Three Dimensional Hydrodynamic Mine Impact Burial Prediction

Dr. Peter Chu and LCDR Ashley Evans
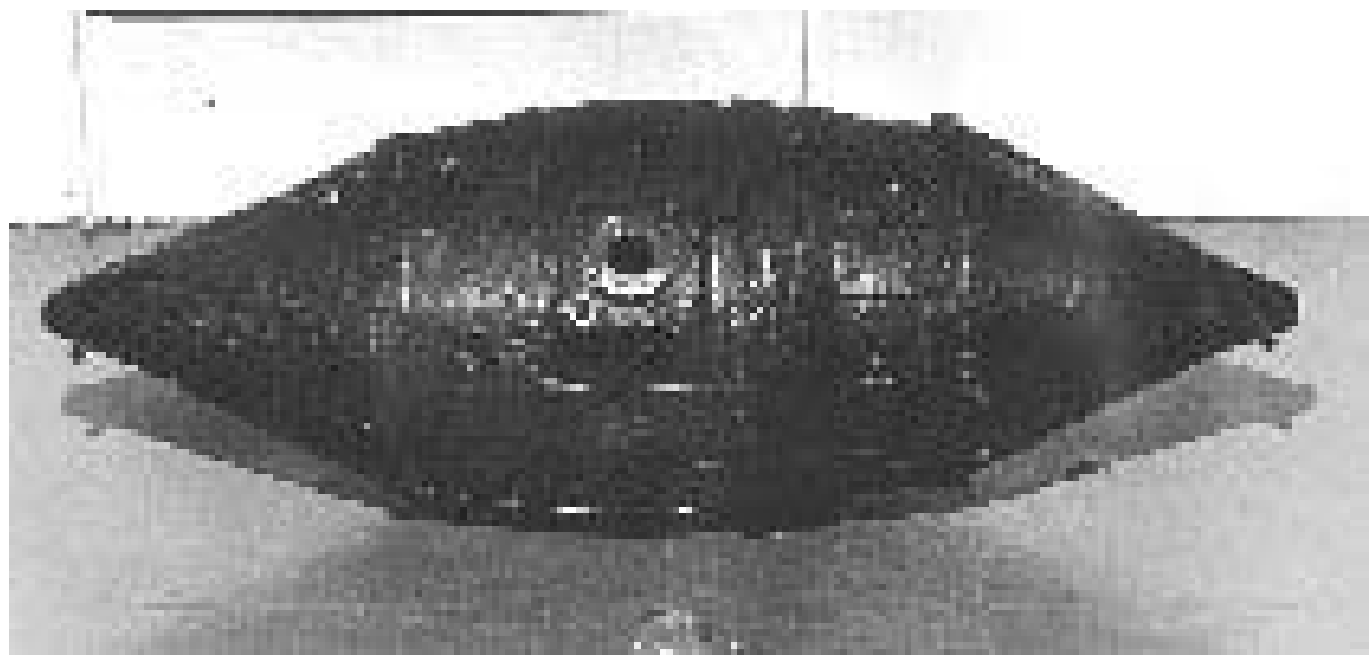
Naval Postgraduate School

Dr. Peter Fleischer

Naval Oceanographic Office

Hydrodynamics of Mine Burial

Bushnell Keg Mine, 1776

http://www.ae.utexas.edu/~industry/mine/bushnell.html

Acknowledgements

- Mr. Steven D. Haeger – NAVO

- Mr. Mark Null - NAVO

- Dr. Philip Valent – NRL-SSC

- Dr. Linwood Vincent - ONR

Work Overview

• Participated in two critical path experiments within the ONR sponsored Mine Burial Prediction Program

> ➤ Carderock Mine Drop Experiment, 10-14 Sept 2001 NSWC-CCD, Carderock, MD, 1/3 scale mine shapes, 5 meters depth.

> ➤ Corpus Christi Mine Drop Experiment, 2 –17 May 2002 Corpus Christi Mine Warfare Operating Areas, full scale mine drops, 16-18 meters depth.

• Full data analysis of 1/15 scale mine drop (Gilless 2001) and 1/3 scale mine drop data sets. Performed preliminary analysis of full scale mine drop data set for NRL-SSC.

• 3-D hydrodynamic model development and validation.

Brief Overview

- Mine Warfare Overview
- Mine Impact Burial Doctrine
- Impact Burial Prediction Model Development
- Hydrodynamic Theory
- 3-D Model Development
- NPS Mine Drop Experiment
- Carderock Mine Drop Experiment
- Corpus Christi Mine Drop Experiment
- Data Analysis
- Results
- Discussion
- Conclusions

Mine Warfare History Lesson
Wonson Harbor, Korea, 1950

"We have lost control of the seas to a nation without a Navy, using pre-World War I weapons, laid by vessels that were utilized at the birth of Christ"

Rear Admiral Allan "Hoke" Smith
Commander, Amphibious Task Force, Wonson, Korea, 1950

Republic of Korea minesweeper *YMS-516* is blown up by a magnetic
mine, during sweeping operations west of Kalma Pando, Wonsan
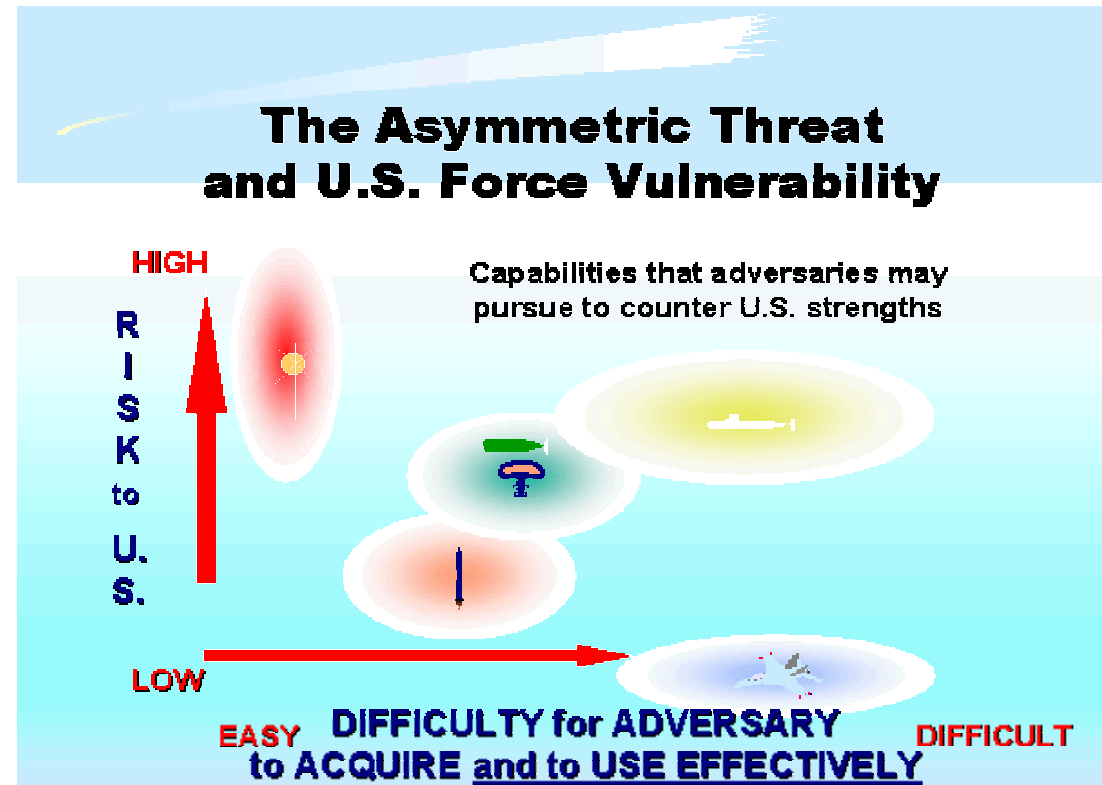harbor, on 18 October 1950. From http://www.history.navy.mil

Naval Warfare Operational Focus Shift

- Breakdown of Soviet Union Forced Change in U.S. Navy Mission Requirements.

- Primary Guiding Documents: ***Joint Vision 2010, … From the Sea, Forward … From the Sea, Operational Maneuver from the Sea, and Sea Strike, Sea Shield, Sea Basing 2002.***

- Shift in Mission Focus from open Ocean to the Littoral.

- Greatest Threat to U.S. Forces operating in the Littoral: the Naval Mine.

The Asymmetric Threat and U.S. Force Vulnerability

Capabilities that adversaries may pursue to counter U.S. strengths

HIGH

RISK to U.S.

LOW

EASY   DIFFICULTY for ADVERSARY   DIFFICULT
to ACQUIRE and to USE EFFECTIVELY

Naval Mine Threat

Inexpensive Force Multiplier

- 3rd world countries
- Non-government factions
- Terrorists

Gulf War Casualties

Roberts (FFG-58)
Tripoli (LPH-10)
Princeton (CG-59)
Damage: $125 Million
Mines Cost: $15K

Widely Available

- Over 50 Countries
  (40% Increase in 10 Yrs)
- Over 300 Types
  (75% Increase in 10 Yrs)
- 32 Countries Produce
  (60% Increase in 10 Yrs)
- 24 Countries Export
  (60% Increase in 10 Yrs)

Numerous Types

WWI Vintage to Advanced Technologies
(Multiple Sensors, Ship Count Routines,
Anechoic Coatings and Non-Ferrous Materials)

Naval Mine Characteristics

Characterized by:

• *Method of Delivery*: Air, Surface or Subsurface.

• *Position in Water Column*: Bottom, Moored or Floating.

• *Method of Actuation*: Magnetic and/or Acoustic Influence, Pressure, Controlled or Contact.

• Composed of metal or reinforced fiberglass.

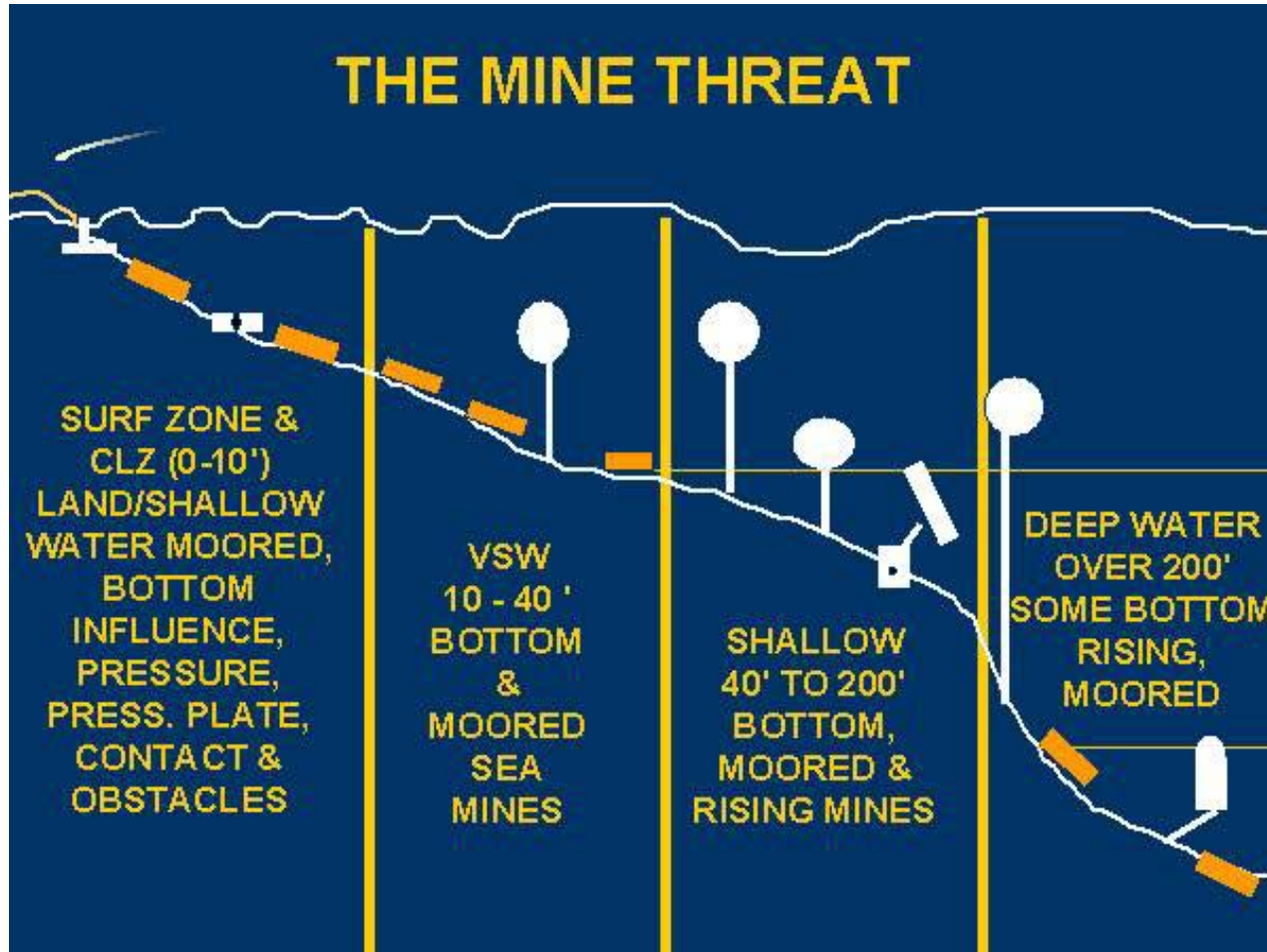• Shapes are Typically Cylindrical but Truncated Cone (Manta) and Wedge (Rockan) shaped mines exist.

RUSSIAN AMD/KMD – II – 1000
BOTTOM CYLINDRICAL

12 SMALL HOLES FOR ACOUSTIC SENSOR

285 CM LENGTH/53 CM DIAMETER
1000 KG WT/700 KG WARHEAD
6 - 50 M DEPTH
MAGNETIC, ACOUSTIC

WWII Vintage; 300,000 mines in stockpile

Naval Mine Characteristics
by littoral battle space region

THE MINE THREAT

SURF ZONE & CLZ (0-10') LAND/SHALLOW WATER MOORED, BOTTOM INFLUENCE, PRESSURE, PRESS. PLATE, CONTACT & OBSTACLES

VSW 10 - 40' BOTTOM & MOORED SEA MINES

SHALLOW 40' TO 200' BOTTOM, MOORED & RISING MINES

DEEP WATER OVER 200' SOME BOTTOM RISING, MOORED

From the U.S. Naval Mine Warfare Plan

Mines can also be characterized by the regions they occupy in the littoral battle space

Important Environmental Parameters for MCM Operations

- Water Properties
- Weather
- Beach Characteristics
- Tides and Currents
- Biologics
- Magnetic Conditions
- ❖ Bathymetry (Bottom Type)
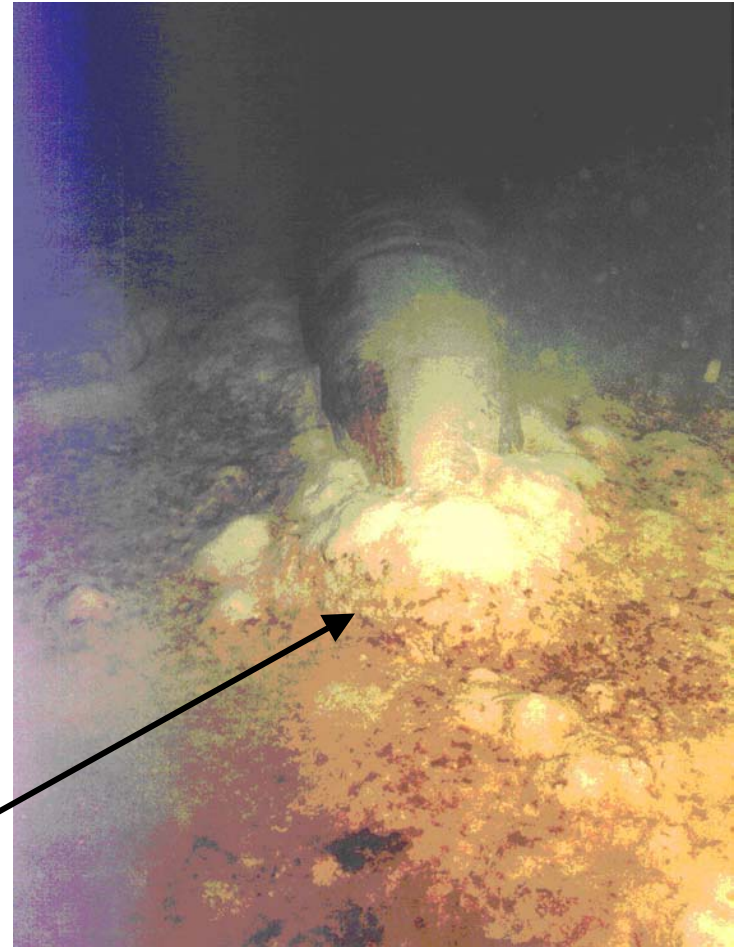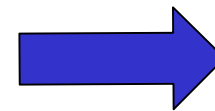

From NRL-SSC: Dr Philip Valent

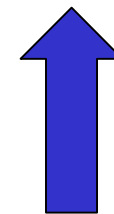# Mine Countermeasure Doctrine

- Mine Impacting Bottom will Experience a Certain Degree of "Impact Burial (IB)".
  - Highest Degree of IB in Marine Clay and Mud.
  - IB Depends on Sediment Properties, Impact Orientation, Shape and Velocity.
- MCM Doctrine Provides only a Rough "anecdotal" Estimate of IB.

Bottom Composition	Predicted Mine Case Burial %	Bottom Roughness	Bottom Category
Rock	0	Smooth	B
		Moderate	C
		Rough	C
MUD OR SAND	0 TO 10	Smooth	A
		Moderate	B
		Rough	C
	10 TO 20	Smooth	A
		Moderate	B
		Rough	C
	25 TO 75	Smooth	A
		Moderate	B
		Rough	C
	75 TO 100	All	C

Mine Warfare Bottom Category

| NOMBOS KM$_2$	Clutter Category
< 4	1
>4 and <12	2
>12	3

Development of Navy's Impact Burial Prediction Model (IBPM)

- IBPM was designed to calculate mine trajectories for air, water and sediment phases.

- Arnone & Bowen Model (1980) – No Rotation.

- Improved IBPM (Satkowiak, 1987-88)

- Improvements made by Hurst (1992)

  - Included torque calculation and rotation

  - More Accurately Calculates Fluid Drag and Air-Sea and Sea-Sediment Interface Forces.

  - Improved Treatment Layered Sediments.

- Improvements made by Mulhearn (1993)

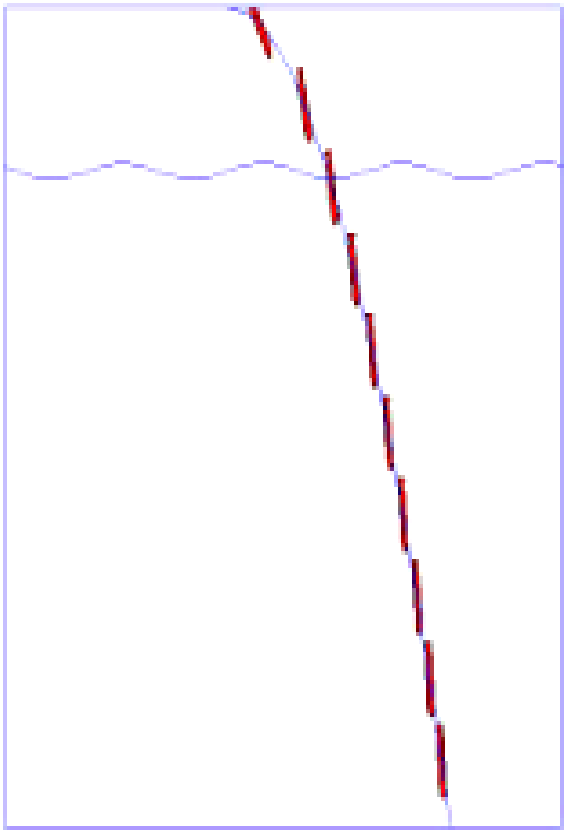 - Allowed for offset between COM and COV
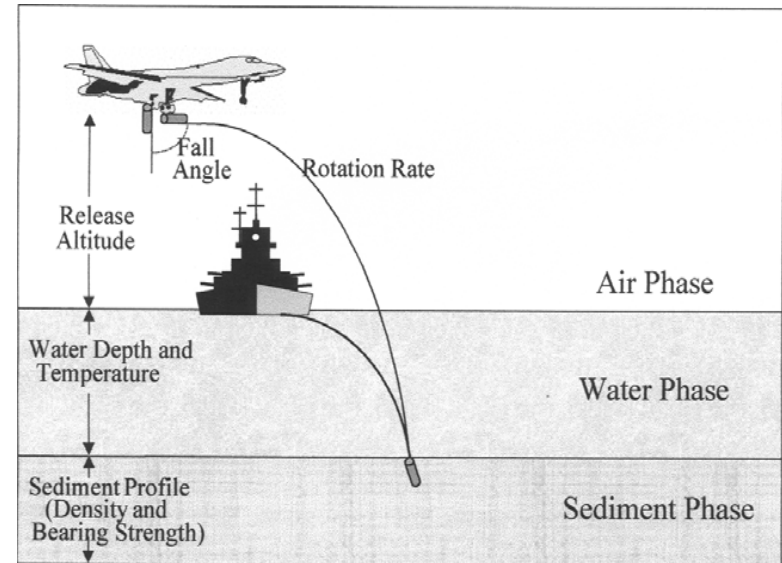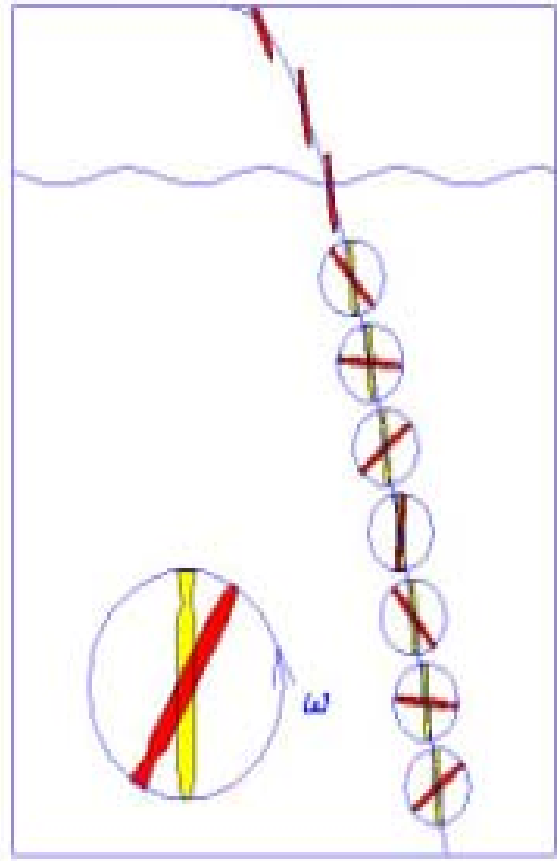
Simple Hydrodynamic Theory and Motion

Arnone-Bowen IBPM
Without Moment Equation

Improved IBPM with rotation but
without Moment Equation

Mine Burial Prediction Model IMPACT 28

- Main Limitations of Hydrodynamic portion:

  1. Model numerically integrates x-z momentum balance equations only. Does not consider moment balance equations.

  2. Introduces an artificial rotation around the pitch axis to calculate dampening torque.

  3. Limited empirical drag and lift coefficient data.

- If a mine's water phase trajectory is not accurately modeled, then IB predictions will be wrong.

- Recent sensitivity studies by (Mulhearn 1993, Chu et al. 1999, 2000, Taber 1999, Smith 2000) focused on sediment phase calculations.

- Gilless (2001) pursued and demonstrated sensitivities in the hydrodynamic portion of IMPACT28.

Hydrodynamic Theory

- A solid body falling through a fluid medium should obey two Newtonian principles:

1. Momentum Balance

$$\int (dV^* / dt^*)dm^* = W^* + F_b^* + F_d^*$$

2. Moment of Momentum Balance

$$\int [r^* \times (dV^* / dt^*)]dm^* = M^*$$

- Denotes dimensional variables
  - $V^* \rightarrow$ Velocity
  - $W^* \rightarrow$ gravity
  - $F_b^* \rightarrow$ buoyancy force
  - $F_d^* \rightarrow$ drag force
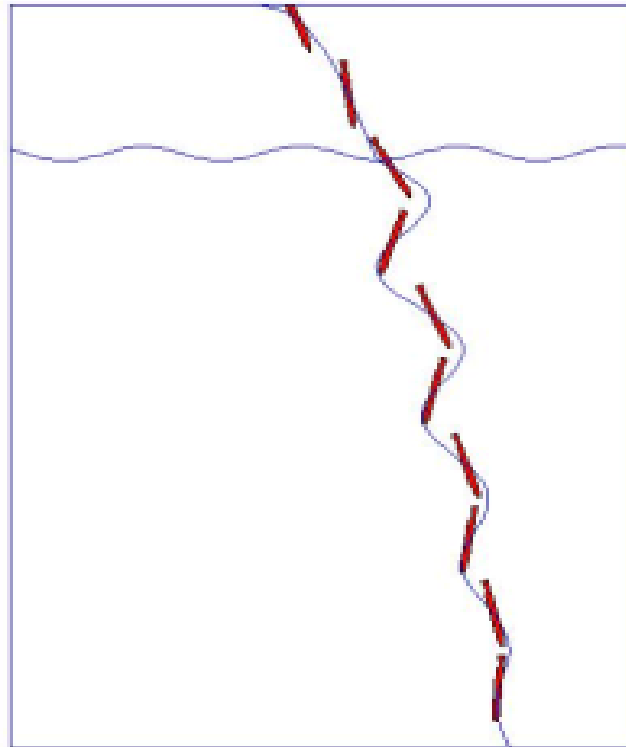 - $M^* \rightarrow$ resultant moment

Hydrodynamic Theory

- By considering all degrees of freedom, mine will exhibit a complex fall pattern.

With Moment Equations

Hydrodynamic Theory

- Considering both momentum and moment of momentum balance yields 9 governing component equations that describe the mine's water phase trajectory and orientation.

$$\frac{du}{dt} = \frac{F_{sx}}{\overline{\rho} \cdot \Pi}$$

$$\frac{dv}{dt} = \frac{F_{sy}}{\overline{\rho} \cdot \Pi}$$

$$\frac{dw}{dt} = -\left(1 - \frac{\rho_w}{\overline{\rho}}\right) g + \frac{F_{sz}}{\overline{\rho} \cdot \Pi}$$

$$\frac{d\Omega}{dt} = \frac{M_{s1}}{J_1}$$

$$\frac{d\omega_2}{dt} = \frac{\Pi \chi g \rho_w}{J_2} \cdot \cos \psi_2 + \frac{M_{s2}}{J_2}$$

$$\frac{d\omega_3}{dt} = \frac{M_{s3}}{J_3}$$

$$\frac{d}{dt} \cos \psi_1 = \omega_3 \cos \psi_2 - \omega_2 \cos \psi_3$$
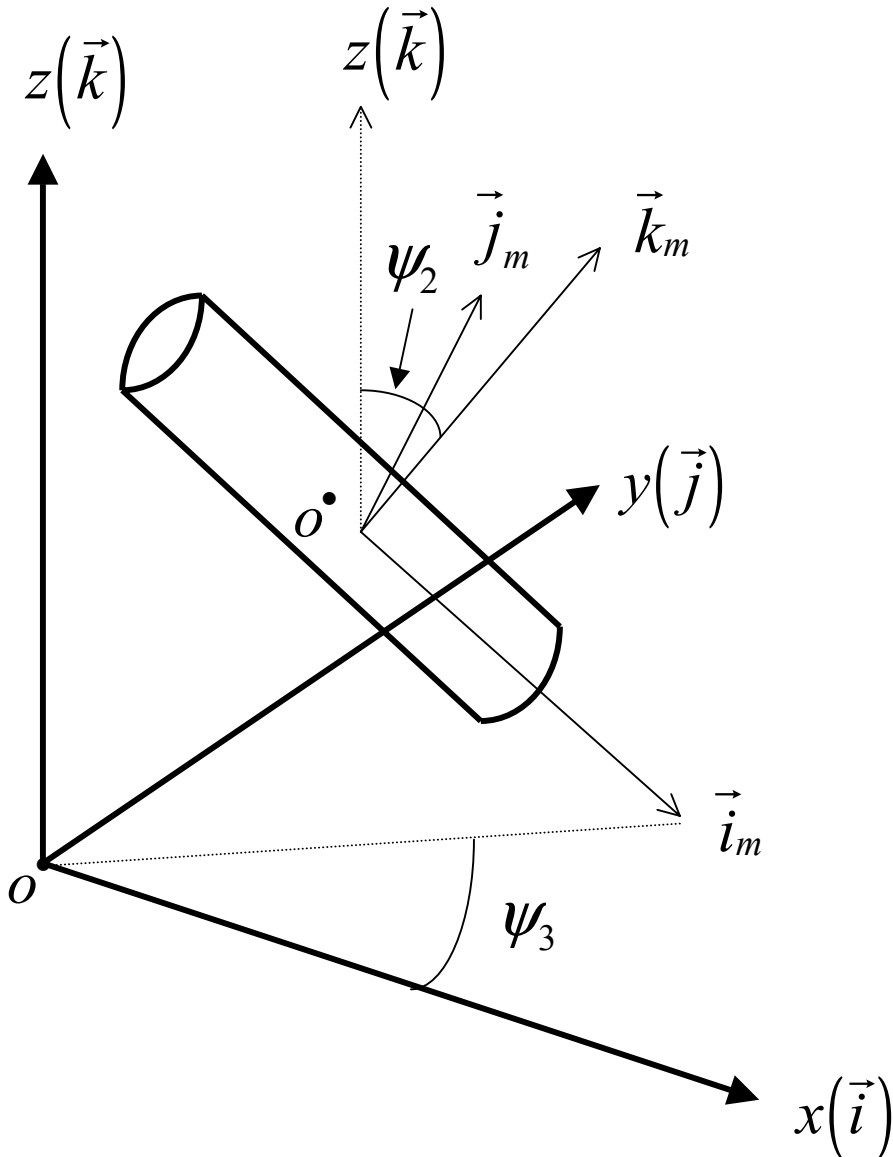
$$\frac{d}{dt} \cos \psi_2 = \omega_1 \cos \psi_3 - \omega_3 \cos \psi_1$$

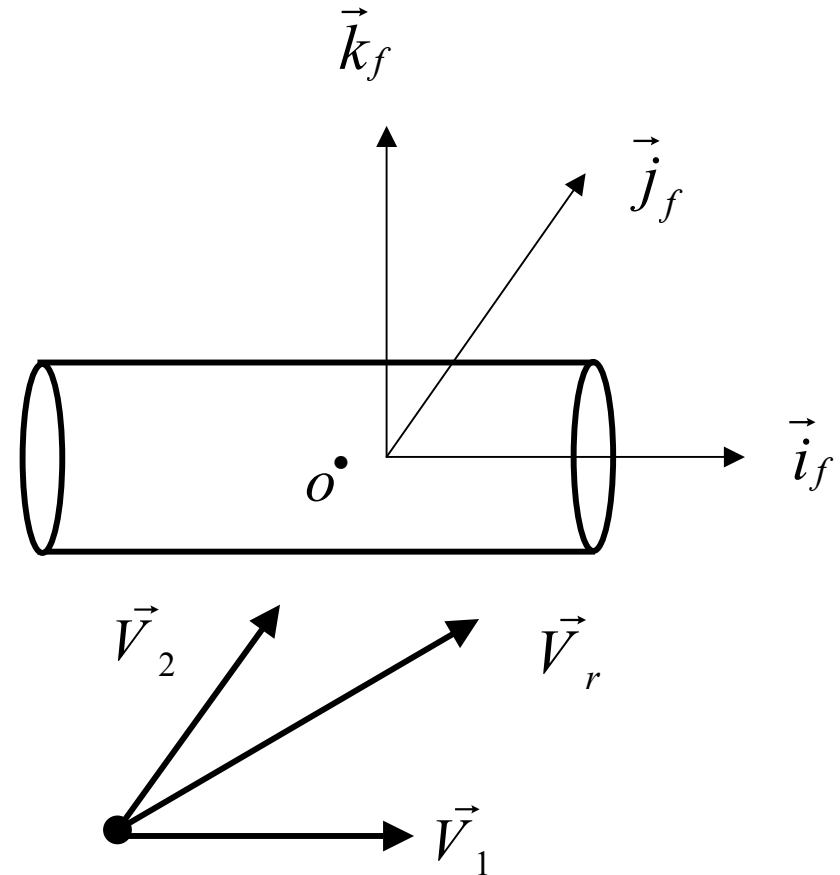$$\frac{d}{dt} \cos \psi_3 = \omega_2 \cos \psi_1 - \omega_1 \cos \psi_2$$

Hydrodynamic Model
3 Reference Frames

- Earth Fixed Coordinate Reference Frame
- Mine Body Coordinate Reference Frame
- Drag-Lift Force Coordinate Reference Frame

Hydrodynamic Model
3 Reference Frames - 3 Transformation Matrices

Earth Fixed Coordinate to Mine Body
Coordinate Transformation Matrix

$$\vec{i}_M = e_{11}\vec{i} + e_{21}\vec{j} + e_{31}\vec{k}$$
$$\vec{j}_M = e_{12}\vec{i} + e_{22}\vec{j} + e_{32}\vec{k}$$
$$\vec{k}_M = e_{13}\vec{i} + e_{23}\vec{j} + e_{33}\vec{k}$$

$$
{}_M^E R = \begin{bmatrix} \cos\psi_3 & -\sin\psi_3 & 0 \\ \sin\psi_3 & \cos\psi_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\psi_2 & 0 & \sin\psi_2 \\ 0 & 1 & 0 \\ -\sin\psi_2 & 0 & \cos\psi_2 \end{bmatrix} = \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix}
$$

Earth Fixed Coordinate to Drag-Lift
Force Coordinate Transformation Matrix

$$\vec{i}_f = e_{11}\vec{i} + e_{21}\vec{j} + e_{31}\vec{k}$$
$$\vec{j}_f = e'_{12}\vec{i} + e'_{22}\vec{j} + e'_{32}\vec{k}$$
$$\vec{k}_f = e'_{13}\vec{i} + e'_{23}\vec{j} + e'_{33}\vec{k}$$

$$
{}_D^E R = \begin{bmatrix} e_{11} & e'_{12} & e'_{13} \\ e_{21} & e'_{22} & e'_{23} \\ e_{31} & e'_{32} & e'_{33} \end{bmatrix}
$$

Mine Body Coordinate to Drag-Lift Force
Coordinate Transformation Matrices

$$
{}_D^M R = {}_E^M R \cdot {}_D^E R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix}
$$

$$
{}_M^D R = {}_E^D R \cdot {}_M^E R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & d_{22} & d_{32} \\ 0 & d_{23} & d_{33} \end{bmatrix}
$$

Hydrodynamic Model
Momentum and Drag/Lift Forces

$$\vec{F} - m\frac{d\vec{V}}{dt} = 0, \qquad \vec{F} = \vec{F}_b + \vec{F}_s$$

$$\frac{du}{dt} = \frac{F_{sx}}{\bar{\rho}\cdot\Pi}$$

$$\frac{dv}{dt} = \frac{F_{sy}}{\bar{\rho}\cdot\Pi}$$

$$\frac{dw}{dt} = -\left(1 - \frac{\rho_w}{\bar{\rho}}\right)g + \frac{F_{sz}}{\bar{\rho}\cdot\Pi}$$
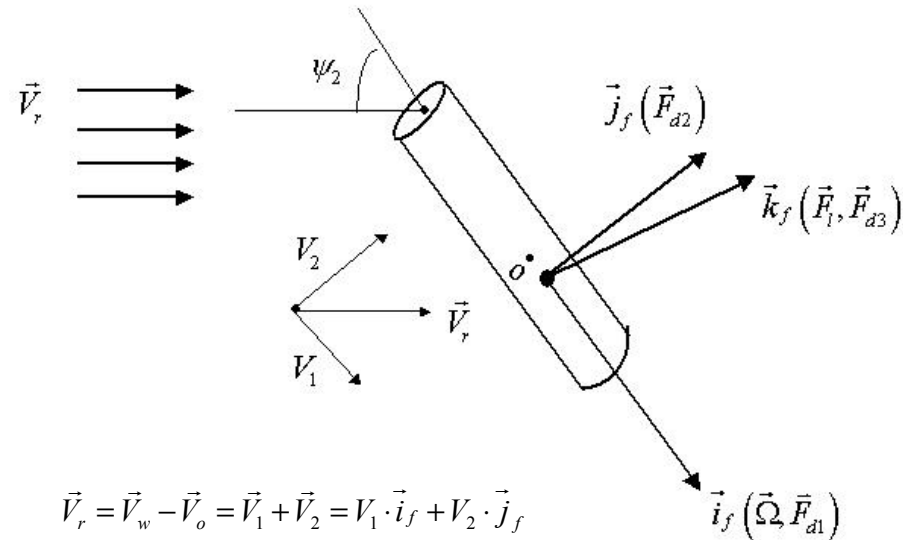
$$\vec{F}_b = -\Pi\left(\bar{\rho} - \rho_w\right)g\vec{k}$$

$$\vec{F}_s = \vec{F}_{d1} + \vec{F}_{d2} + \vec{F}_{d3} + \vec{F}_l$$

$$\vec{F}_l = \frac{\frac{1}{2}C_l\cdot d\cdot L\cdot\rho_w\cdot|V_2|\cdot\vec{V}_2}{f_{k2}} = C_{fl}\cdot V_2\cdot\left(e'_{13}\vec{i} + e'_{23}\vec{j} + e'_{33}\vec{k}\right)$$

$$\vec{F}_{d1} = \frac{\left(\frac{1}{2}C_{d1}\cdot\frac{\pi d^2}{4}\cdot\rho_w\cdot|\vec{V}_1|\cdot\vec{V}_1\right)}{f_{k1}} = C_{f1}\cdot|V_1|\cdot\left(e_{11}\vec{i} + e_{21}\vec{j} + e_{31}\vec{k}\right)$$

$$\vec{F}_{d2} = \frac{\frac{1}{2}C_{d2}\cdot d\cdot L\cdot\rho_w\cdot|V_2|\cdot\vec{V}_2}{f_{k2}} = C_{f2}\cdot V_2\cdot\left(e'_{12}\vec{i} + e'_{22}\vec{j} + e'_{32}\vec{k}\right)$$

$$\vec{F}_{d3} = \frac{\frac{1}{2}C_{d3}\cdot d\cdot\rho_w\cdot\omega'_2\cdot|\omega'_2|}{f_{k2}}\left(\int_0^{\frac{L}{2}-\chi} y^2 dy - \int_{-\frac{L}{2}-\chi}^0 y^2 dy\right)\cdot\vec{k}_f$$

$$= -\frac{\frac{1}{12}C_{d3}\cdot d\cdot\rho_w\cdot\chi\left(3L^2 + 4\chi^2\right)\cdot|\omega'_2|\cdot\omega'_2}{f_{k2}}\cdot\vec{k}_f = C_{f3}\cdot\vec{k}_f$$

$$= C_{f3}\cdot\left(e'_{13}\vec{i} + e'_{23}\vec{j} + e'_{33}\vec{k}\right)$$

$$\vec{V}_r = \vec{V}_w - \vec{V}_o = \vec{V}_1 + \vec{V}_2 = V_1\cdot\vec{i}_f + V_2\cdot\vec{j}_f$$

Hydrodynamic Model
Moment of Momentum and Torques

$$J \cdot \frac{d\vec{\omega}_m}{dt} = \vec{M} - J \cdot \frac{d\vec{\omega}_f}{dt}$$

$$J \cdot \frac{d\vec{\omega}}{dt} = \vec{M}_b + \vec{M}_s$$

$$\vec{\omega} = \Omega \vec{i}_m + \omega_2 \vec{j}_m + \omega_3 \vec{k}_m \qquad \vec{M} = \vec{M}_b + \vec{M}_s$$

$$J = \begin{bmatrix} J_1 & J_{12} & J_{13} \\ J_{21} & J_2 & J_{23} \\ J_{31} & J_{32} & J_3 \end{bmatrix}$$

$$J_1 = \int (r_2^2 + r_3^2) dm$$

$$J_1 = \frac{1}{8} m \cdot d^2$$

$$J_2 = \int (r_3^2 + r_1^2) dm \qquad J_3 = \int (r_1^2 + r_2^2) dm$$

$$J_2 = J_3 = \frac{m}{4} \cdot \left(\frac{d}{2} \right)^2 + \frac{m}{12} \cdot L^2 + \left(\chi^2 + \varsigma \right) \cdot m \cdot L^2$$

$$J_{31} = \int r_3 r_1 dm$$

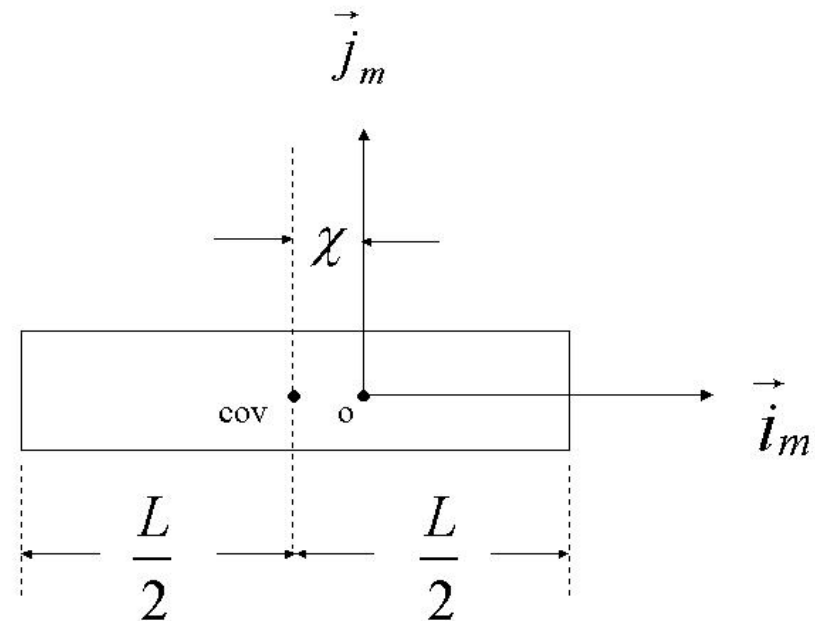$$J_{12} = J_{21} = J_{13} = J_{31} = J_{23} = J_{32} = 0$$

$$\vec{M}_b = \Pi \chi \rho_w g \cdot \cos \psi_2 \cdot \vec{j}_m$$

$$\frac{d\Omega}{dt} = \frac{M_{s1}}{J_1}$$

$$\frac{d\omega_2}{dt} = \frac{\Pi \chi g \rho_w}{J_2} \cdot \cos \psi_2 + \frac{M_{s2}}{J_2}$$

$$\frac{d\omega_3}{dt} = \frac{M_{s3}}{J_3}$$

$$\chi = \frac{\int_{-\frac{L}{2}}^{\frac{L}{2}} \rho \cdot x \cdot dx}{\int_{-\frac{L}{2}}^{\frac{L}{2}} \rho \cdot dx} = \int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{\rho}{\overline{\rho}} \cdot \frac{x}{L} \cdot dx$$

Hydrodynamic Model
Moment of Momentum and Torques

$$M_{sd3} = \frac{\displaystyle\int_{-\frac{L}{2}-\chi}^{\frac{L}{2}-\chi} \frac{1}{2} C_{d2} \cdot d \cdot \rho_w \left(V_2 - \omega_3' y\right)^2 y}{f_{kr}} \cdot dy = C_{m3} \cdot \omega_3' + m_{cm3}$$

$$M_{sd2} = \frac{-\omega_2' |\omega_2'| \displaystyle\int_{-\frac{L}{2}-\chi}^{\frac{L}{2}-\chi} \frac{1}{2} C_{d2} \cdot d \cdot \rho_w y^2 |y|}{f_{kr}} \cdot dy$$

$$M_{sl} = \frac{\displaystyle\int_{-\frac{L}{2}-\chi}^{\frac{L}{2}-\chi} \frac{1}{2} C_l \cdot d \cdot \rho_w \left(V_2 - \omega_3' y\right) y}{f_{kr}} - dy = \frac{-\frac{1}{2}\Omega \cdot d^2 \cdot \rho_w}{f_{kr}} \int_{-\frac{L}{2}-\chi}^{\frac{L}{2}-\chi} \left(V_2 - \omega_3' y\right) y\, dy$$

$$= \frac{\frac{1}{2}\Omega \cdot d^2 \cdot \rho_w \cdot L}{f_{kr}} \cdot \left(V_2 \chi + \frac{1}{12} L^2 \omega_3' + \chi^2 \omega_3'\right) = C_{ml} \cdot \omega_3' + m_{cml}$$

Model Numerical Basics

The external torques and linear forcing terms are converted to The appropriate reference frame and $\frac{d\vec{V}}{dt}$ and $\frac{d\vec{\omega}}{dt}$ are computed For each time step

$$x^{n+1} = x^n + \int_0^{dt} u\,dt$$

$$y^{n+1} = y^n + \int_0^{dt} v\,dt$$

$$z^{n+1} = z^n + \int_0^{dt} w\,dt$$

$$d\psi_2 = \int_0^{dt} \psi_2\,dt$$

$$d\psi_3 = \int_0^{dt} \psi_3\,dt$$

$$\begin{aligned}
{}_M^E R^{n+1} &= \begin{bmatrix} \cos\psi_3 & -\sin\psi_3 & 0 \\ \sin\psi_3 & \cos\psi_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\psi_2 & 0 & \sin\psi_2 \\ 0 & 1 & 0 \\ -\sin\psi_2 & 0 & \cos\psi_2 \end{bmatrix} \\
&= \begin{bmatrix} \cos\psi_3 \cdot \cos\psi_2 & -\sin\psi_3 & \cos\psi_3 \cdot \sin\psi_2 \\ \sin\psi_3 \cdot \cos\psi_2 & \cos\psi_3 & \sin\psi_3 \cdot \sin\psi_2 \\ -\sin\psi_2 & 0 & \cos\psi_2 \end{bmatrix}
\end{aligned}$$

$$\psi_2^{n+1} = arc\cos\left({}_M^E R^{n+1}(3,3) \right)$$

$$\psi_3^{n+1} = arc\cos\left({}_M^E R^{n+1}(2,2) \right)$$

Required Modeling Parameters

Mine Parameters:

χ Center of mass offset

$\overline{\rho_m}$ mine mean density

l mine length

d mine diameter

m mine mass

$[J]$ moment of inertia tensor

Initial Conditions

x_0, y_0, z_0 initial position vector

u_0, v_0, w_0 initial linear velocity vector

$\Omega_{1_0}, \omega_{2_0}, \omega_{2_0}$ initial angular velocity vector

ψ_{2_0}, ψ_{3_0} initial angle vector

Δt time step

Hydrodynamic Parameters:

$\vec{V}_r = \vec{V}_1 + \vec{V}_2$ relative water velocity vector

R_e reynolds number

C_{da} axial drag coefficient

C_{df} cross flow drag coefficient

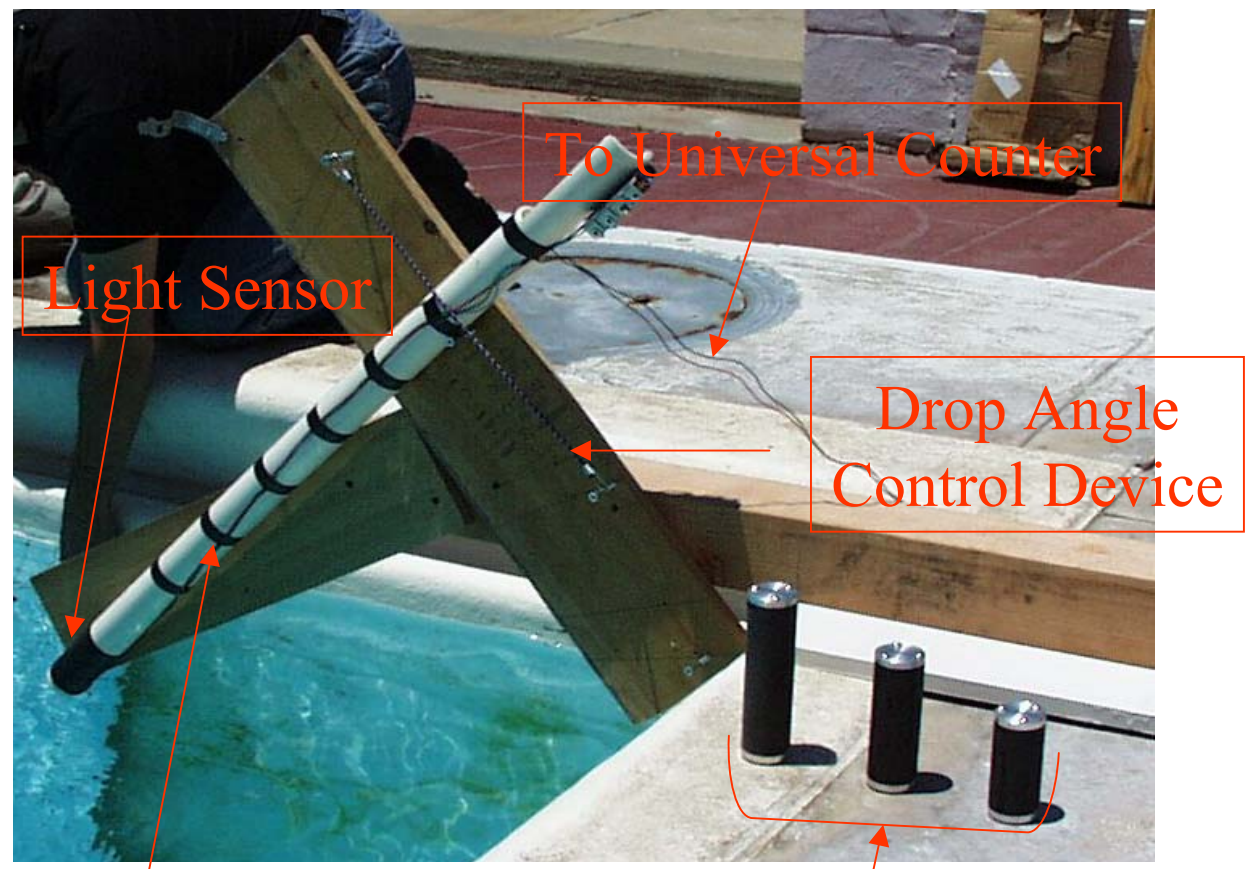C_l lift axis coefficient

T water temperature

ρ_w water density

ν water kinematic viscosity

MIDEX
(July 2001)

Light Sensor

To Universal Counter
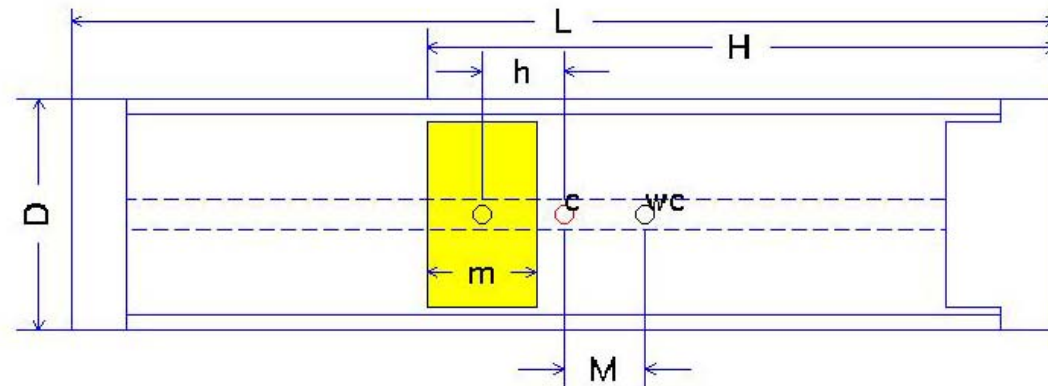
Drop Angle Control Device

Mine Injector

1/15 scale Mine Shapes:
Length: 15, 12, 9 cm
Diameter: 4 cm

MIDEX Mine Shape

MODEL # 1
L=15.1359cm D=4cm   m=2.7cm
Weight=322.5 g Volume=190.2028 cm^3 Density=1.6956 g/cm^3

H:	10.380	8.052	5.725 cm
h:	−1.462	0.866	3.193 cm
M:	0.000	18.468	36.935 mm

MODEL # 2
L=12.0726cm D=4cm   m=1.7cm
Weight=254.2 g Volume=151.709 cm^3 Density=1.6756 g/cm^3

H:	8.450	6.609	4.768 cm
h:	−1.564	0.277	2.119 cm
M:	0.000	12.145	24.290 mm

MODEL # 3
L=9.1199cm D=4cm   m=1.47cm
Weight=215.3 g Volume=114.6037 cm^3 Density=1.8786 g/cm^3

H:	6.662	5.592	4.521 cm
h:	−1.368	−0.297	0.774 cm
M:	0.000	6.847	13.694 mm

Defined COM position as:
2 or -2: Farthest from volumetric center
1or -1
0: Coincides with volumetric center

Carderock Mine Drop Experiment
September 2001
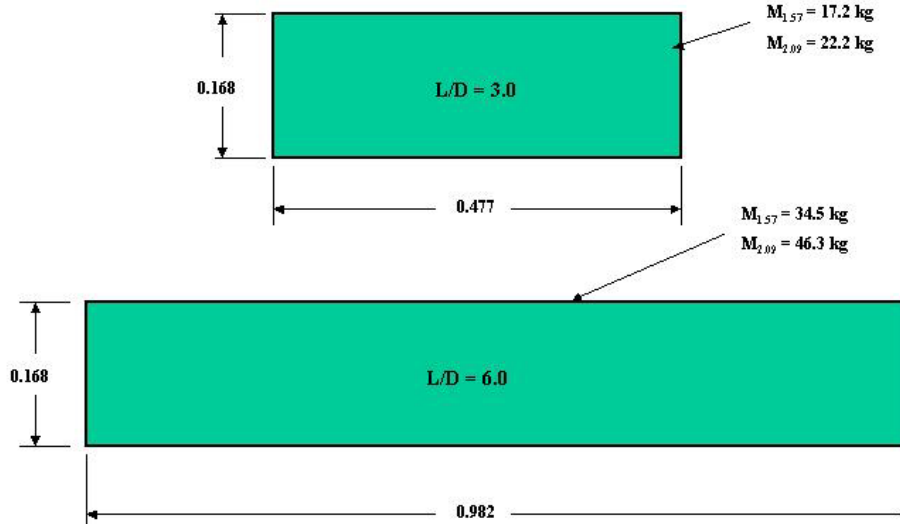
Carderock Experiment Participants
NSWC-CCD Explosive Test Pond

|	
ONR	Dr. Linwood Vincent, Dr. Roy Wilkens
NRL-SSC	Dr. Philip Valent, Dr. Mike Richardson
	Mr. Conrad Kennedy, CDR Chuck King
	Mr. Todd Holland, Mr. Grant Bower
NSWC-CCD	Mr. Bill Lewis, Mr. Peter Congedo,
	Mr. Jim Craig
NPS	Dr. Peter Chu, LCDR A Evans
JHU	Ms. Sarah Rennie
MIT	Dr. Dick Yue, Dr. Yuming Liu
	Dr. Yonghwan Kim,
TAMU	Dr. Wayne Dunlap, Mr. Charles Aubeny
OMNITECH	Dr. Albert Green
Naval Reserve	LCDR R. McDowell, LCDR Pat Hudson
	HM2 William McKinney

Carderock Mine Drop Experiment

$M_{1.57}$ = 17.2 kg
$M_{2.09}$ = 22.2 kg

L/D = 3.0

0.168

0.477

$M_{1.57}$ = 34.5 kg
$M_{2.09}$ = 46.3 kg

L/D = 6.0

0.168

0.982

| CHARACTERISTICS OF MINE MODELS USED IN TEST POND, NSWC CARDEROCK, MD, 10-14 Sept 2001 (Revised 28 Feb 2002)						
Model number	1	2	3	4	5	6
Blunt Mine Parameters						
Diameter, m (in.)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)
Length, blunt, m (in.)	0.477 (18.78)	0.477 (18.78)	0.982 (38.65)	0.982 (38.65)	0.982 (38.65)	0.982 (38.65)
L/D for blunt nose	2.8	2.8	5.8	5.8	5.8	5.8
Volume, cu m (cu ft) (blunt)	0.0106 (0.374)	0.0106 (0.374)	0.0218 (0.771)	0.0218 (0.771)	0.0218 (0.771)	0.0218 (0.771)
Weight (lbs)	38	49	76	102	100	98.5
Mass, kg	17.2	22.2	34.5	46.3	45.4	44.7
Mass Wet kg (4) (blunt)	6.33	11.33	12.13	23.93	23.04	22.34
Bulk density, pcf (Mg/cu m)	101.6 (1.63)	131.0 (2.10)	98.6 (1.58)	132.3 (2.12)	129.7 (2.08)	127.8 (2.05)
χ = (CM - CV) (m)	-0.0002385	-0.001908	-0.001964	-0.008838	0.045172	0.076596
(CM - CV) / (mine length)	-0.0005	-0.004	-0.002	-0.009	0.046	0.078
Moment of Inertia about CM						
I_{xx}[1], kg–m^2 (lb–in^2)	0.0647 (221)	0.0806 (275)	0.1362 (465)	0.1696 (579)	0.1693 (578)	0.1692 (578)
I_{yy}[2], kg–m^2 (lb–in^2)	0.356 (1216)	0.477 (1627)	2.90 (9910)	3.82 (13,050)	3.94 (13,440)	4.57 (15,600)
I_{zz}[3], kg–m^2 (lb–in^2)	0.356 (1214)	0.476 (1625)	2.90 (9910)	3.82 (13,050)	3.94 (13,430)	4.57 (15,600)
Note:						
1. I_{xx}, about long axis (Roll)						
2. I_{yy}, about transverse vertical axis (Yaw)						
3. I_{zz}, about transverse horizontal axis (Pitch)						
4. Wet mass calculations required for IMPACT28						
Wet mass calculation based on water density 1025.8 kg/m^3						

Carderock Data Acquisition
Digital Collection 125 fps
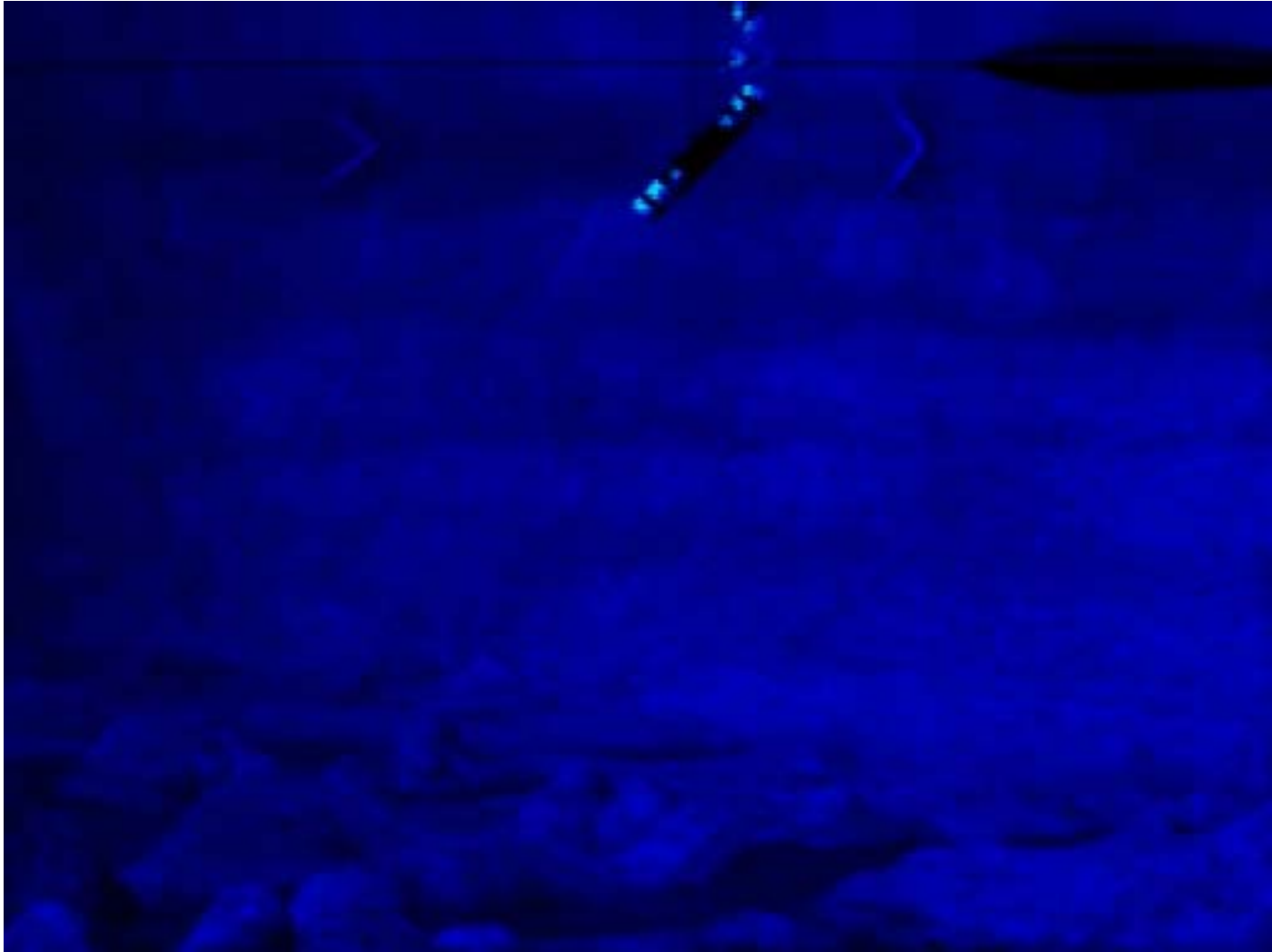
Carderock Data Acquisition
3 Camera Tracking Data Analysis and Archive
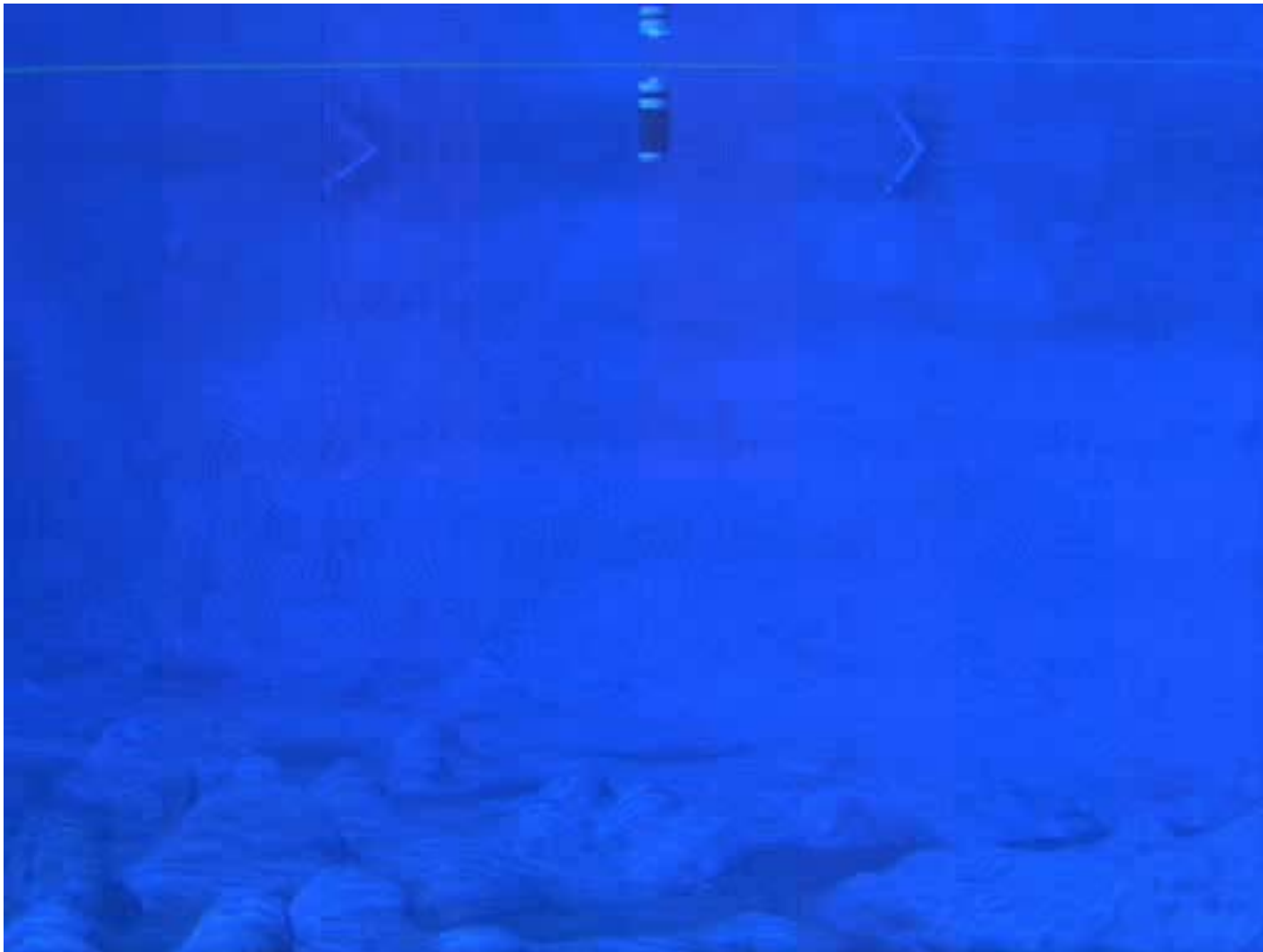
Full Scale Mine Drop Experiment Results

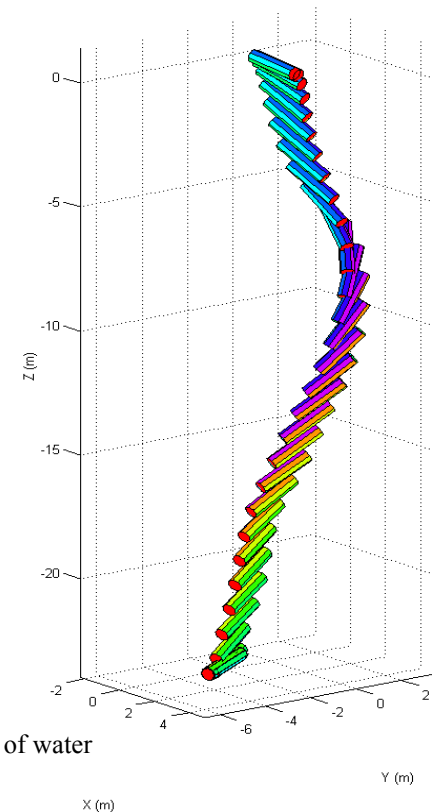• Blunt, Chamfered and Hemispherical noses on 1200 lb mine shape

Telemetry Package
• 3 FOGs
• 6 accelerometers
• 3 magnetometers
• On board data recorder

Image courtesy of Mr. Grant Bower, NRL-SSC

Corpus Christi Mine Drop Experiment
Data 2-17 May 2002

12 drops into 80ft of water

Corpus Christi Experiment Participants
Corpus Christi Mine Warfare Operating Areas A-E

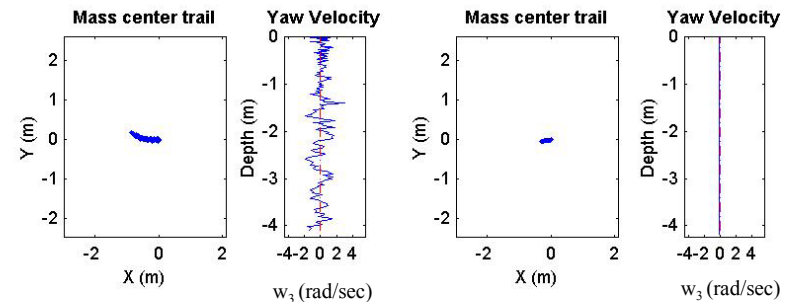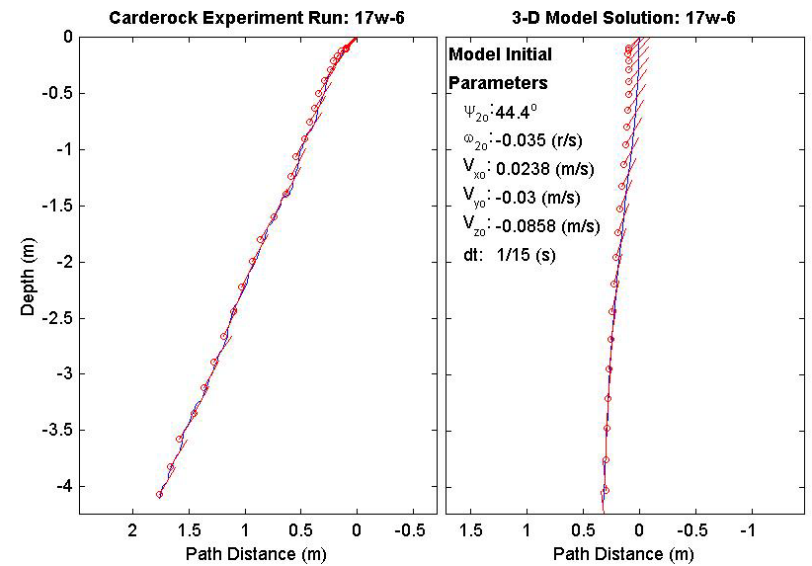|	
NRL-SSC	Dr. Philip Valent, Dr. Mike Richardson
	Mr. Conrad Kennedy, CDR Chuck King
	Mr. Grant Bower, Mr. Dale Bibee
NAVOCEANO	Mr. J. Burrell
University of Hawaii	Dr. Roy Wilkens
Columbia University	Dr. Ives Bitte, Dr. Yue-Feng Sun
NPS	LCDR A Evans
TAMU	Dr. Wayne Dunlap, Mr. C Brookshire
OMNITECH	Mr. Dan Lott, Mr. J. Bradley
Naval Reserve	HM2 William McKinney
USM	Mr. Andrei Abelev
RV Gyre	Captain Desmond Rolf

Data Analysis

1. Each Video converted to digital format

2. Analyzed 2-D data to obtain mine's x,y and z center positions; ψ_2 and ψ_3 angle; u, v, and w components of velocity; and Ω_1, ω_2, and ω_3 angular velocities

3. The data transformed to the reference framework of the model

4. Initial model conditions mine parameters and hydrodynamic parameters fed to the model

5. Results prepared for presentation graphics and database archive

Final Drop Parameters

time:	1.64(s)
xy_{fe}:	0.87 (m)
V_{xfe}:	-1.01 (m/s)
V_{yfe}:	0.641 (m/s)
V_{zfe}:	-3.99 (m/s)
ψ_{2fe}:	55.4°
depth:	4.106 (m)

Mine Shape Parameters

d:	0.168 (m)
L:	0.982 (m)
m:	44.7 (kg)
J_1:	0.169 (kg*m²)
J_2:	4.57 (kg*m²)
J_3:	4.57 (kg*m²)
χ:	0.0766 (m)

Final Model Parameters

time:	1.47 (s)
xy_{fm}:	0.311 (m)
V_{xfm}:	-0.191 (m/s)
V_{yfm}:	-0.016 (m/s)
V_{zfm}:	-4.25 (m/s)
ψ_{2fm}:	97°

Model Initial Parameters

ψ_{2o}:	44.4°
ω_{2o}:	-0.035 (r/s)
V_{xo}:	0.0238 (m/s)
V_{yo}:	-0.03 (m/s)
V_{zo}:	-0.0858 (m/s)
dt:	1/15 (s)

Sources of Error

1. Grid plane behind mine trajectory plane. Results in mine appearing larger than normal , MIDEX.

2. Camera reference to calibration grid error, Carderock.

3. Position data affected by parallax distortion and binocular disparity from camera reference, NRL estimates +/- 5cm.

4. Air cavity affects on mine motion not considered in calculations.

5. Camera plane not parallel to x-y plane due to pool slope.

6. Determination of initial linear and angular velocities from position data can lead to large errors.
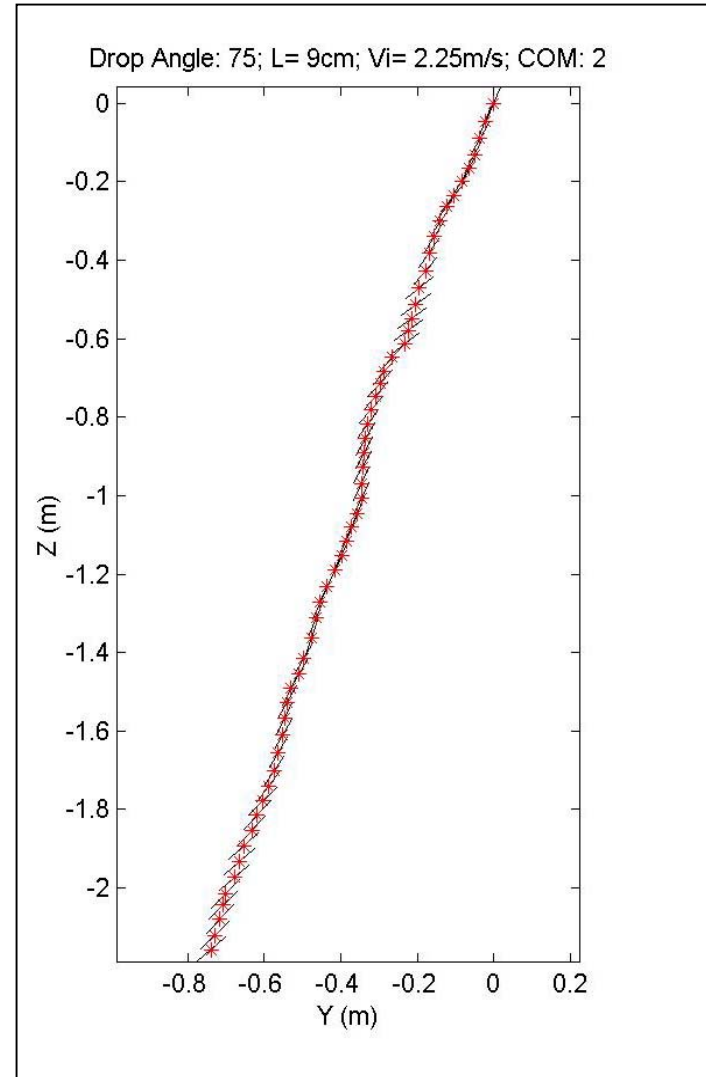
Trajectory Patterns
(Chu et al 2001)
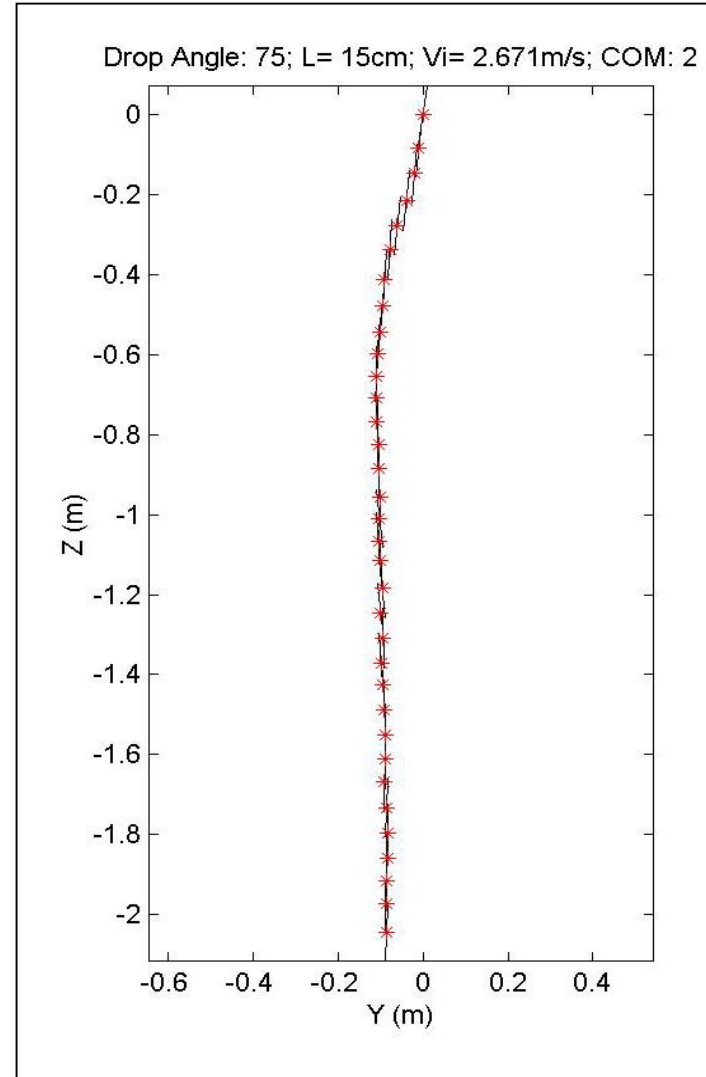
1. Straight

Drop Angle: 75; L= 15cm; Vi= 2.671m/s; COM: 2

Trajectory Patterns
(Chu et al 2001)

1. Straight

2. Slant

Drop Angle: 75; L= 9cm; Vi= 2.25m/s; COM: 2

Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
3. Spiral

Drop Angle: 45; L= 9cm; Vi= 1.553m/s; COM: 1

Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
3. Spiral
4. Flip

Drop Angle: 45; L= 12cm; Vi= 1.996m/s; COM: -2

Trajectory Patterns

(Chu et al 2001)

1. Straight
2. Slant
3. Spiral
4. Flip
5. Flat

Drop Angle: 30; L= 12cm; Vi= 0.812m/s; COM: 0

Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
3. Spiral
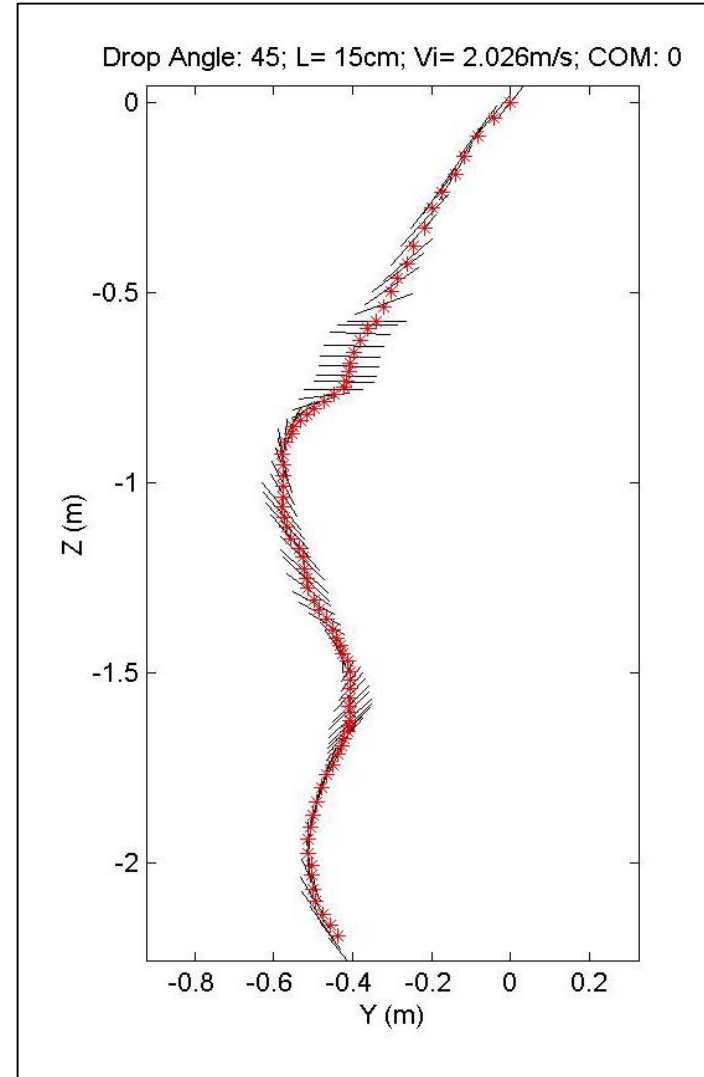4. Flip
5. Flat
6. See Saw

Drop Angle: 30; L= 9cm; Vi= 1.028m/s; COM: 0
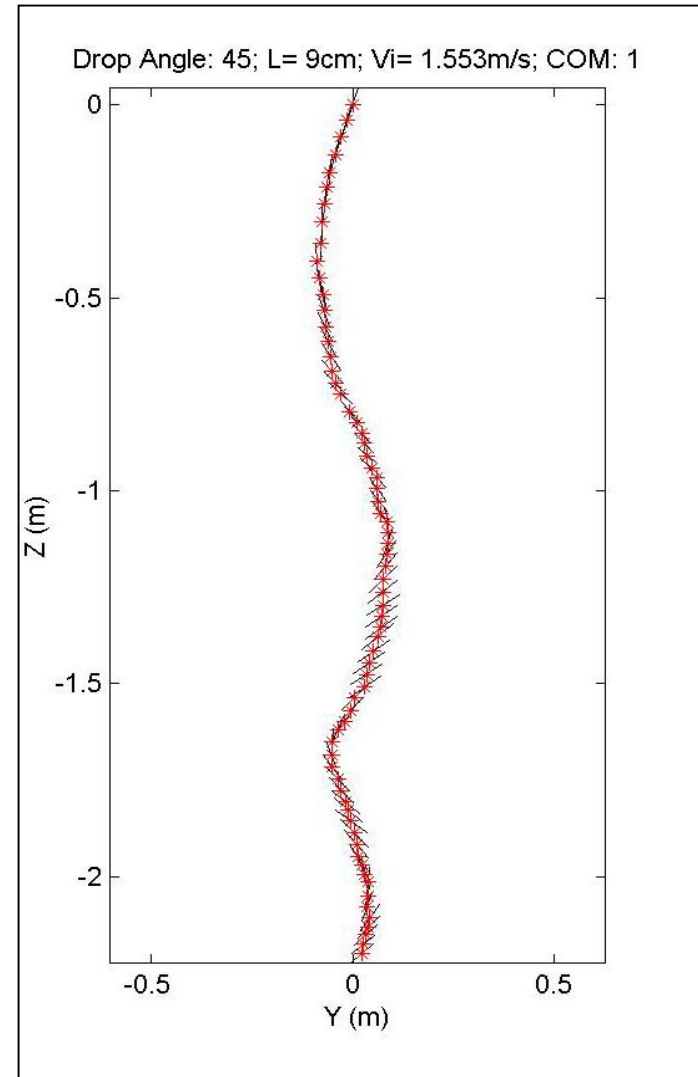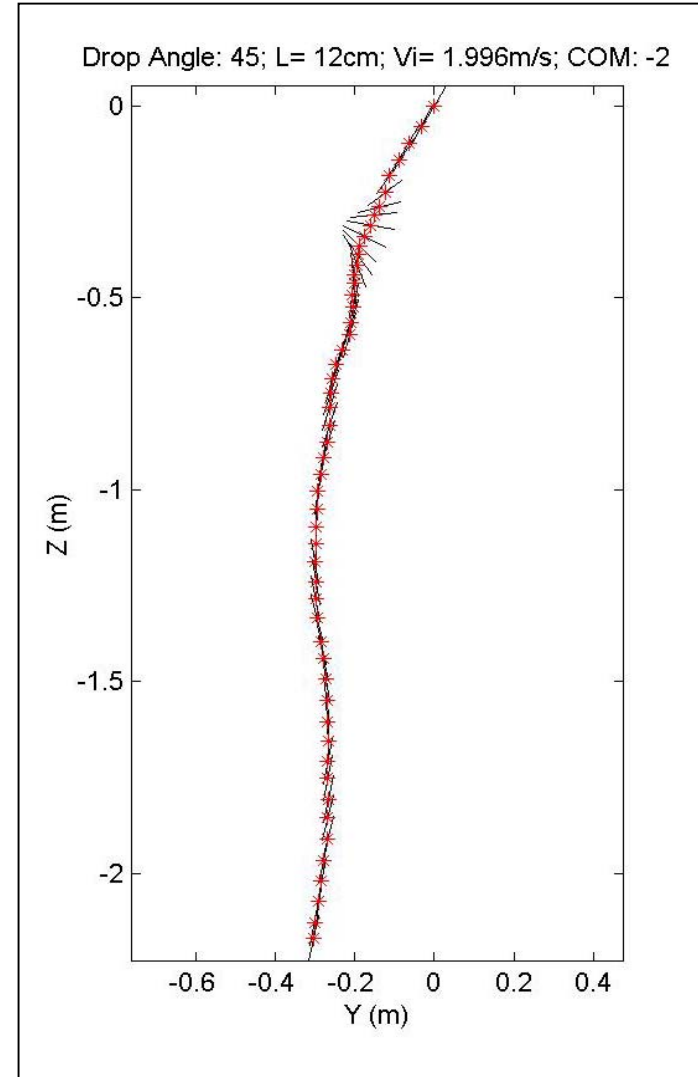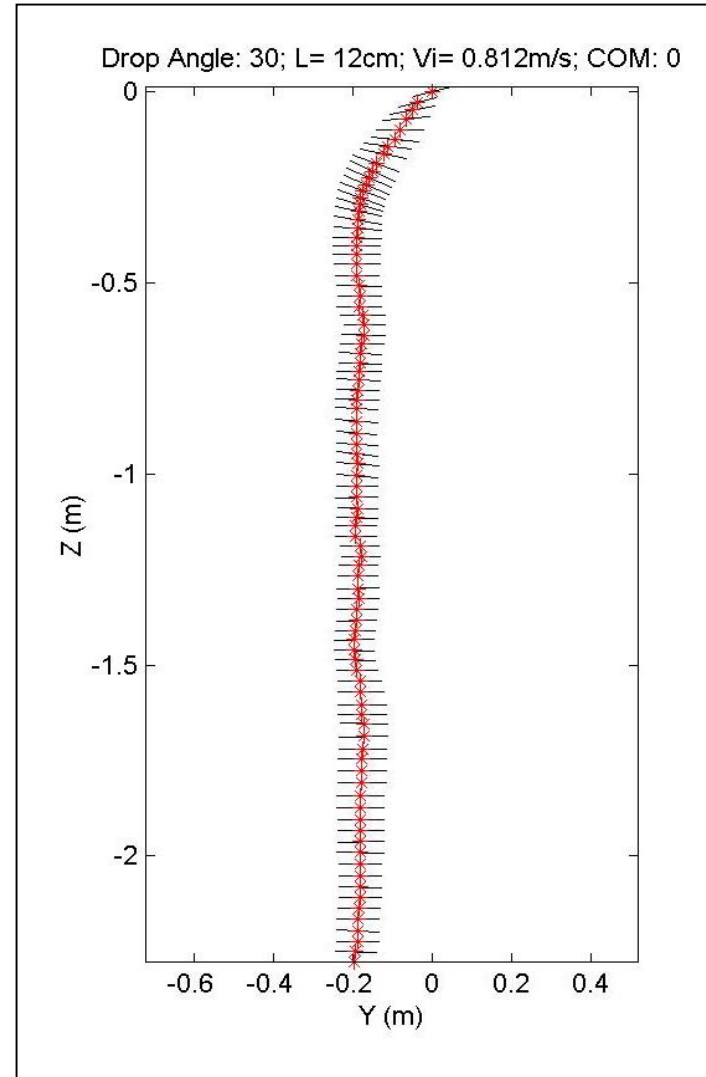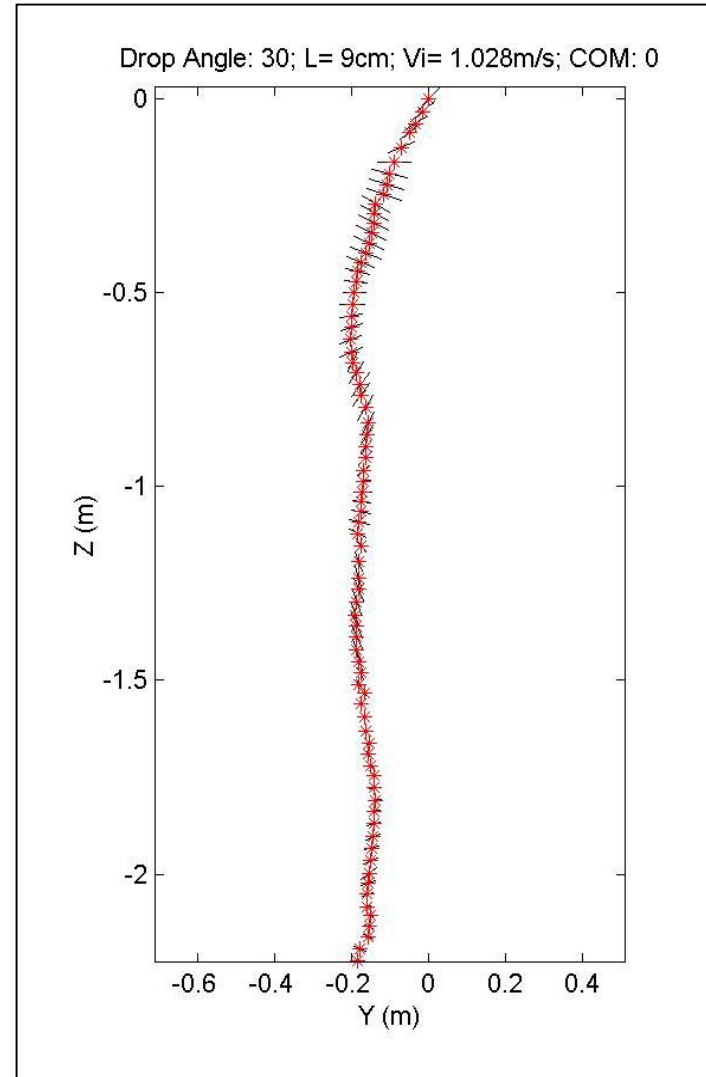
Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
3. Spiral
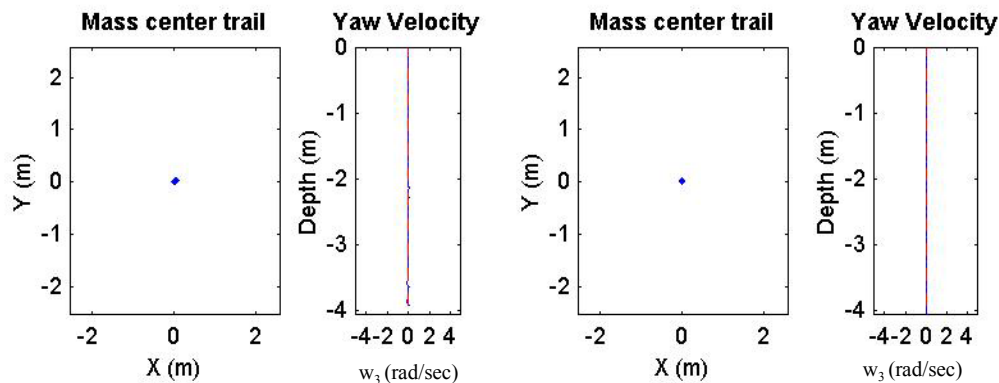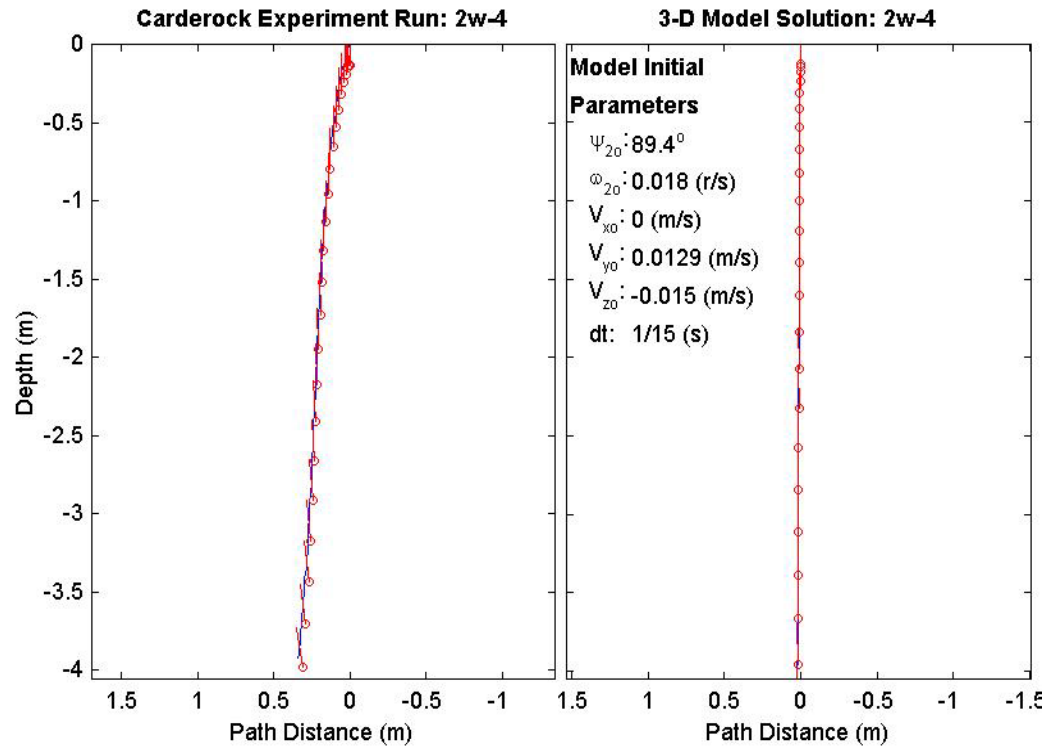4. Flip
5. Flat
6. See Saw
7. Combination

Drop Angle: 45; L= 15cm; Vi= 2.026m/s; COM: 0

Carderock Data Trajectory Analysis

Mine Drop Number:	1	2	3	4	5	6
Blunt Nosed Mine Shapes						
Horizontial Drops						
1w-series	Flat-Spiral	Flat-Spiral	Flat	Flat-Spiral	Slant	Slant-Spiral
10w-series	Flat	Flat	Flat	Flat	Slant	Slant-Spiral
11w-series	Flat-Spiral	Flat	Flat	Flat	Slant-Flat	Slant-Spiral
Vertical Drops						
2w-series	Straight-Flat	Straight-Flat	Straight	Straight	Straight	Straight-Slant
12w-series	Straight-Flat-Seesaw	Straight-Flat-Spiral	Straight-Spiral	(flooded mine)	Straight	Straight
13w-series	Straight-Flat	Straight-Flat	Straight	(flooded mine)	Straight	Straight
45 degree down						
17w-series	Flat-Seesaw-Spiral	Flat-Seesaw	Flat-Seesaw	Slant-Flat	Straight-Slant	Slant-Spiral
20w-series	Flat-Seesaw	Flat-Seesaw	Slant-Flat-Seesaw	(flooded mine)	Slant-Spiral	Slant-Spiral
21w-series	Seesaw-Spiral	Flat-Seesaw	Flat-Seesaw	(flooded mine)	Slant-Spiral	Slant

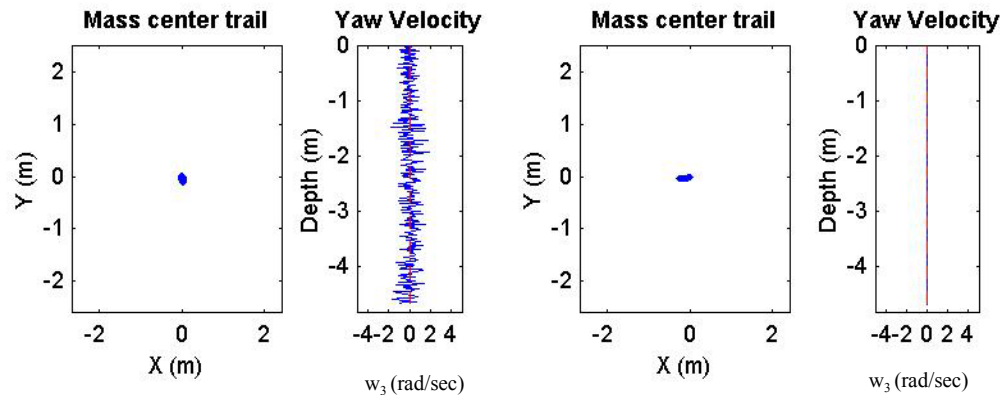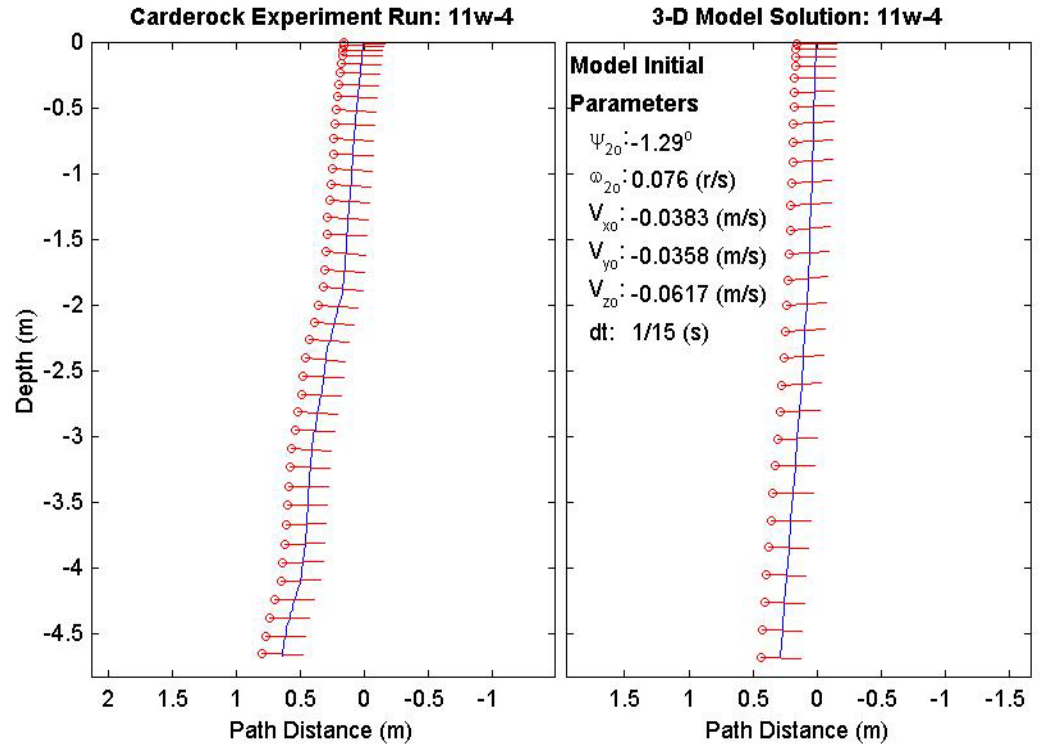| Mine Trajectory Pattern	Description
Vertical	Mine exhibited little angular change about z-axis. $d\psi < 10°$.
Spiral	Mine experienced rotation about z-axis. $d\psi > 10°$.
Flip	Initial water entry point rotated at least 180° during mine motion.
Flat	Mine's angle with vertical near 90° for most of the trajectory.
See-Saw	Similar to the flat pattern except that mine's angle with vertical would oscillate between greater (less) than 90° and less (greater) than 90° - like a see-saw.
Combination	Complex trajectory where mine exhibited several of the above patterns.

Simple Motion Model Mechanics

Straight Motion

Carderock Experiment Run: 2w-4

3-D Model Solution: 2w-4

Model Initial Parameters

Ψ_{2o}: 89.4°

ω_{2o}: 0.018 (r/s)

V_{xo}: 0 (m/s)

V_{yo}: 0.0129 (m/s)

V_{zo}: -0.015 (m/s)

dt: 1/15 (s)

Mass center trail

Yaw Velocity

Mass center trail

Yaw Velocity

w_3 (rad/sec)

w_3 (rad/sec)

Simple Motion Model Mechanics

Flat Motion

Carderock Experiment Run: 11w-4

3-D Model Solution: 11w-4

Model Initial Parameters

ψ_{2o}: -1.29°
ω_{2o}: 0.076 (r/s)
V_{xo}: -0.0383 (m/s)
V_{yo}: -0.0358 (m/s)
V_{zo}: -0.0617 (m/s)
dt: 1/15 (s)

Mass center trail

Yaw Velocity

w_3 (rad/sec)

Simple Motion Model Mechanics

Slant Motion

Carderock Experiment Run: 10w-6

3-D Model Solution: 10w-6

Model Initial Parameters

Ψ_{2o}: -6.98°
ω_{2o}: 0.24 (r/s)
V_{xo}: -0.0304 (m/s)
V_{yo}: -0.0633 (m/s)
V_{zo}: 0.00375 (m/s)
dt: 1/15 (s)

Mass center trail   **Yaw Velocity**   **Mass center trail**   **Yaw Velocity**

w_3 (rad/sec) w_3 (rad/sec)
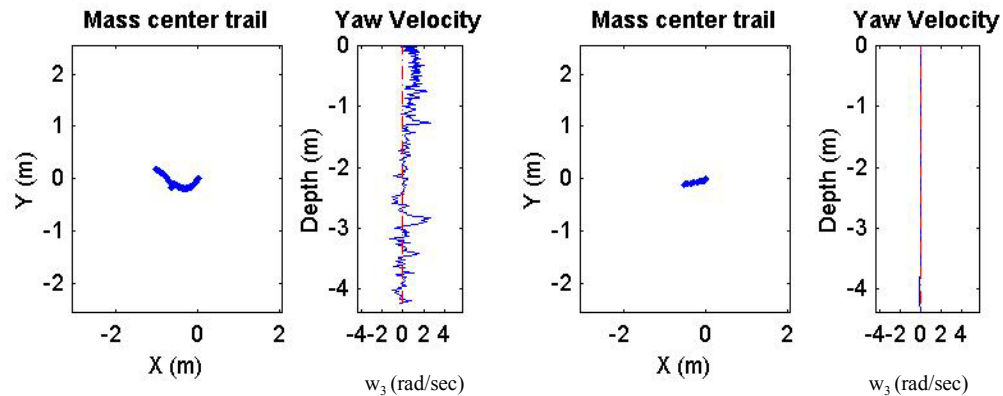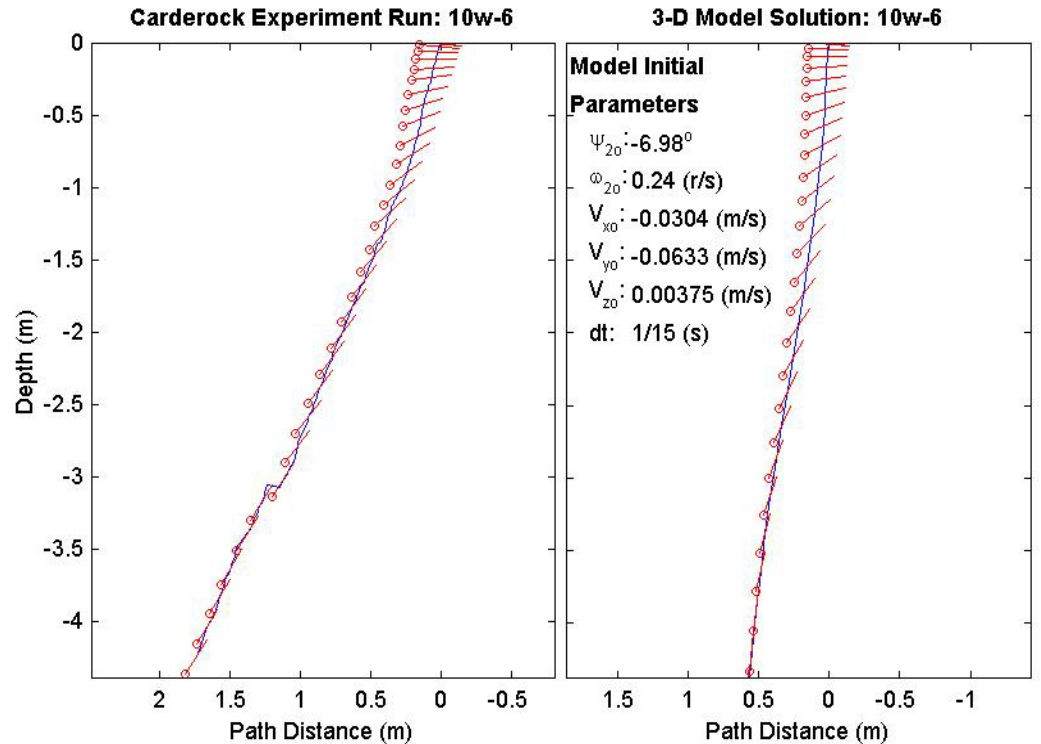
Simple Motion Model Mechanics

Complex Motion

MIDEX Run 15--2-45, Run 1

3-D Model Output 15--2-45, Run 1

Model Initial Parameters

ψ_{2o}: 60°
ω_{2o}: -0.7 (r/s)
V_{xo}: 0 (m/s)
V_{yo}: -0.858 (m/s)
V_{zo}: -1.5 (m/s)
dt: 1/30 (s)

Depth (m) — Path Distance (m)

Mass center trail — **Yaw Velocity** — **Mass center trail** — **Yaw Velocity**
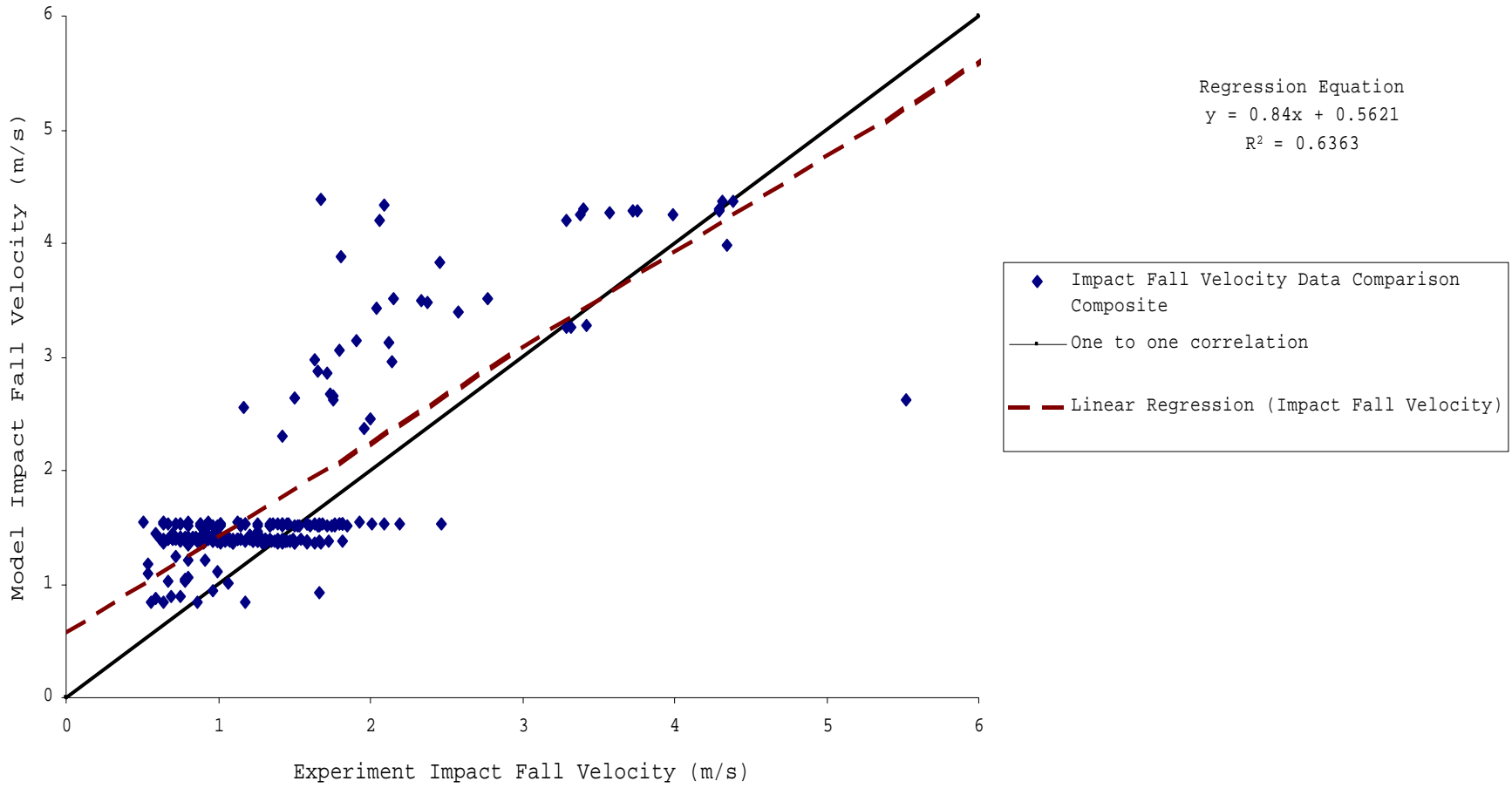
w_3 (rad/sec)

w_3 (rad/sec)
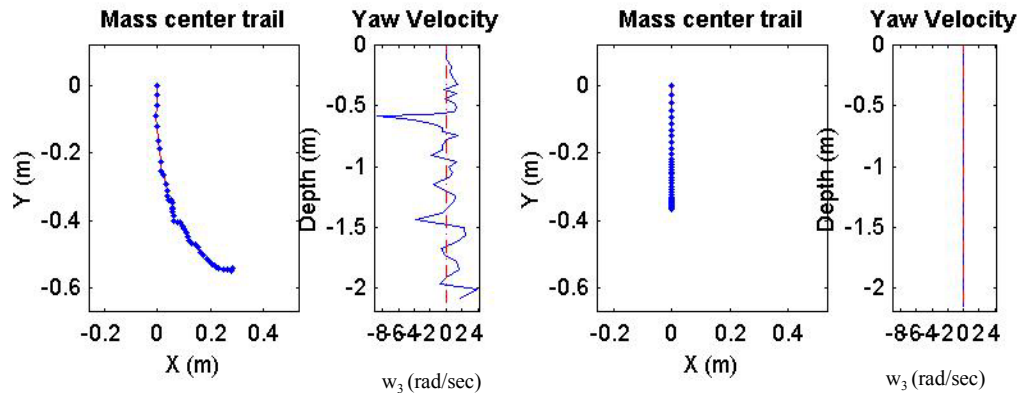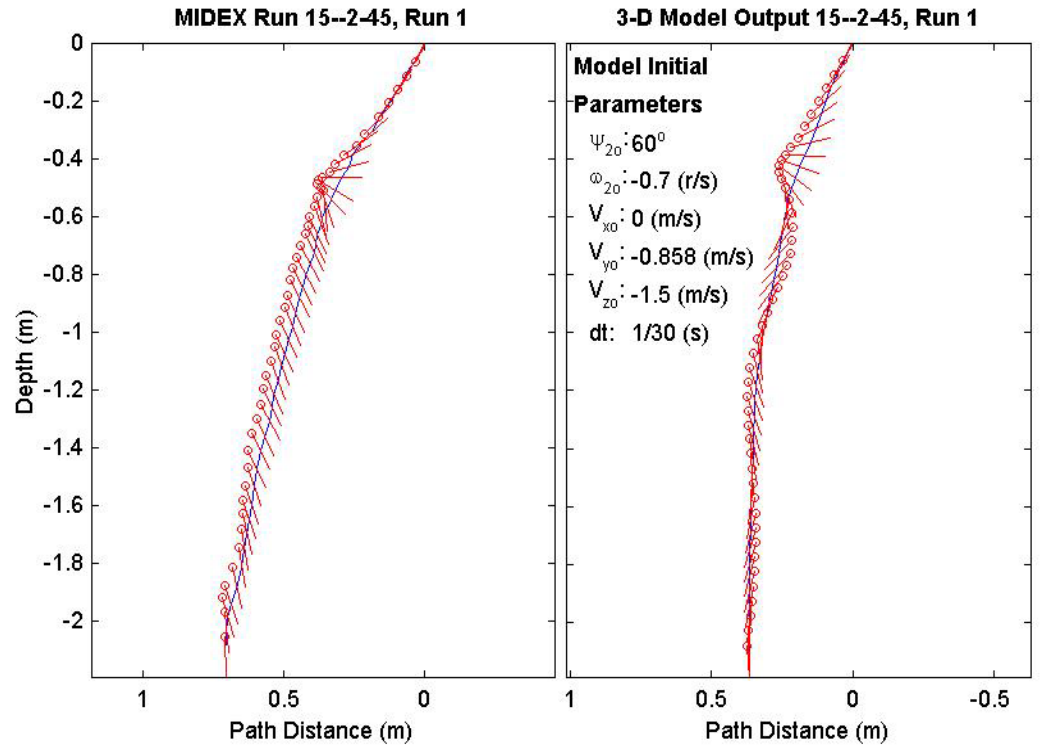
Impact Velocity Correlation

**3-D Model Impact Fall Velocity Versus Composite
Experimental Data Impact Fall Velocity**

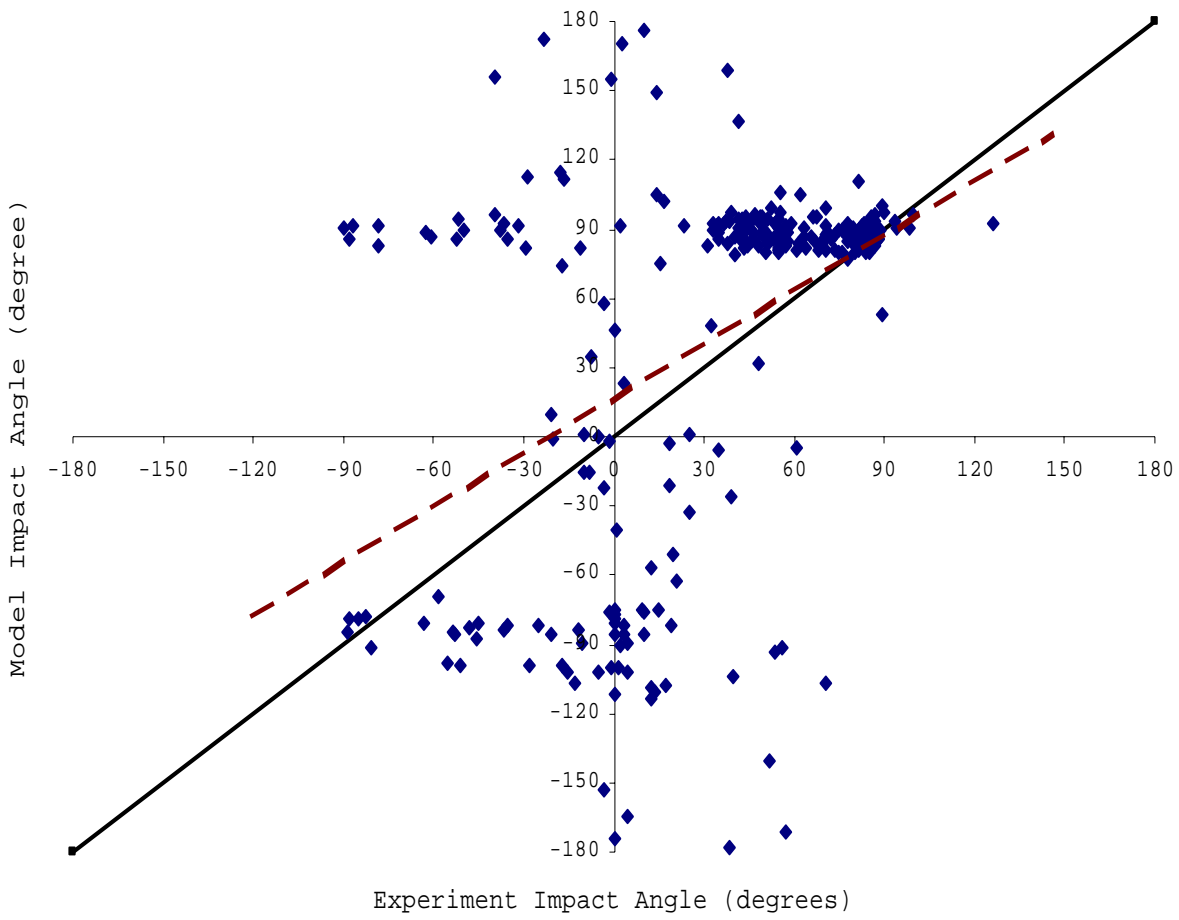Regression Equation
y = 0.84x + 0.5621
$R^2 = 0.6363$

Impact Angle Correlation

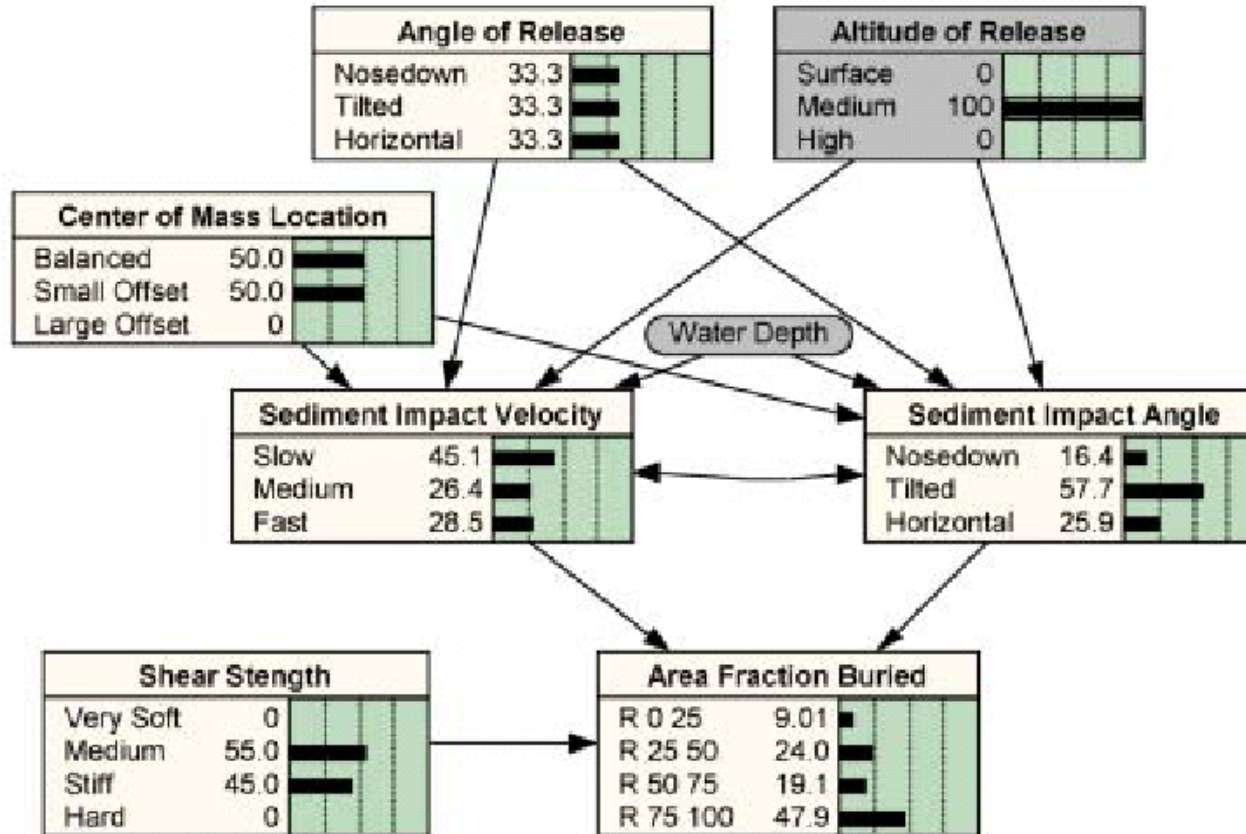**3-D Model Impact Angle Versus Composite
Experiment Data Impact Angle**

Regression Equation
$y = 0.7899x + 16.765$
$R^2 = 0.2099$

♦ Impact Angle Composite Data Comparison
■— One to one correlation
▬ ▬ Linear Regression (Impact Angle)

Model Impact Angle (degree)

Experiment Impact Angle (degrees)

Mine Burial Prediction Future
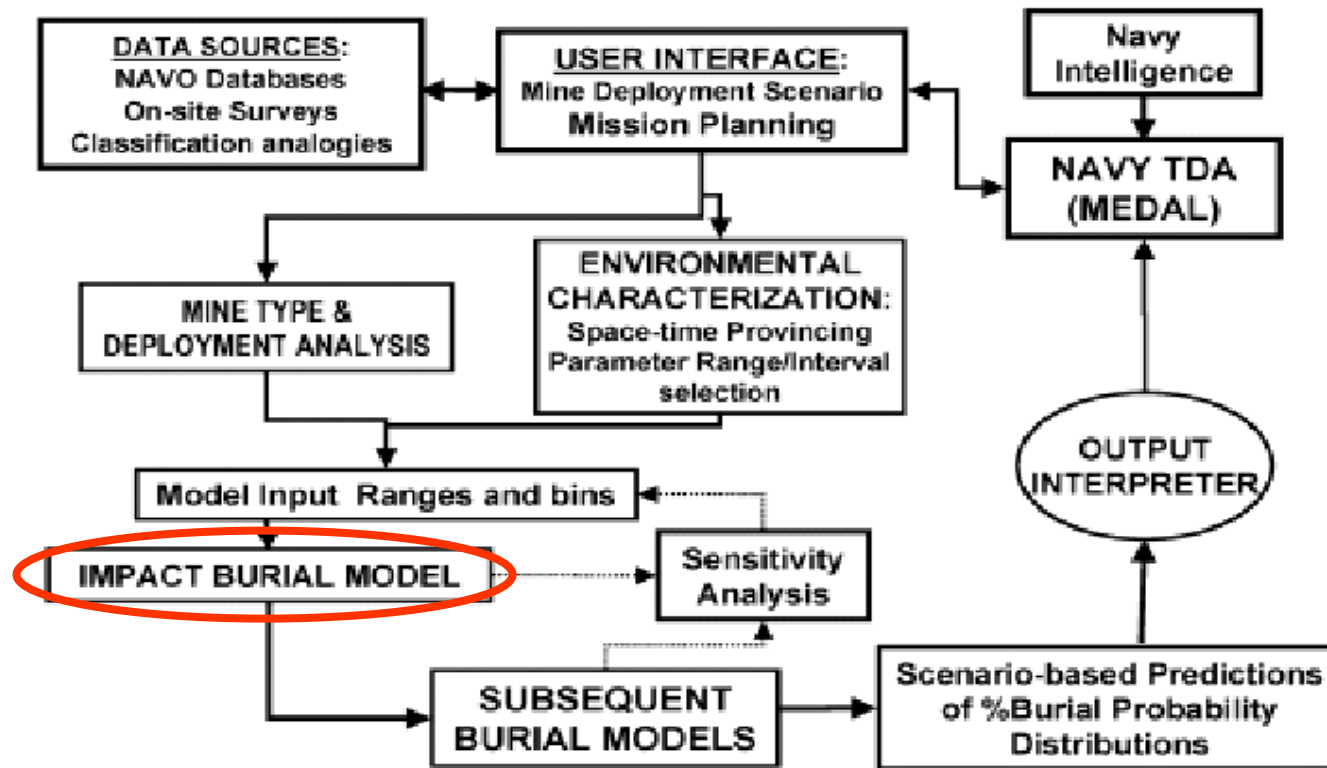## Probabilistic Prediction

Probability Distribution Function Characterization
of Mining Factors in an Operating Area

Sarah Rennie and Alan Brandt
Johns Hopkins University
Applied Physics Laboratory, 2002

An Expert Systems Approach for Predicting Mine Burial

Sarah Rennie and Alan Brandt
Johns Hopkins University
Applied Physics Laboratory, 2002

Conclusions

- Simple two dimension hydrodynamic model extended to three dimensions encompassing all 6 degrees of freedom using modern modeling application.
- Carderock data displayed the same six types of trajectories discussed in Gilless (2001).
- Model Mechanics correctly model vertical and horizontal hydrodynamics of mine shapes.
- Model does handle complex trajectories such as spiral slants and flip rotations, but the outcome is highly sensitive to initial parameters
- Model provides a good statistical measure of impact fall velocity.
- Model is inadequate at producing a statistical measure of impact angle. Performs worse than IMPACT28. Future work in this area includes stability analysis for neutrally stable mine shapes.
- Database now exists of ~ 300 mine drops including initial conditions and complete position data.
- 120 hemispheric nose 1/3 scale model drops to model and incorporate into the database. Full scale mine drop series from Corpus Christi Experiment will be available in January for analysis, as well as data from full scale drops in Mississippi in 2001.
- Investigation required into modeled mine stability for a neutrally stable mine shape to improve impact angle output results.