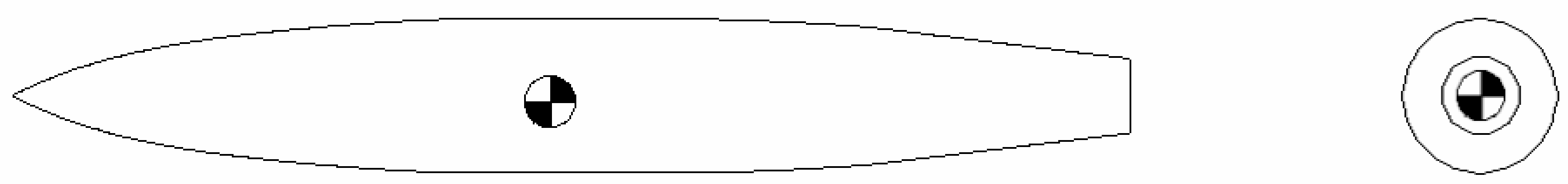
MK-84 1/12 Scale Model Bomb

- 8 Runs Total
- V_{max} : 87.1 m/s V_{min} : 42.6 m/s
- 6/8 displayed straight arc



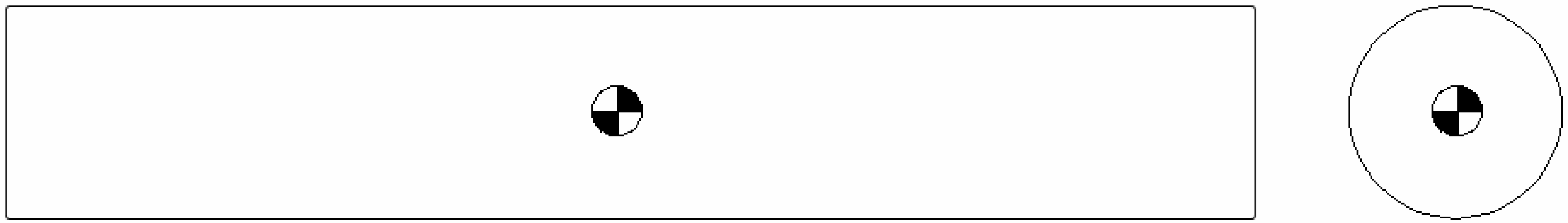
Shell Shape (MK-84 w/ No Fins)

- 11 Runs Total
- V_{max} : 109.5 m/s V_{min} : 29.1 m/s
- 8/11 displayed short-arc-flip



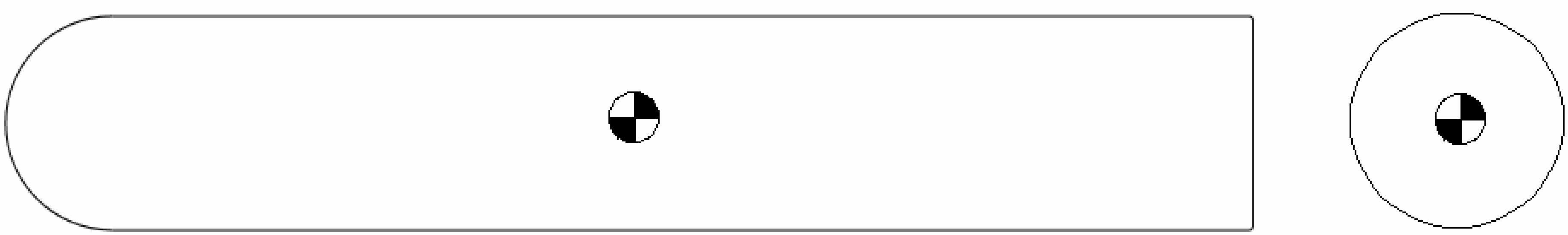
Cylinder Shape

- 12 Runs Total
- V_{max} : 67.9 m/s V_{min} : 28.2 m/s
- 9/12 displayed straight spiral



Capsule Shape

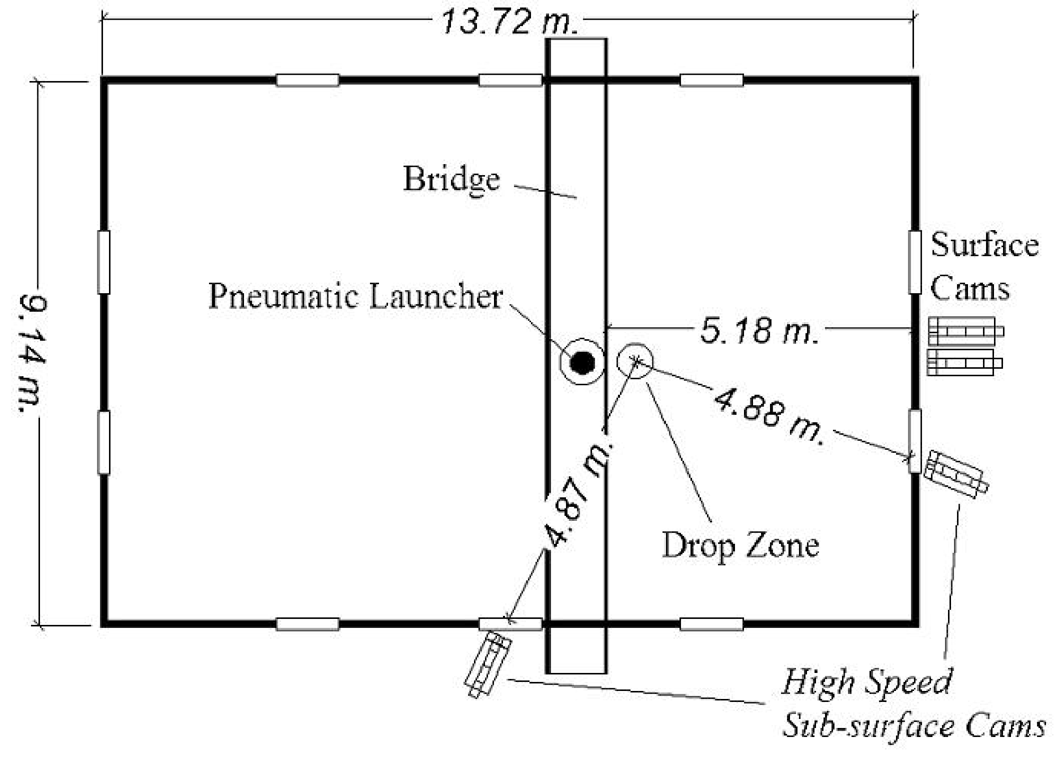
- 11 Runs Total
- V_{max} : 83.2 m/s V_{min} : 56.2 m/s
- 9/11 displayed long-arc-flip

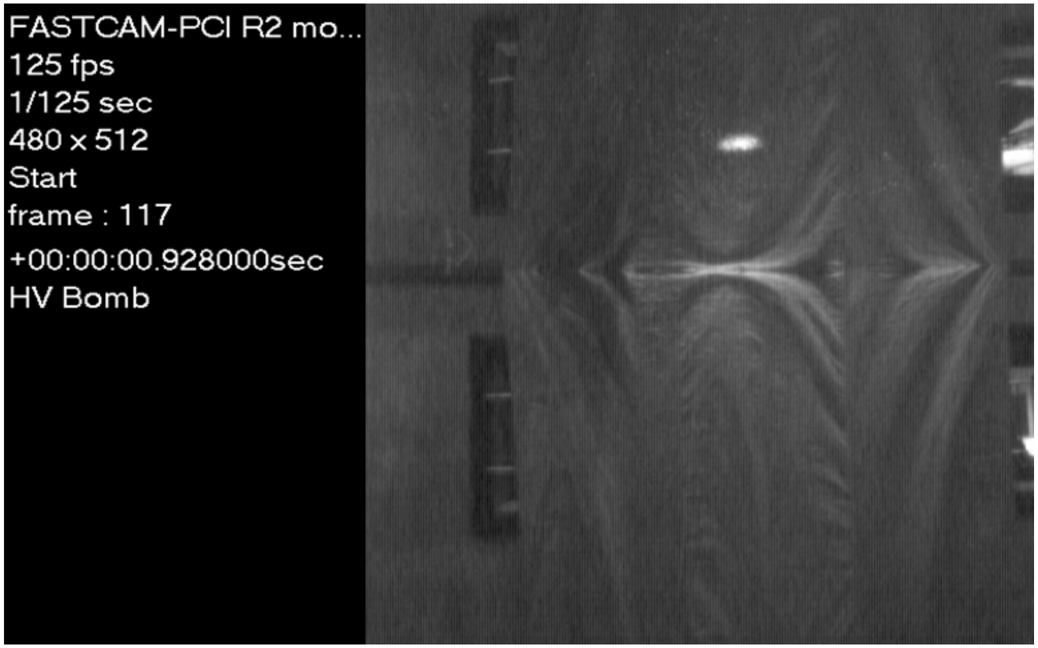


MBARI Unmanned Underwater Vehicle Test Tank
above surface (left panel)
below surface (right panel)

Pneumatic Launcher Mounted on Bridge

Test Facility Plan View




FASTCAM-PCI R2 mo...
125 fps
1/125 sec
480 x 512
Start
frame : 117
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HV Bomb


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125 fps
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Start
frame : 97
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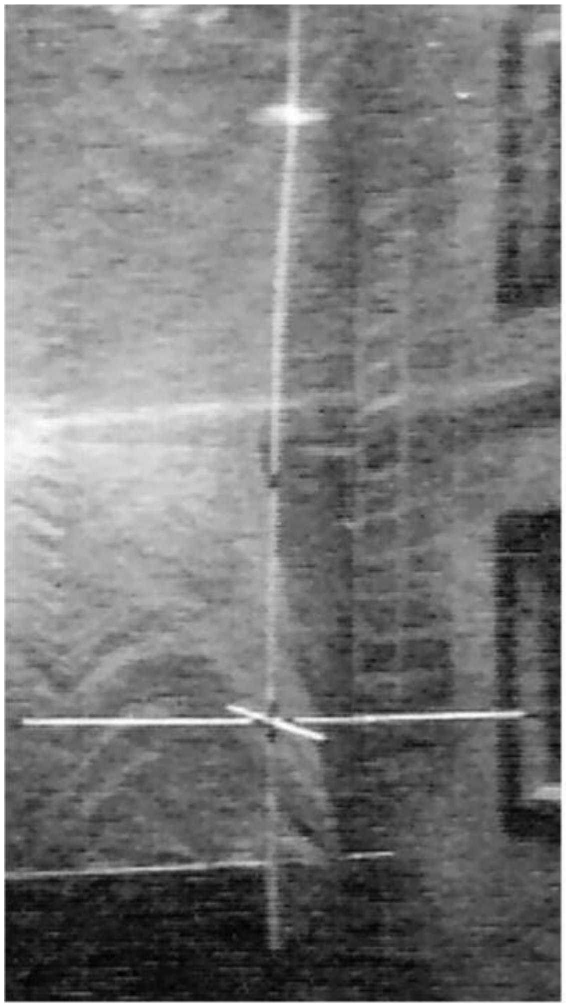
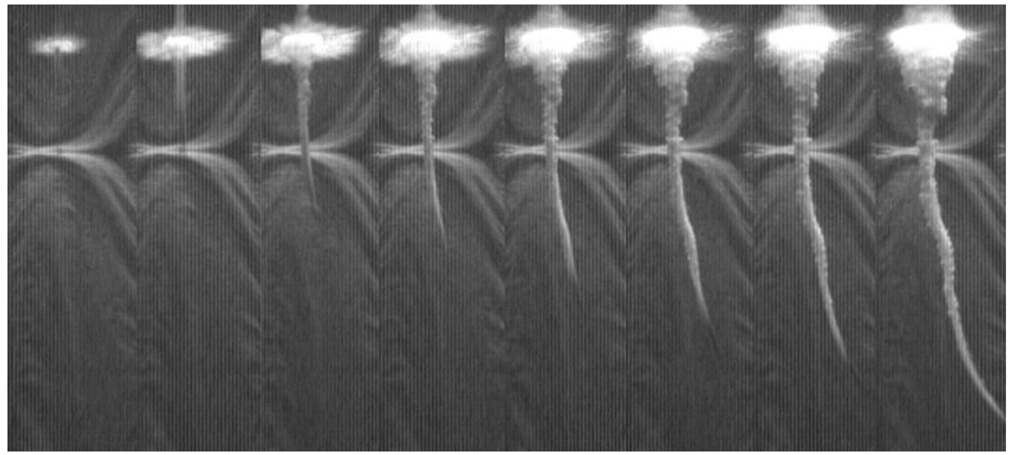
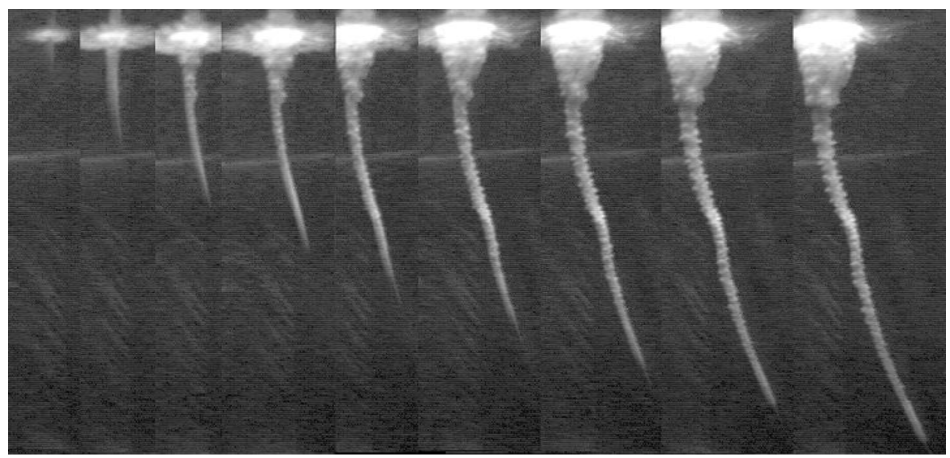
HV 3-fin Bomb

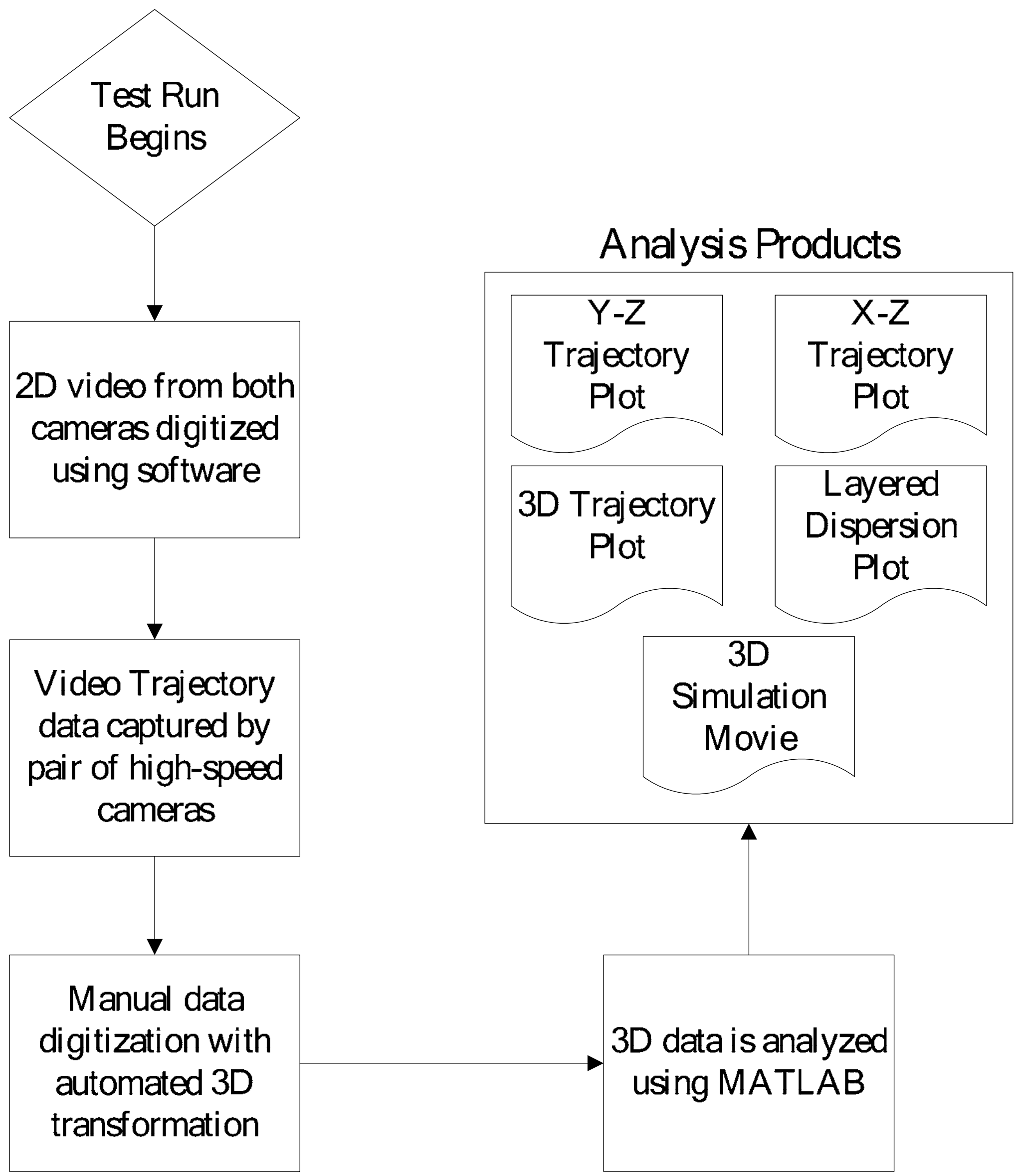
Underwater View



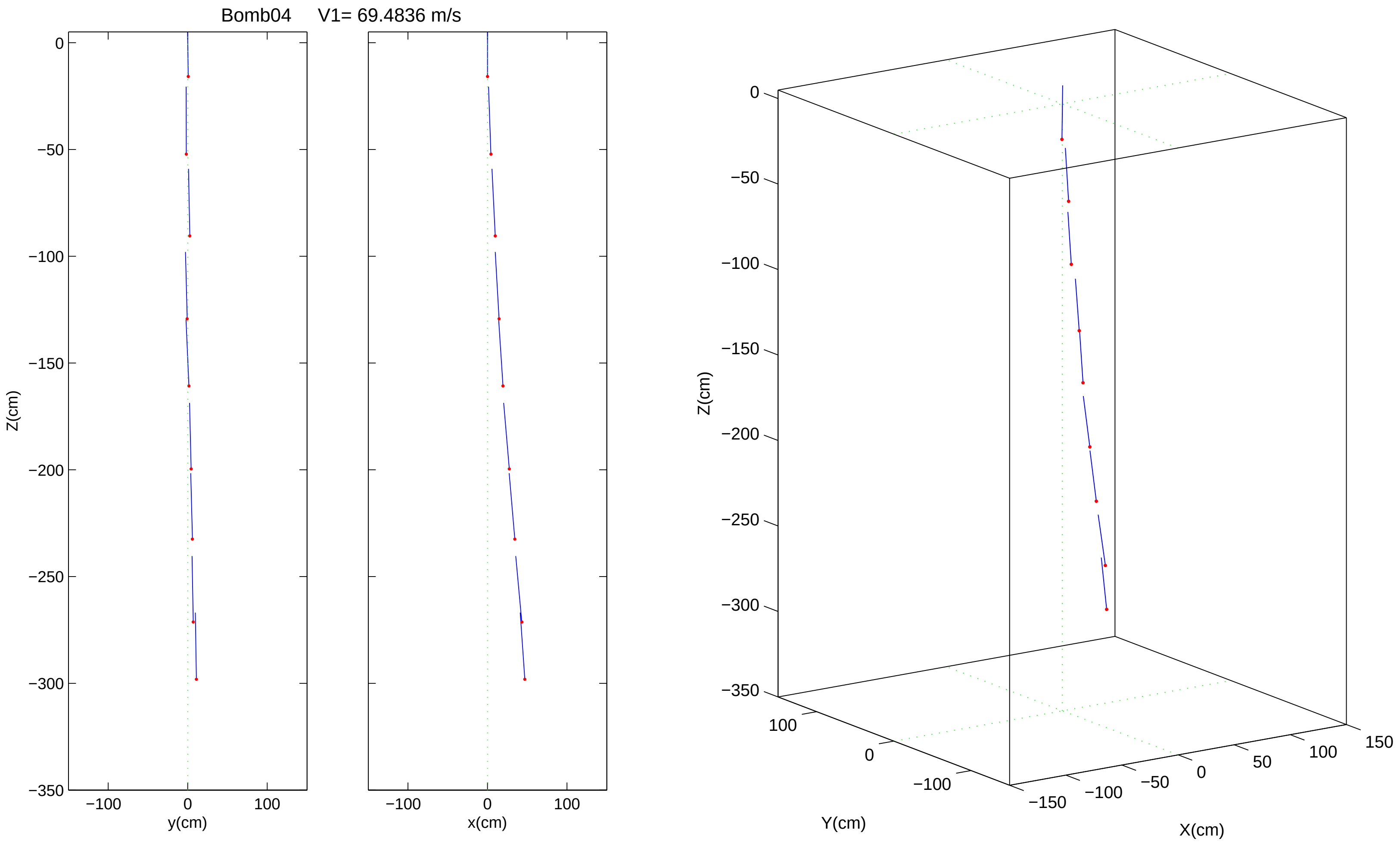




Data Retrieval and Analysis



Straight-Arc



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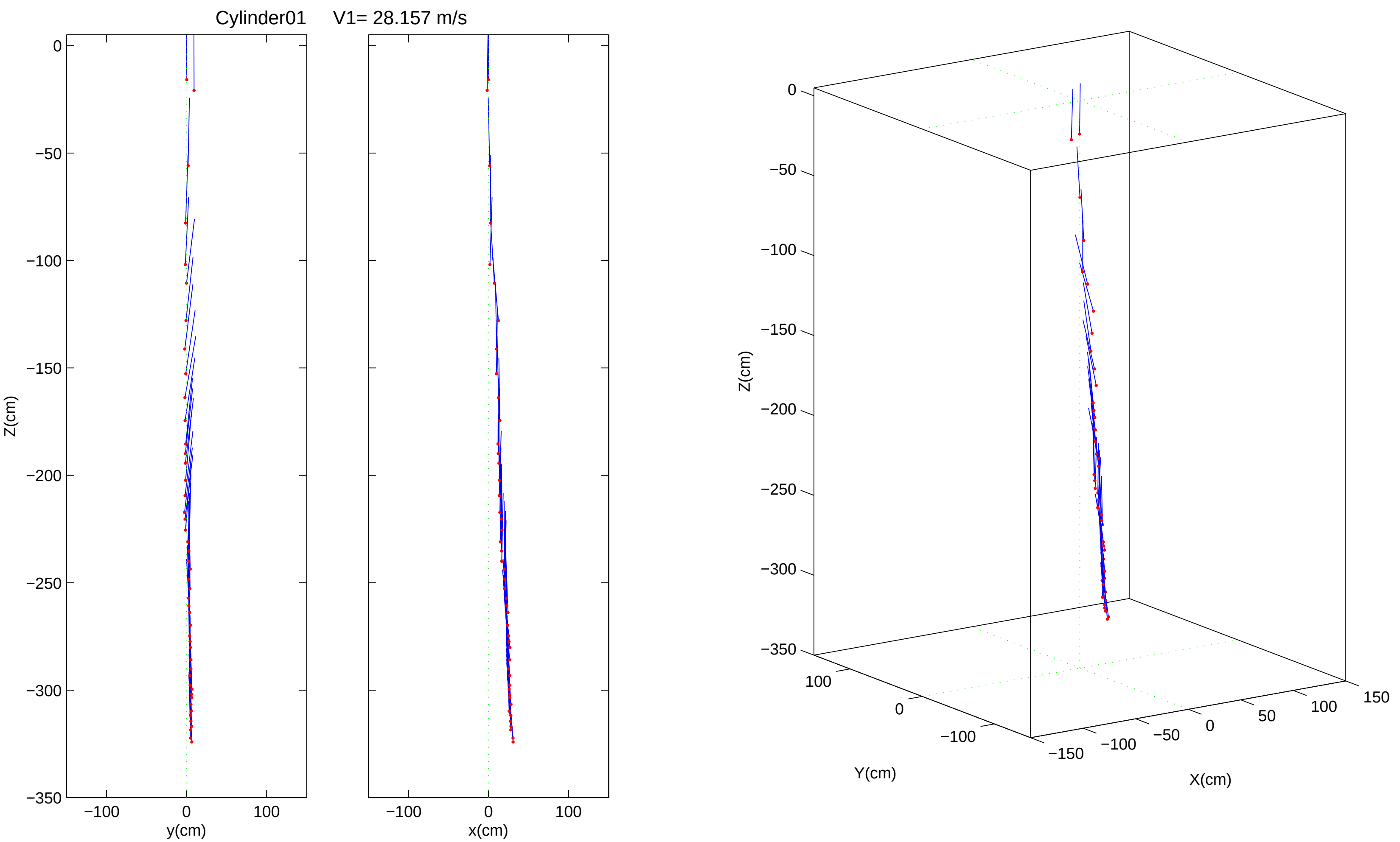
Straight Spiral



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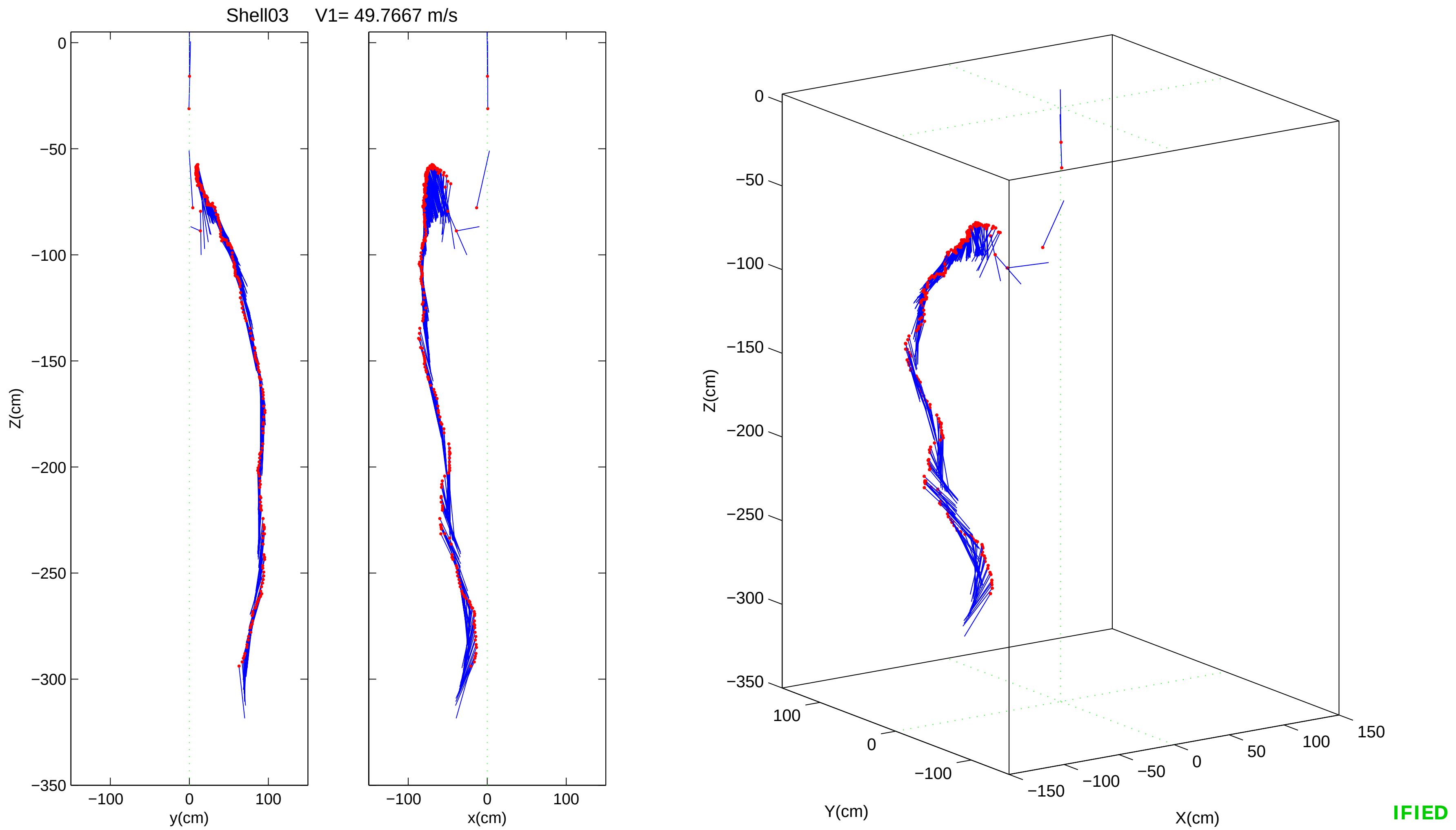
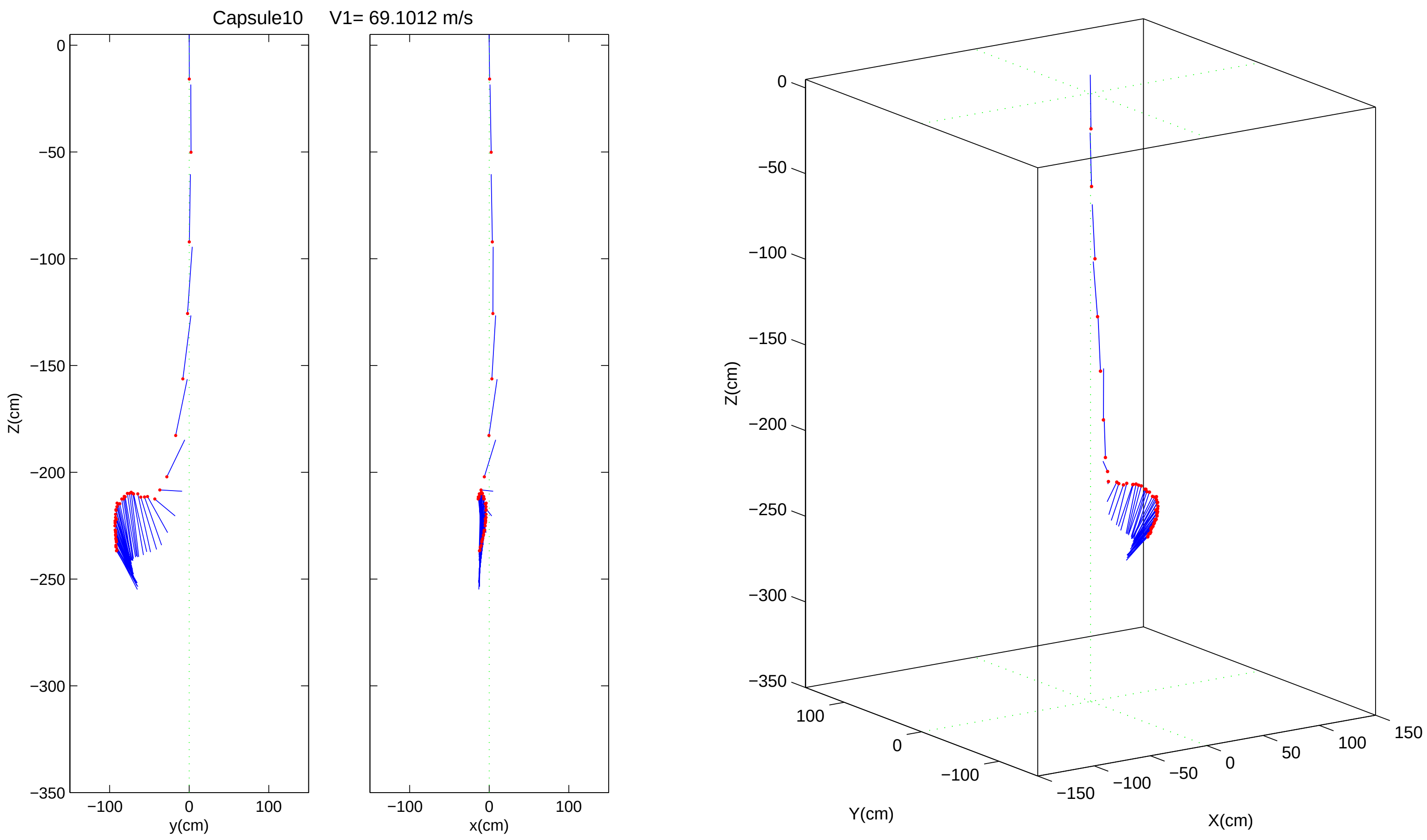
Short-Arc-Flip



Long-Arc-Flip



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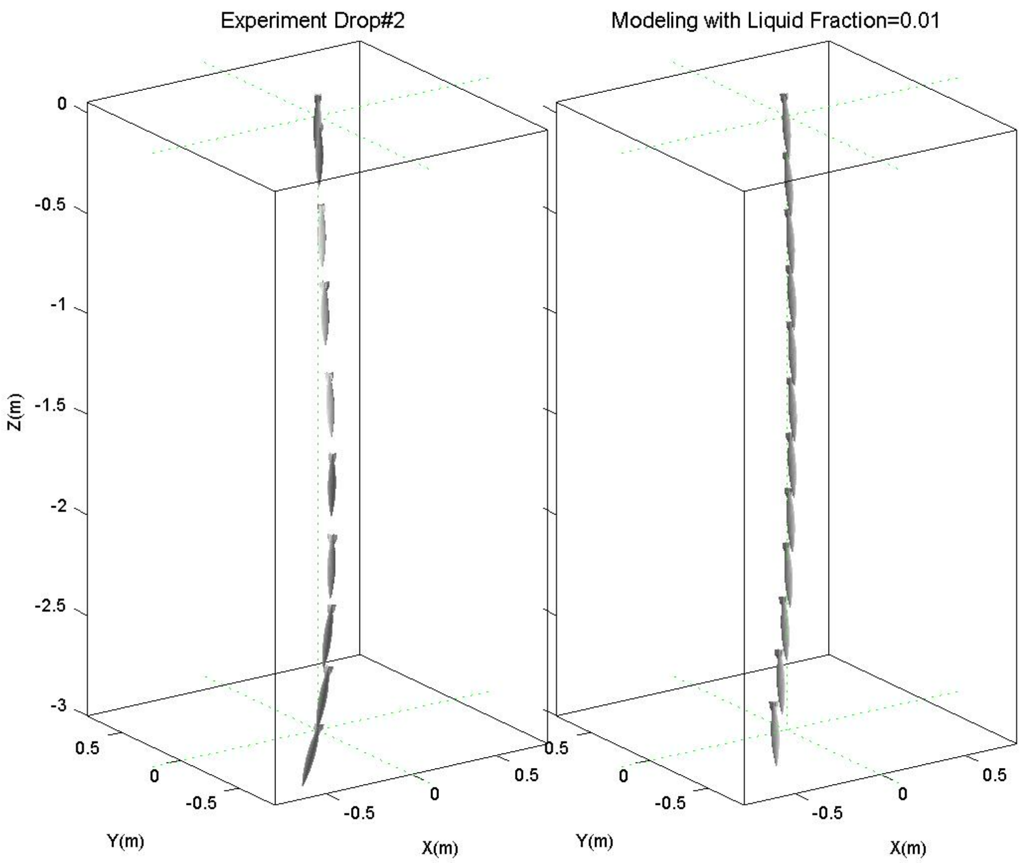
Trajectory Pattern Classifications

Pattern	**Description**
Straight-Arc	Straight & direct flight path on one vertical axis, with slow smooth arc until terminus on remaining vertical axis
Straight Spiral	Direct path to terminus of flight with tail spiraling in the wake.
Short-Arc-Flip	Abrupt & immediate arc within 75 cm of water entry followed by a flip of the projectile and tail first decent to terminus
Long-Arc-Flip	Shallow arc for majority of flight path developing into an abrupt turn upwards near the terminus and then descending tail first.

Shape	# of Runs	Avg. V_{in}	Trajectory
Bomb	8	83.0 m/s	Straight-Arc
Shell	13	82.3 m/s	Short-Arc-Flip
Capsule	11	68.2 m/s	Long-Arc-Flip
Cylinder	12	56.6 m/s	Straight-Spiral

Model-Data Inter-comparison



- Trajectories of shapes were consistent within a single shape type, but greatly varied between shape types.

- The most erratic shape was the “Shell,” probably due to shape of rigid body, off COM, and lack of stabilizing fins.

- Most consistent shape is Cylinder & Bomb (Cylinder a little less due to lack of stabilization)

- Based on these results unitary weapon could successfully be targeted in the littoral war zone.

- The major factor in determining shape trajectory was overall design of test shape and its interaction in the bubble plume
  - Shapes that were stable went straight.
  - Finless shapes had complex trajectories

- Dispersion Pattern was consistent for all shapes within their type. Both accurate and precise therefore predictable in a modeling scenario.