Test Options & Analysis Techniques:

Aerodynamic Coefficients:

What's Important & How Can I Measure Them?

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Outline

- What's Important & Why?
- Data Acquisition Options
- Accuracy & Cost Comparison
- Summary and Conclusions

What's Important & Why?

Aerodynamic Coefficient / Item	Symbol	Description & Affects
Zero Yaw Drag Force	C_{X0}	Acts along projectile axis; Deceleration & retained velocity, minor affect on dispersion
Yaw Drag Force	C_{X2}	Added drag factor along proj. axis; Decel. & retained velocity of yawing bullet
Normal Force Derivative	$C_{N\alpha}$	Acts in plane of angle of attack; Causes swerve motion of yawing bullet, dispersion. Influences dynamic stabilty
Magnus Force	$C_{YP\alpha}$	Out of plane force from spin; source of the destabilizing Magnus moment
Pitching Moment Derivative	$C_{m\alpha}$	Acts in the plane of angle of attack; influences Gyroscopic Stability & Dispersion
Pitch Damping Moment	C_{mq}	Acts counter to pitching moment; affects Dynamic Stability
Spin Damping Moment	C_{lp}	Acts counter to projectile spin; affects down range gyroscopic stability
Roll Moment Product	$C_{ld}D$	Roll moment coefficient x fin cant angle: Increases/maintains projectile spin rate
Magnus Moment	$C_{np\alpha}$	Acts perpendicular to the plane of the angle of attack; affects Dynamic Stability
GN&C Forces & Moments	CN_{α}/ Cm_{α}	Typically Increases Angle of Attack to provide maneuver authority

- **What can you afford to ignore?**

What's Important & Why?

- **Jump Equation (Dispersion)**

$$\Theta_j = \left[\left[\left(\frac{C_{N\alpha} - C_D}{C_{m\alpha}}\right)\left(\frac{I_y - I_x}{md^2}\right)\left(\frac{d}{V_m}\right)\left(\alpha_g \bullet p_m\right)\right]^2 + \left[\Delta_{CG} \bullet \frac{p_m}{V_m}\right]^2\right]^{\frac{1}{2}}$$

- **Gyroscopic Stability Equation**

$$S_{gp} = \frac{(2)(I_x^2)(p^2)}{(\pi)(\rho_o)(I_y)(C_{m\alpha})(d^3)(V_m^2)}:$$

- **Dynamic Stability Damping Exponents**

$$\lambda_F = \frac{\rho A}{4m}\left[-C_{N\alpha}(1-\frac{1}{\sigma}) + (k_2^{-2}/2)(1+\frac{1}{\sigma})C_{mq} + (k_1^{-2}/\sigma)C_{np\alpha}\right]$$

$$\lambda_S = \frac{\rho A}{4m}\left[-C_{N\alpha}(1+\frac{1}{\sigma}) + (k_2^{-2}/2)(1-\frac{1}{\sigma})C_{mq} - (k_1^{-2}/\sigma)C_{np\alpha}\right]$$

What's Important & Why?

- **Deceleration** $$dV/dX = \frac{1000 \rho V A C_x}{2m}$$

- **Steady State Roll Rate (Statically Stable Bullets)**

  $- C_{l\delta}\delta = (pd/2V)C_{lp}$ or: $\frac{-2\,C_{l\delta}\delta}{d\,C_{lp}} = p_{steady\ state}$ (rad/m)

What are my Aero Data Acquisition Options?

- **Witness & Yaw Cards**
- **Doppler Radar**
- **Wind Tunnel (& Variants)**
- **Spark Range**
- **On-Board Telemetry (Yawsonde, Magsonde, etc..)**
- **Data "Fusion"**

Witness Cards

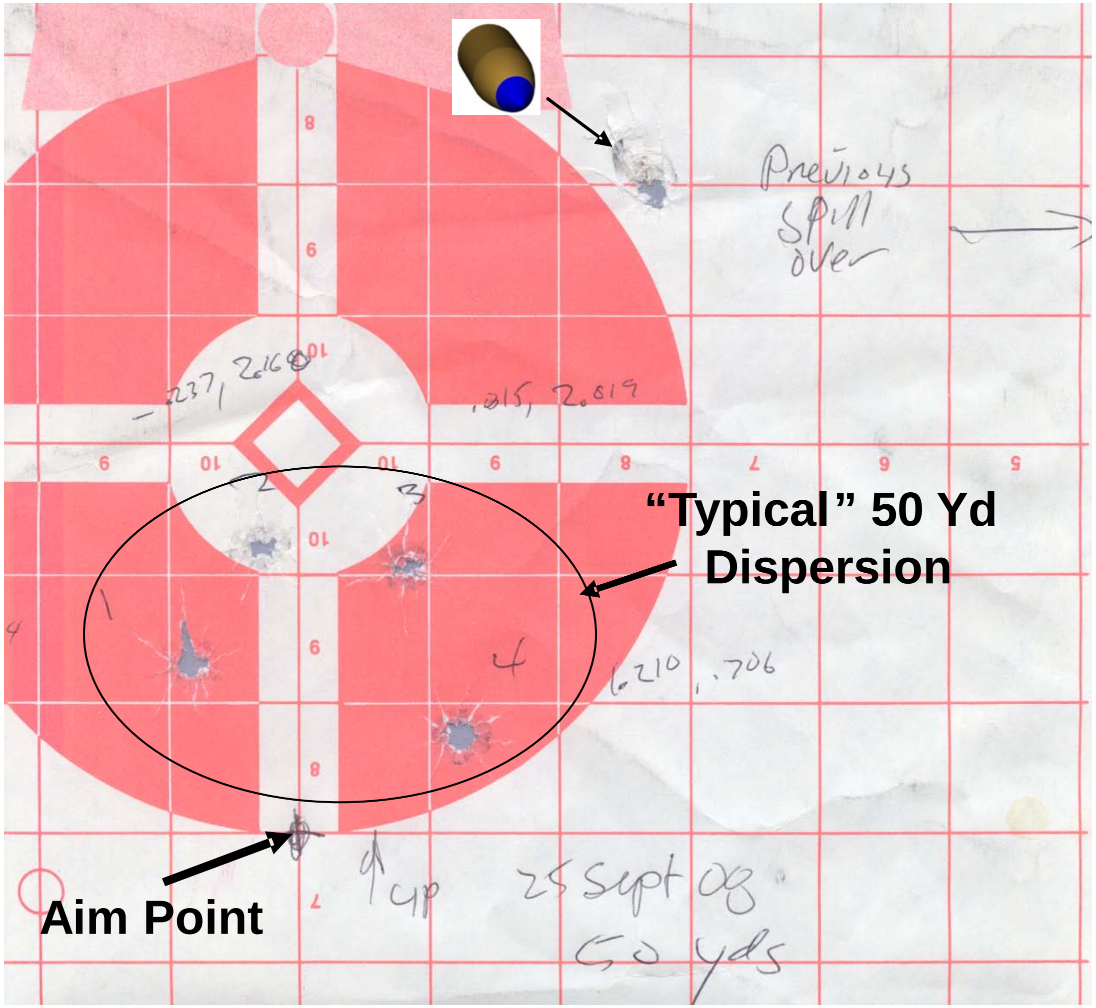
Simple paper target at convenient distance from gun

- **Aim point & projectile impact points**
- **Limited examination of projectile angle of attack info**

Provides:

- **Dispersion & MPI distance from Aim Point estimates**
- **Evidence of in-flight stability or projectile damage**
- **Point value angle of attack not recorded by acoustic targeting systems…**
  (verification of stable, low yaw flight)

Witness Card Example

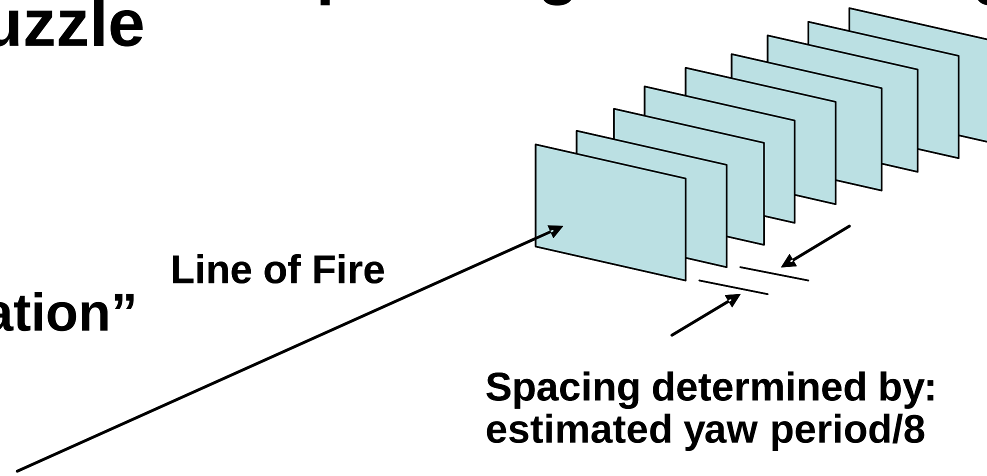


- **Record of aim point and impact point of various shots…**
- **Impact in upper right was aimed at center of adjacent target, exhibits large angle of attack @ 50 yards**

Yaw Cards

Series of target cards

- **Record total angle of attack & pointing vector change vs. distance from muzzle**



Advantages:

- Simple technique
- Low cost "instrumentation"

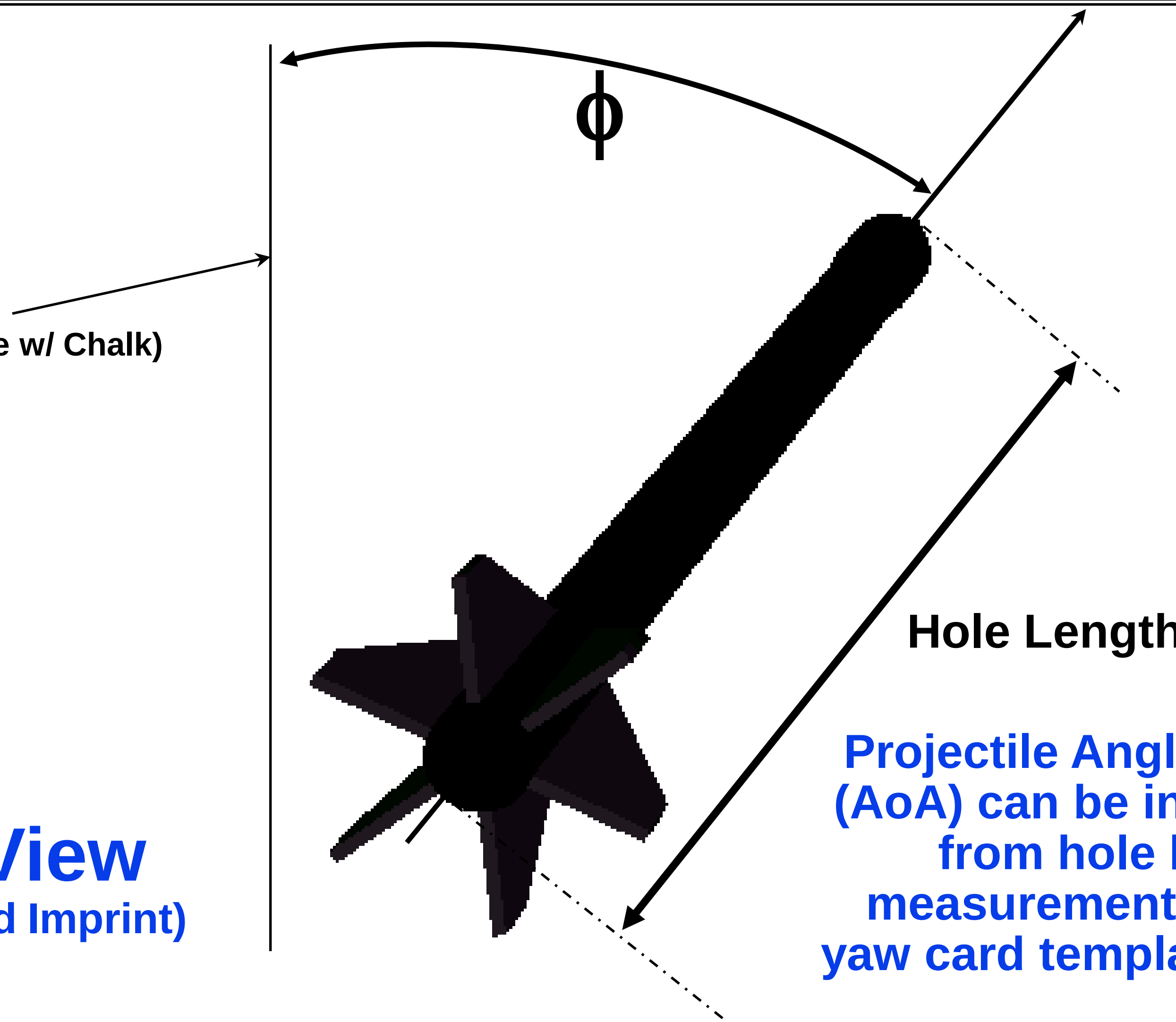
Provides:

- Pitching moment, pitch damping, Magnus moment, roll moment, roll decay moment
- Is yaw causing dispersion or only MPI shift?

Drawbacks:

- Need sufficient yaw to allow observation (Yaw Inducer Needed?)
- Yaw card impact affects projectile motion

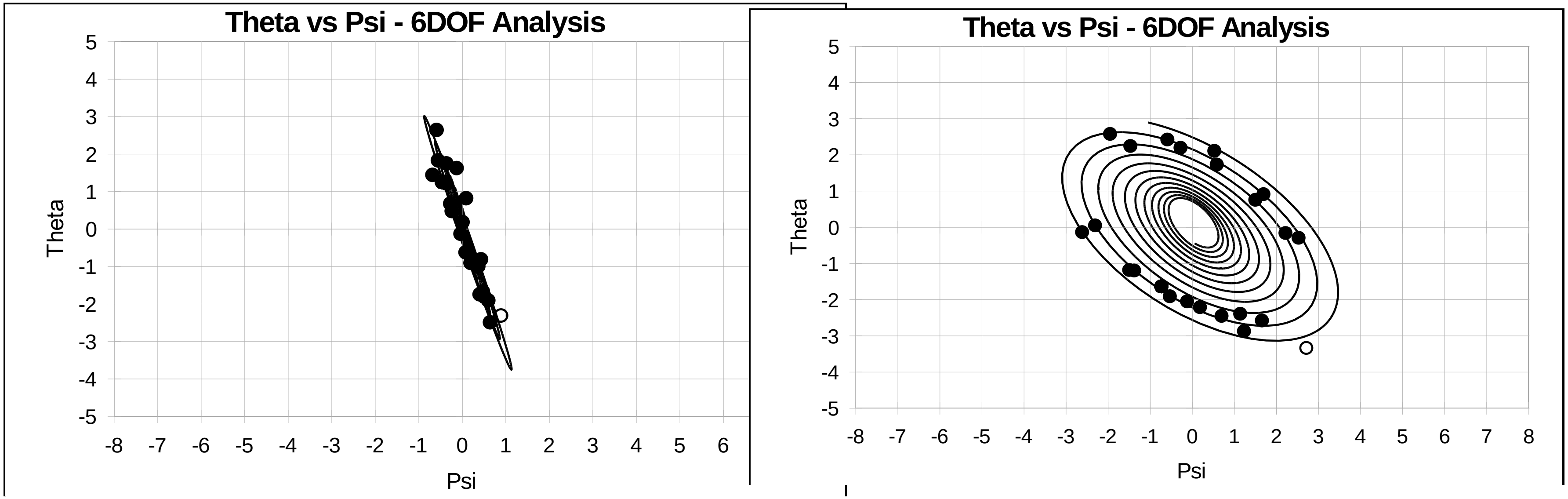
Yaw Card Data



Aft View
(Yaw Card Imprint)

Projectile Angle of Attack (AoA) can be interpolated from hole length measurements or from yaw card template overlays

Yaw Card Diagnostics



"Planar" Motion
Caused by In-Bore Disturbances

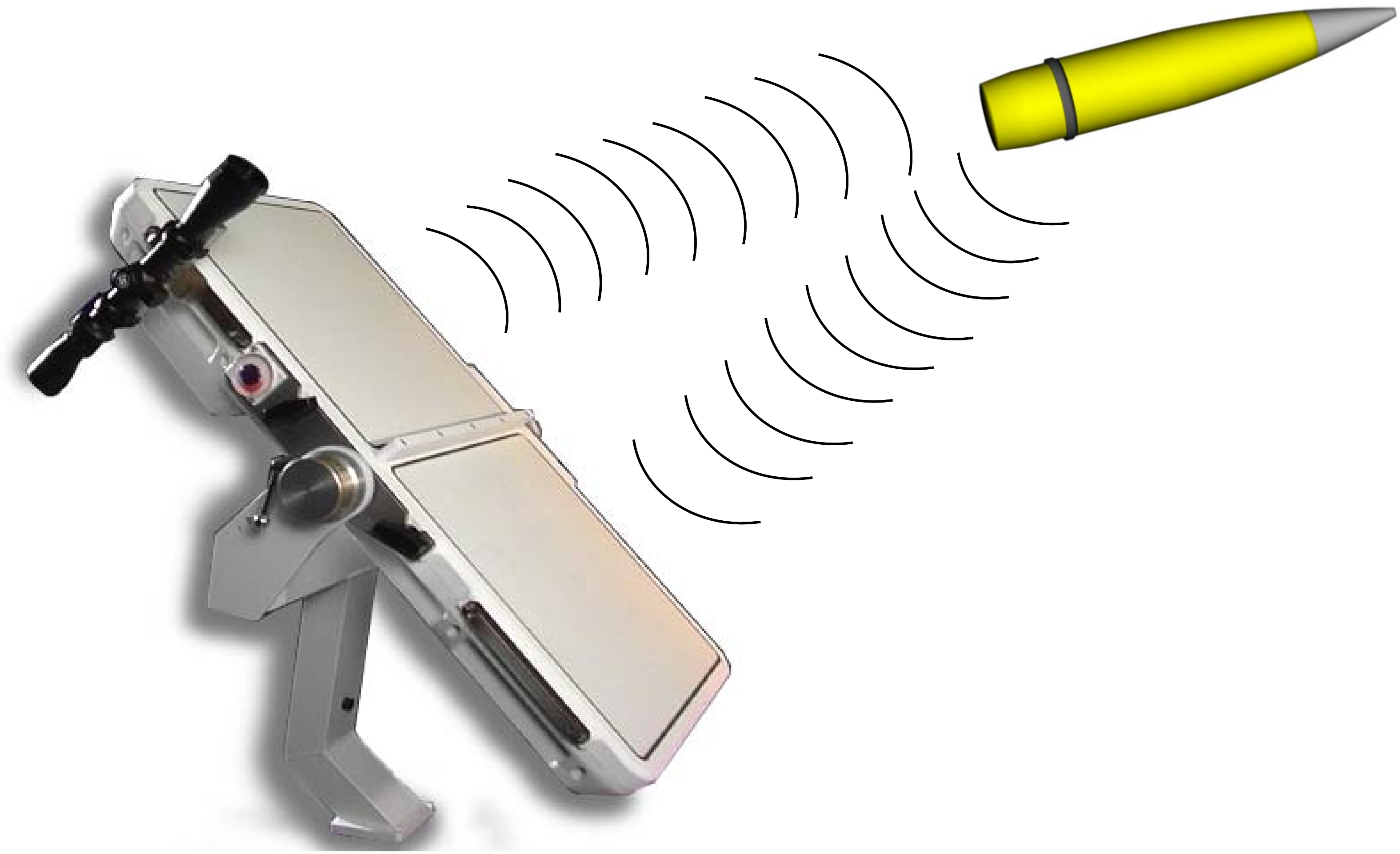
Coning Motion
External Disturbance Source

ARROW TECH

If you can't get a bigger target...

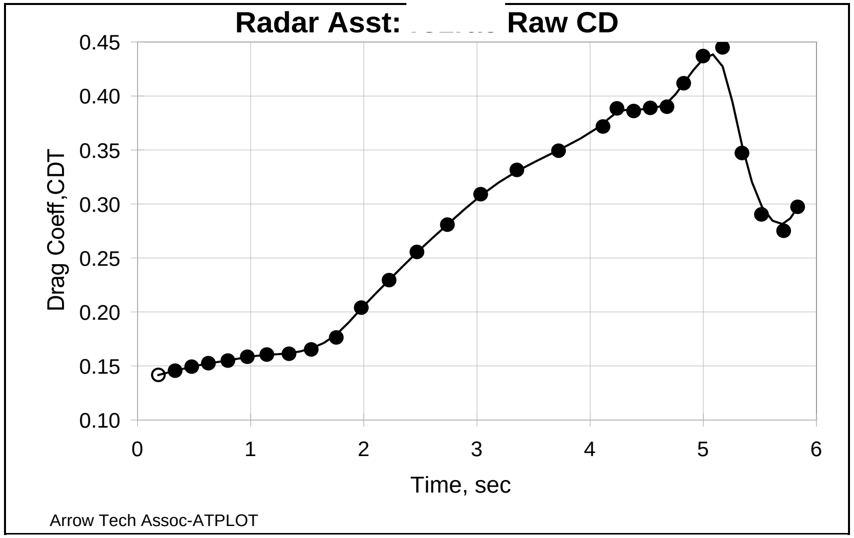
Doppler Radar Testing

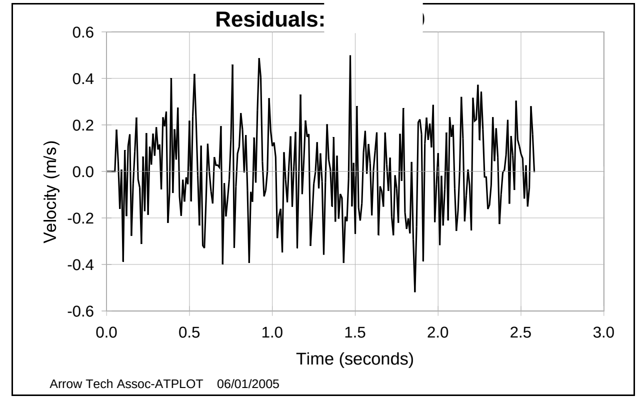
(Radar image courtesy of Infinition, Inc.)

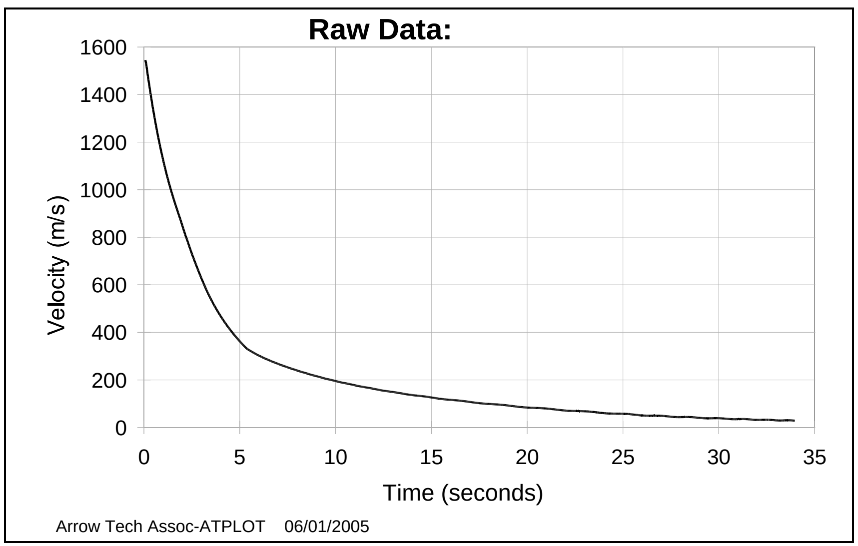


If you can't get a bigger target...

Radar Testing







- **Point-point initial solution**
- **Simulate Trajectory via 4 DoF.**
- **Compare Vel-Time of Simulation to Experimental Data.**
- **Iteratively Adjust Drag Coeff Until Difference between Simulation & Experiment is minimized.**
- **Assess groups of like projectiles to determine statistical behavior (Mean & sigma of MV & Drag).**

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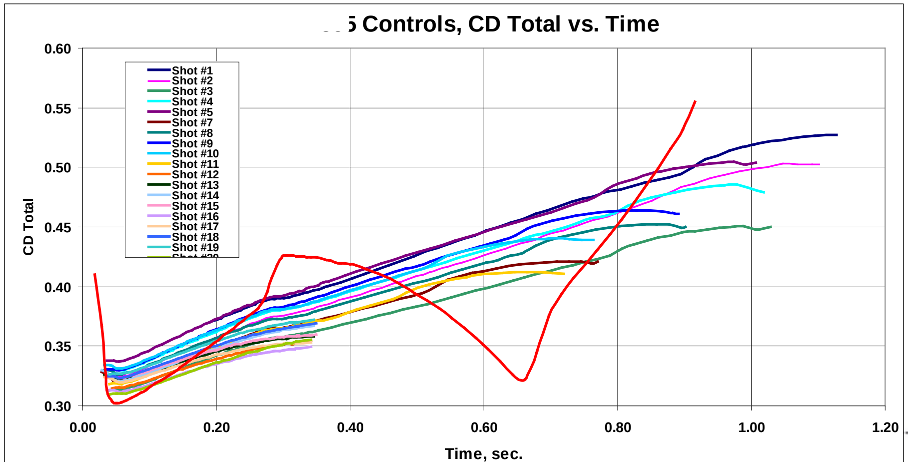
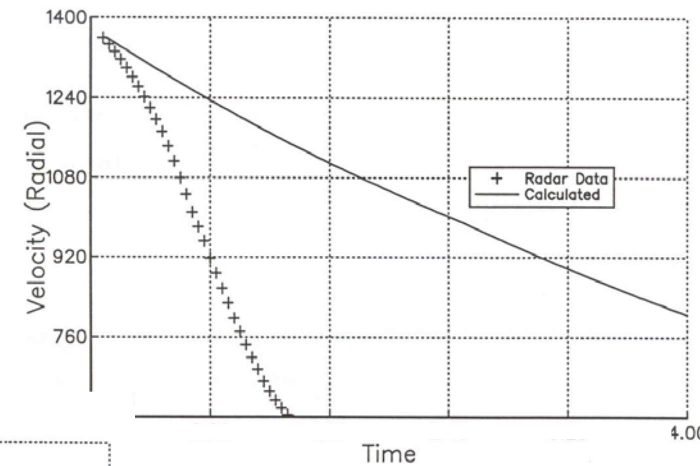
If you can't get a bigger target...

Doppler Radar Diagnostic Signatures

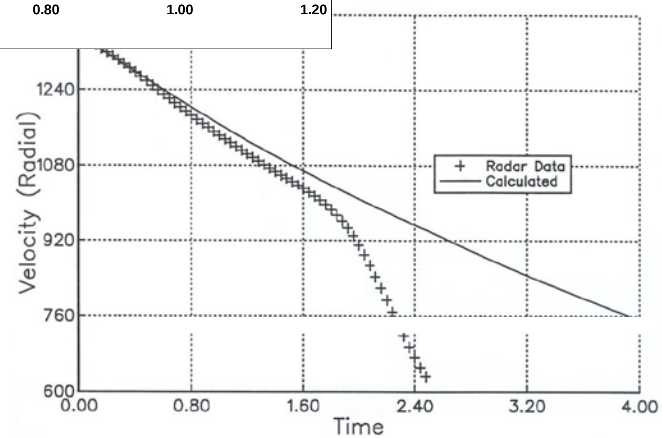
Moving Parts



Structural Resonance



Aerodynamic Resonance



- **Various flight dynamic problems have characteristic signatures that can be rapidly categorized & diagnosed w/ Doppler Radar**
- **Spin reflector can be used to obtain C_{lp}, C_{ld}Delta…**

Wind Tunnel

Range from "home made" subsonic to precision supersonic blow-down or steady state tunnels

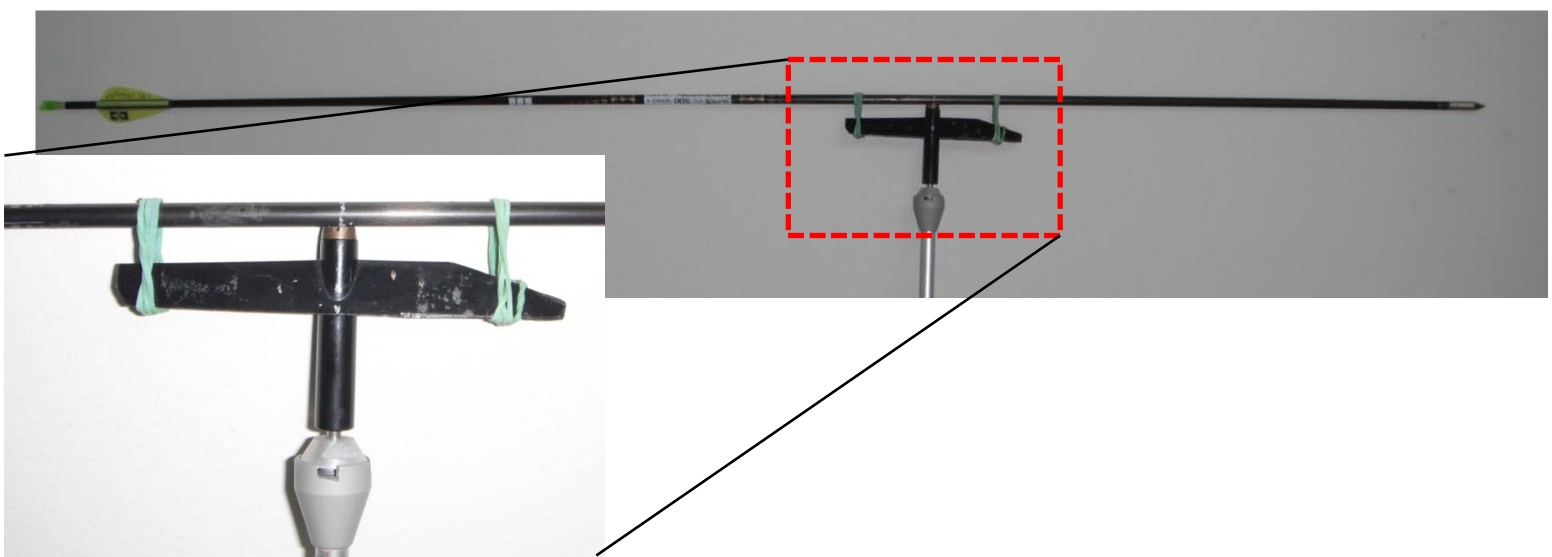
Provides: Normal force coeff., pitching moment, roll moment, roll decay moment.

Drawbacks:

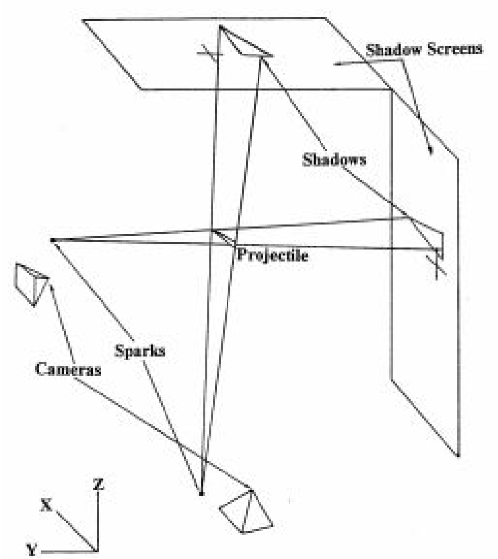
- Pitch damping moment, Roll moment, roll damping moment determination are contaminated by bearing friction….
- "Sting" or support muddles base flow subsonically

"Captive Free Flight"

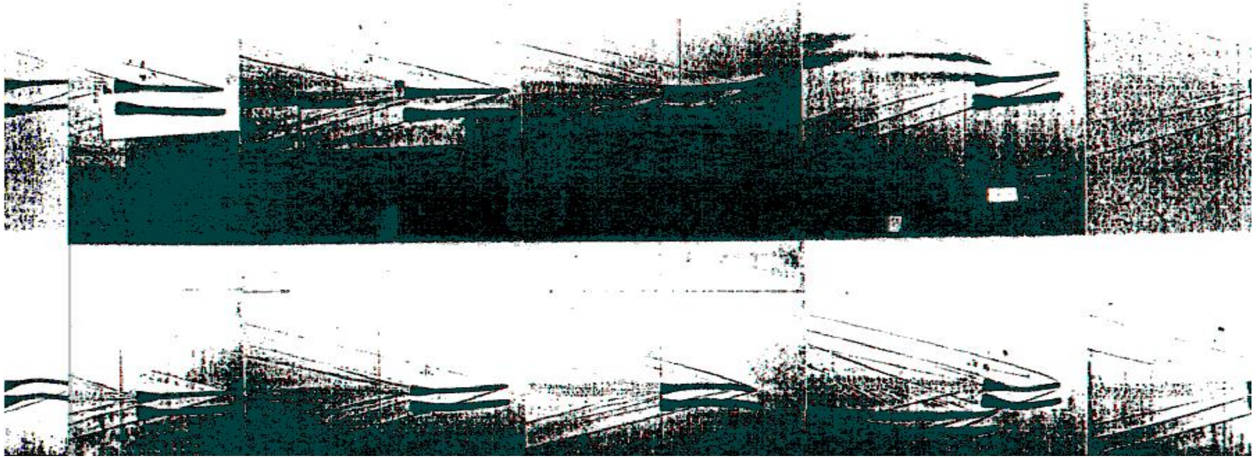
- **Fasten model to low friction bearing (e.g. sailboat "windex")**
- **Affix to appropriately modified vehicle**
- **Drive (moderately fast)**
- **Disturb model & record oscillation frequency (time base on video..)**
- **Pitching moment, pitch damping moment can be extracted from data**



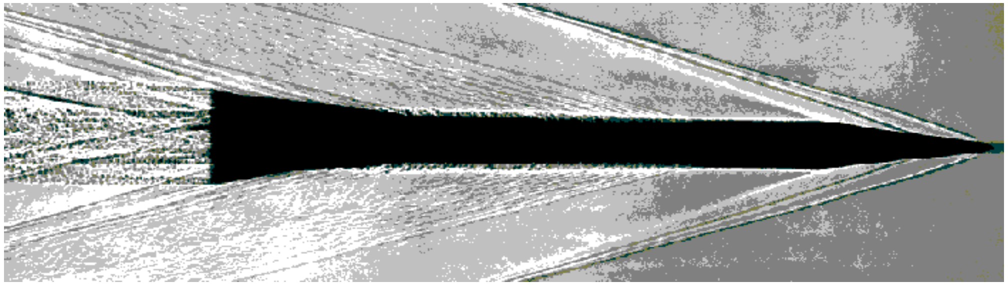
Aeroballistic Range

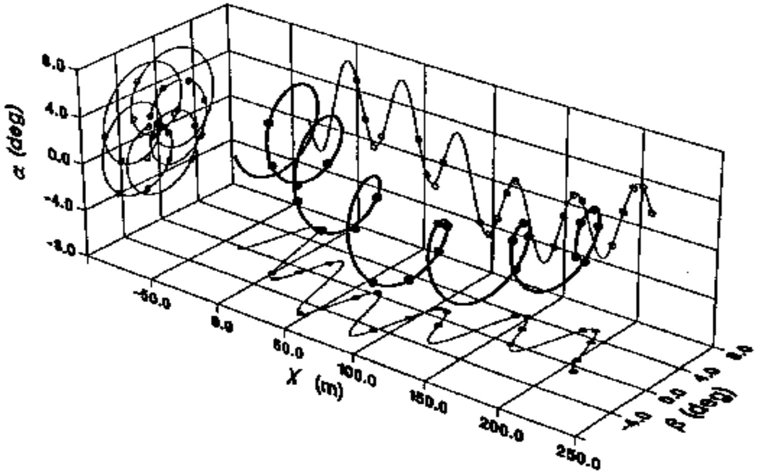


- **Concept:**
  - **Orthogonal Photographs of Projectile Shadow from "Spark" Sources**
  - **Fit 6 DoF Coefficients to Observed Flight Motion in Series of Photos**

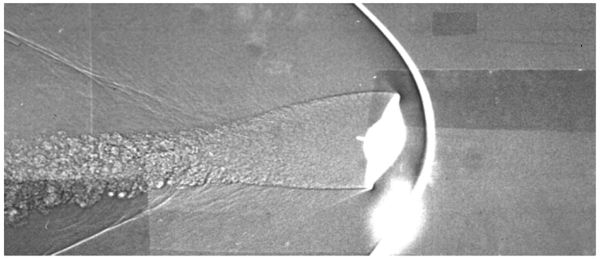


Aeroballistic Range





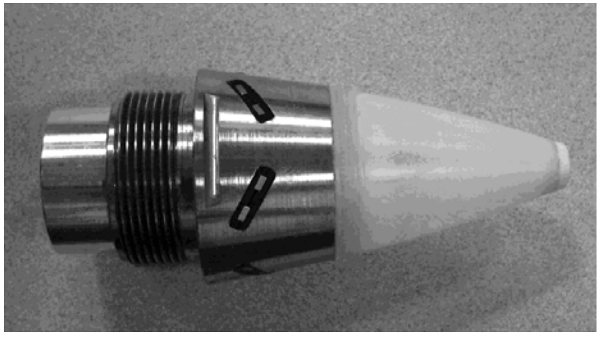
- **Positive Aspects**
  - **Full Scale Testing (5.56mm to 200mm)**
  - **Excellent Mach Number Control**
  - **Reynolds Number Match**
  - **Direct Observation of Angular-Translational Motion**
    - > **Motion Growth - Damping**
  - **Initial Conditions / Initial Motion Match Real World**



- **Negative Aspects**
  - **Exact Angle of Attack, Roll Orientation cannot be precisely controlled**
  - **Apogee / Terminal Conditions (Spin/ Velocity) not matched**
  - **Low Velocity Tests of High Velocity Projectiles do not match rotating band wear conditions**

Yawsonde/Dfuze Testing

On-Board Telemetry Hardware



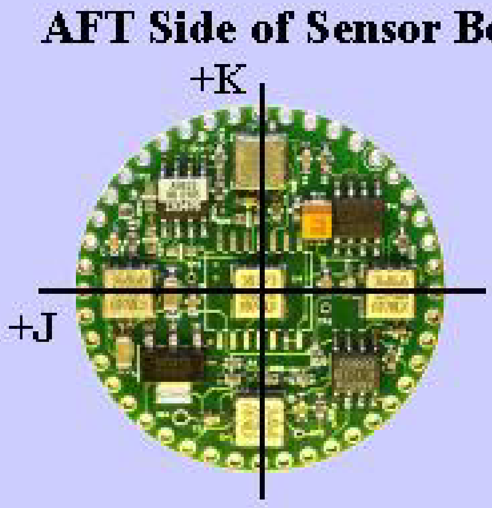
Aeroballistic Diagnostic Fuze

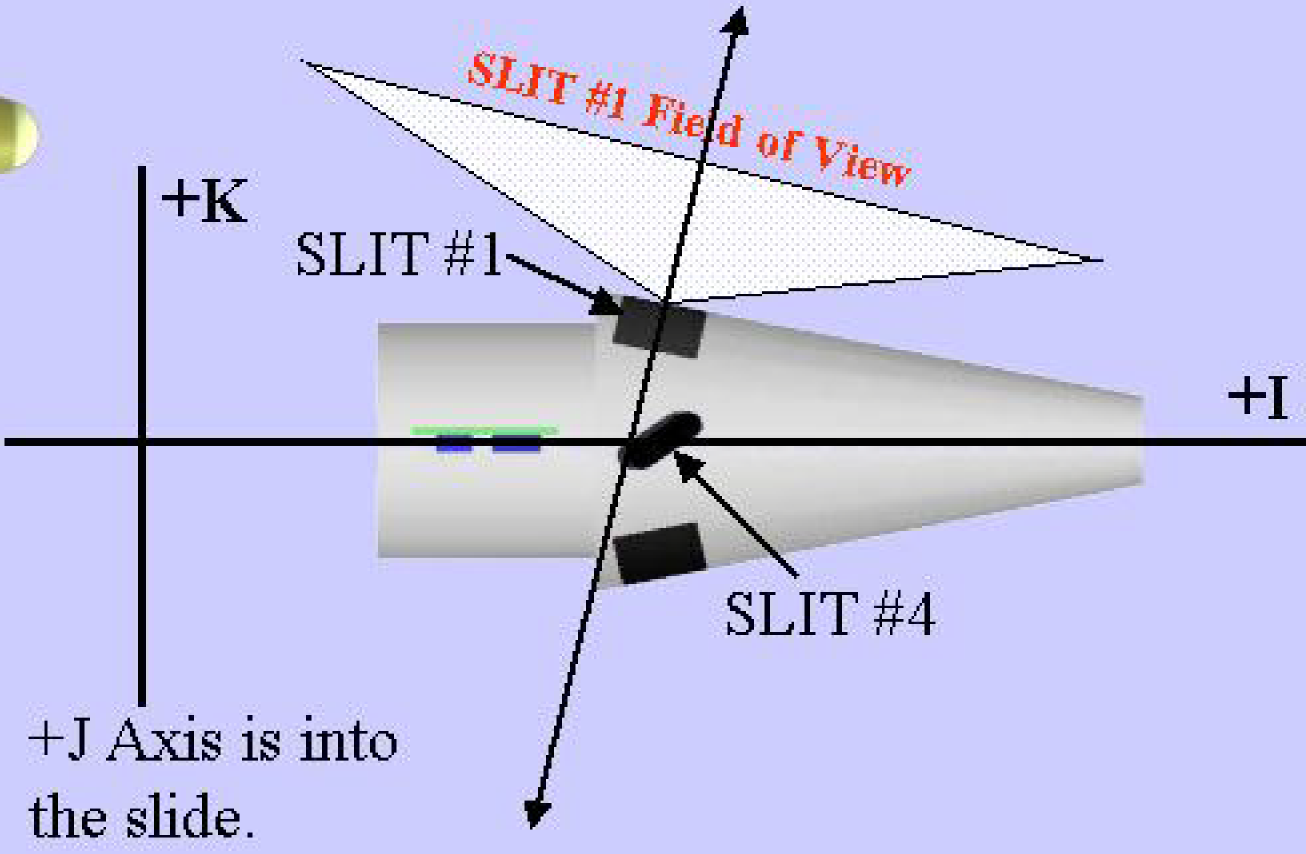
Instrumented 2.75-inch Rocket

In conjunction with Doppler Radar

ARL INERTIAL SENSOR SUITE
BOARD INSTALLATION ORIENTATION IN DFUZE

The INERTIAL SENSOR SUITE BOARDS are mounted within the FUZE bodies so that the field of view of SLIT #1 lies in the I,+K half-plane.





ARROW TECH

If you can't get a bigger target...

What Methods for Which Coefficients?

Aerodynamic Coefficient/ Item	Symbol	Yaw Card	Doppler Radar	Wind Tunnel	Spark Range	On Board Telemetry
Zero Yaw Drag Force	C_{X0}		X	X	X	
Yaw Drag Force	C_{X2}		X	X	X	
Normal Force Derivative	$C_{N\alpha}$			X	X	
Magnus Force	$C_{YP\alpha}$				X	
Pitching Moment Derivative	$C_{m\alpha}$	X		X	X	X
Pitch Damping Moment	C_{mq}	X		X	X	X
Spin Damping Moment	C_{lp}	X (Finner)	X	X	X	X
Roll Moment Product	$C_{ld}D$	X (Finner)	X	X	X	X
Magnus Moment	$C_{np\alpha}$				X	X
GN&C Forces & Moments	CN_{α}/ Cm_{α}				X	X

- **Combinations of non-spark range techniques can provide all aeros**
- **Limitations (size, cost, range availability, etc) determine choices…**

ARROW TECH

If you can't get a bigger target...

Aero Data Acquisition Options Cost & Accuracy Summary

Measurement Option	Caliber Applicability	Goal	Accuracy	Data Acquisition Cost / Shot or run
Witness Card	All	Dispersion & MPI	~ Location, 0.010"	Pennies
Yaw Card	All	Static & Dynamic Stability	~±15-25%	\$2-\$10 depending on setup & shots fired
Doppler Radar Data	All	Drag & Muzzle Velocity	± 1.5% on drag, ±0.1 m/sec on MV	\$20-\$100/shot if equipment/operator is leased, less if owned.
Wind Tunnel	Med & Large	Normal Force, Pitching Moment	± 3-5% on most aeros, 15-25% on Pitch damping, roll damping, Magnus moment	\$10-\$50 and up, + setup fees
Captive Flight	All, limited Mach Numbers	Normal Force, Pitching & Pitch Damping Moments	± 1 -20% low subsonic Pitching & Pitch damping moments	\$5-\$25/ run
Spark Range	All	The whole smash	Best available…	\$2000-\$2500/shot
On-Board Telemetry	Med & Large	Everything but Normal Force Coeff.	Good for everything but Normal Force Coeff.	\$800-\$25000/shot depending on infrastructure, etc. required for test. Radar coverage req'd .

- **What are my aero coeff. collection requirements?**

Summary & Conclusions

- **Numerous options available to all munitions engineers to measure actual aerodynamic coefficients, regardless of caliber**
- **Coefficient measurement accuracy is generally proportional to cost, but good measurements can be made inexpensively in a wide variety of cases**
- **"Cut-and-try", especially with small caliber ammunition, is no longer cost effective for schedule reasons; scientific methods can be brought to bear at reasonable costs**
- **"Simulate the test" can prevent test repeats**
- **Competent testing early in the program can uniquely identify specific function problems, helping ensure project stays on schedule & under budget**
- **"Right Sized" test program provides the Right Response**