# U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

## Air Drag Measurements for the NATO Insensitive Munitions Fragment

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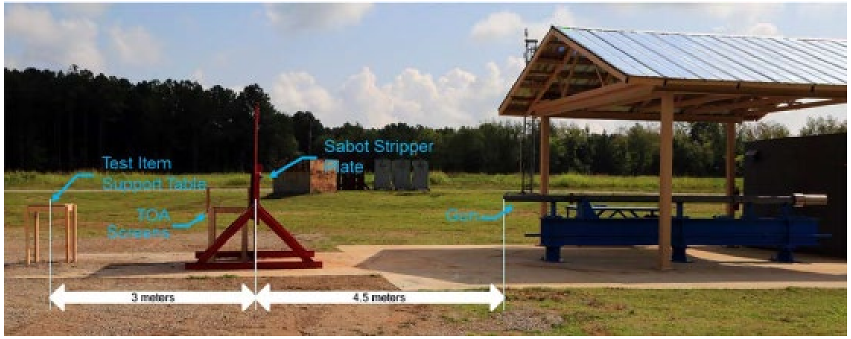
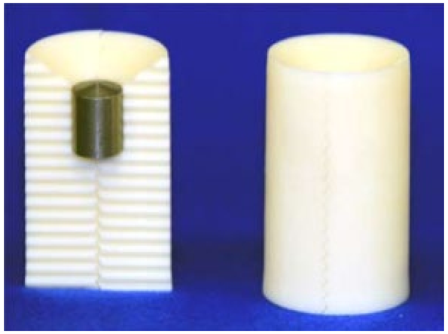
# OUTLINE

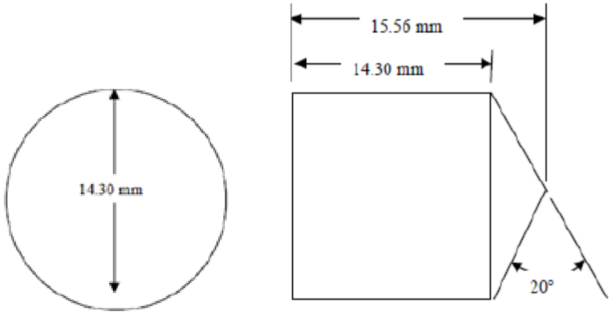
- Background
- Theory
- Experimental Methodology
- Results and Discussion
- Summary and Conclusions; Future Work

# BACKGROUND

- Test article placed as close to FI gun as is practical
- Larger test items may need to be moved further down the shot line
- 2530 m/s challenging for powder guns, barrel wear
- Accounting for air drag should provide increased confidence in impact velocity
- In this work we have performed a series of drag coefficient measurements at test velocities of interest





# THEORY

$$m\frac{dV}{dt} = -\frac{1}{2}\rho V^2 S C_D \qquad s = \frac{1}{l} = \int_{t_0}^{t} V dt$$

F=ma

$$\frac{d(\ln V)}{ds} = \frac{1}{V}\frac{dV}{ds} = -\left(\frac{\rho S l}{2m}\right) C_D \equiv -C_D^*$$

F=ma (dimensionless length)

$$t = t_0 + \frac{l\left(e^{C_D^* s} - 1\right)}{V_0 C_D^*}$$

Solution for time of arrival (dimensionless length)

$$\approx t_0 + \left(\frac{l}{V_0}\right) s + \left(\frac{l C_D^*}{2V_0}\right) s^2 + \cdots$$

Solution for time of arrival (Taylor series expansion)

$$\approx t_0 + \left(\frac{1}{V_0}\right) x + \left(\frac{\rho S C_D}{4 m V_0}\right) x^2 + \cdots$$

# THEORY (CONT'D)

$$t = t_0 + a_1 x + a_2 x^2 + a_3 x^3 \quad \text{where}$$

$$a_1 = \frac{1}{V_0} \qquad a_2 = \frac{\rho S C_D}{4 m V_0} \quad \rightarrow \quad C_D = \left(\frac{4m}{\rho S}\right)\left(\frac{a_2}{a_1}\right)$$

Solution for time of arrival (actual length)

- Perform cubic least squares fit to TOA data with x=0, V=V0, t=t0 at **range midpoint**
- Linear term determines velocity at range midpoint (x=0)
- Quadratic, second order term contains drag coefficient
- Cubic, third order term absorbs Mach number variation

How long a range length needed to accurately measure $C_D$?

# THEORY (CONT'D)

$$d_t = \frac{l\left(e^{C_D^* s} - 1\right)}{V_0 C_D^*} - \frac{ls}{V_0} \approx \frac{l C_D^* s^2}{2V_0} = \frac{\rho S l^2}{16 m V_0} C_D L^2$$

Maximum time decrement – difference in TOA at range endpoints, assuming drag vs. no drag

$$e_t / d_t$$

TOA measurement error $e_t$ should be small compared to $d_t$ for accurate drag measurements!

$d_t$ increases with square of total range length!

# THEORY (CONT'D)

$$d_t = \frac{l\left(e^{C_D^* s} - 1\right)}{V_0 C_D^*} - \frac{ls}{V_0} \approx \frac{l C_D^* s^2}{2V_0} = \frac{\rho S l^2}{16 m V_0} C_D L^2$$

| | | |
|---|---|---|
| rho | 1.225 | Air Density, kg/m^3 |
| len | 0.0143 | Fragment Diameter, m |
| S | 0.000160606 | Fragment Presented Area, m^2 |
| m | 0.0186 | Fragment Mass, kg |
| V0 | 2530 | Fragment Velocity, m/s |
| CD | 1.4 | Assumed Drag Coefficient, dimensionless |
| Lft | 75 | Assumed Total Range Length, ft |
| Lm | 22.86 | Assumed Total Range Length, m |
| Lcal | 1598.601399 | Assumed Total Range Length, calibers |
| dt | 191.1723526 | Maximum Time Decrement, us |
| terr | 1 | Timing Error, us |
| xerr in | 1 | Spacing error, in |
| xerr m | 0.0254 | Spacing error, m |
| xeq | 10.03952569 | Spacing Equivalent Timing Error, us |
| teq | 10.08920592 | Total Equivalent Timing Error, us |
| toterr | **5.28** | Anticipated Measured Drag Error, % |

Long flight path needed so that detected deceleration not overwhelmed by measurement error!

# THEORY (CONT'D)

How many timing stations do you need assuming uniform known measurement error?

$$e_i^2 = \left(\frac{\partial a_i}{\partial t_1} e_{t1}\right)^2 + \left(\frac{\partial a_i}{\partial t_2} e_{t2}\right)^2 + \cdots + \left(\frac{\partial a_i}{\partial t_n} e_{tn}\right)^2$$

Can explicitly calculate error in each least squares fit coefficient as function of number and spacing of timing stations!

$$\left(\frac{e_i}{e_t}\right)^2 = \sum_{j=1}^{n} \left(\frac{\partial a_i}{\partial t_j}\right)^2$$

- Long story short, optimal spacing is half the stations at range midpoint, 1/4 of them at each range endpoint
- We used 6 equally spaced TOA gauges over ~75ft

# DRAG COEFFICIENT MEASUREMENT TESTING

| | Test 1 (RT21463) | | Test 2 (RT21464) | | Test 3 (RT21465) | | Test 4 (RT21466) | | Test 5 (RT21467) | | Test 6 (RT21468) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TOA (ms) | X (in) | TOA (ms) | X (in) | TOA (ms) | X (in) | TOA (ms) | X (in) | TOA (ms) | X (in) | TOA (ms) | X (in) |
| **GUN-TOA1** | 25.4180 | 120.0000 | 24.7467 | 120.2500 | 22.6041 | 103.5000 | 21.9282 | 104.0000 | 23.0228 | 104.0000 | 22.0304 | 104.0000 |
| **TOA1-TOA2** | 26.6044 | 120.0000 | 25.9591 | 119.2500 | 24.4072 | 179.3750 | 23.6915 | 179.3750 | 24.7955 | 180.3125 | 23.8304 | 180.8750 |
| **TOA2-TOA3** | 27.8177 | 120.0000 | 27.1960 | 119.2500 | 26.2653 | 180.1250 | 25.5208 | 178.8750 | 26.6321 | 178.8750 | 25.6687 | 178.2500 |
| **TOA3-TOA4** | 29.0660 | 120.0000 | 28.4682 | 120.8750 | 28.1943 | 179.1250 | 27.4107 | 179.0000 | 28.5503 | 179.1250 | 27.5918 | 178.9375 |
| **TOA4-TOA5** | 30.3597 | 120.0000 | 29.7834 | 120.8750 | 30.2280 | 181.1875 | 29.4085 | 181.1875 | 30.5653 | 181.1875 | 29.6188 | 181.3125 |
| **TOA5-TOA6** | 31.6837 | 120.0000 | 31.1328 | 120.0000 | 32.3423 | 178.8125 | 31.4505 | 178.8125 | 32.6443 | 178.5625 | 31.7180 | 178.5000 |

# DRAG COEFFICIENT MEASUREMENT TESTING

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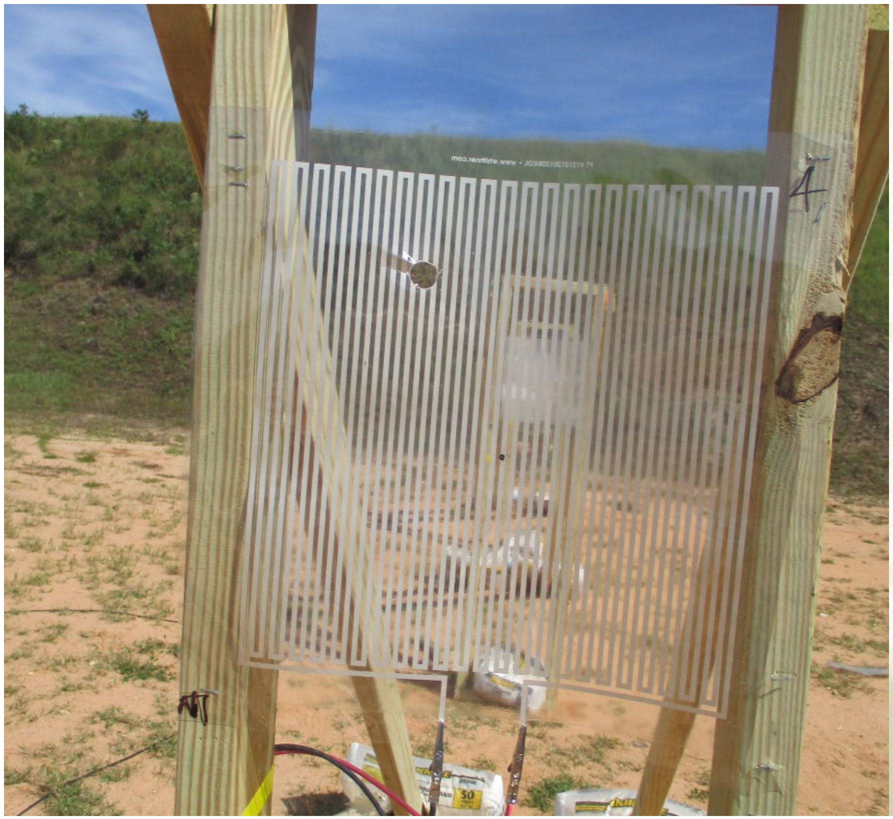
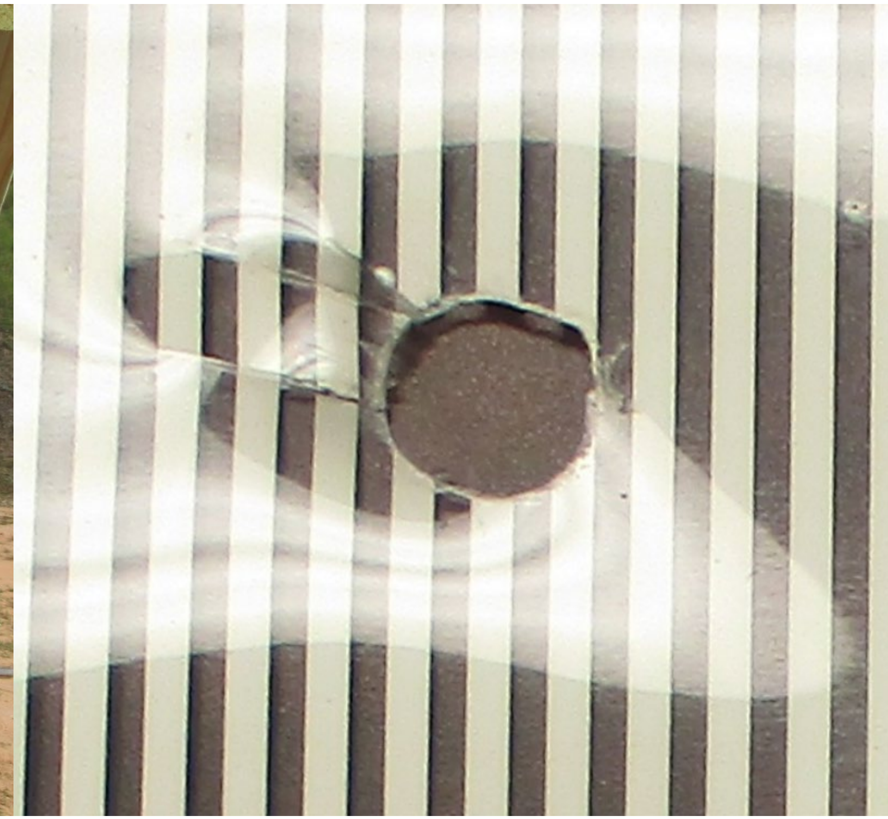




TOA gauges a little heavy…

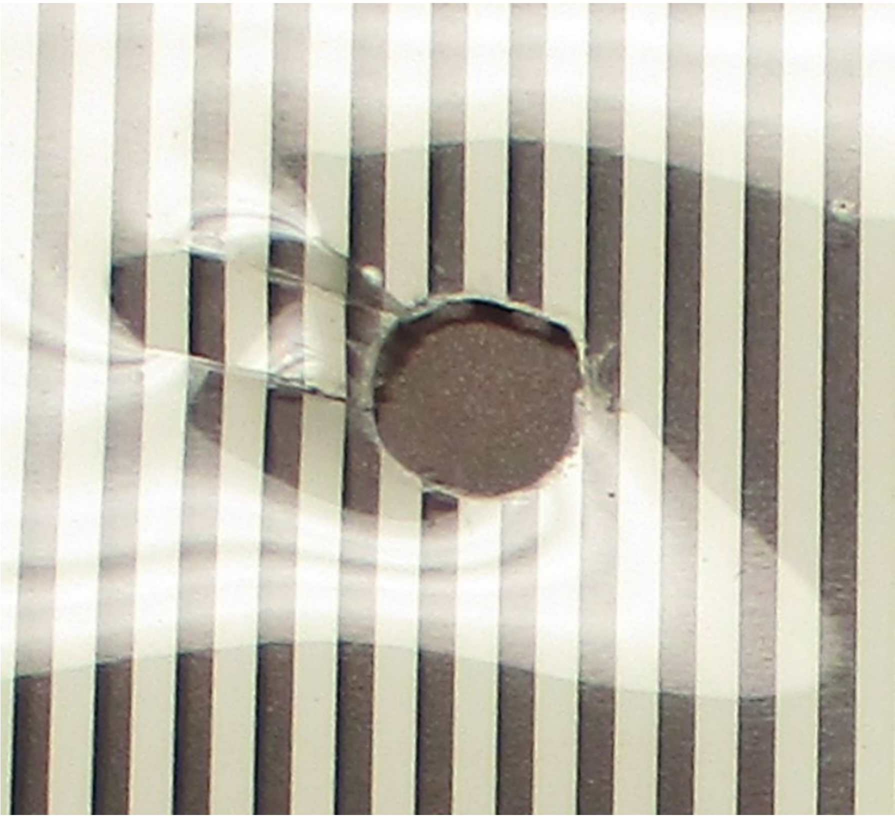
# DRAG COEFFICIENT CALCULATION

| | Test 1 (RT21463) | | Test 2 (RT21464) | | Test 3 (RT21465) | | Test 4 (RT21466) | | Test 5 (RT21467) | | Test 6 (RT21468) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TOA (s) | x(m) | TOA (s) | x(m) | TOA (s) | x(m) | TOA (s) | x(m) | TOA (s) | x(m) | TOA (s) | x(m) |
| **TOA1** | 0.0254180 | -7.6200 | 0.0247467 | -7.6099 | 0.0226041 | -11.4128 | 0.0219282 | -11.3900 | 0.0230228 | -11.4104 | 0.0220304 | -11.4102 |
| **TOA2** | 0.0266044 | -4.5720 | 0.0259591 | -4.5810 | 0.0244072 | -6.8567 | 0.0236915 | -6.8339 | 0.0247955 | -6.8305 | 0.0238304 | -6.8159 |
| **TOA3** | 0.0278177 | -1.5240 | 0.0271960 | -1.5520 | 0.0262653 | -2.2815 | 0.0255208 | -2.2905 | 0.0266321 | -2.2871 | 0.0256687 | -2.2884 |
| **TOA4** | 0.0290660 | 1.5240 | 0.0284682 | 1.5182 | 0.0281943 | 2.2683 | 0.0274107 | 2.2561 | 0.0285503 | 2.2627 | 0.0275918 | 2.2566 |
| **TOA5** | 0.0303597 | 4.5720 | 0.0297834 | 4.5884 | 0.0302280 | 6.8704 | 0.0294085 | 6.8583 | 0.0305653 | 6.8649 | 0.0296188 | 6.8620 |
| **TOA6** | 0.0316837 | 7.6200 | 0.0311328 | 7.6364 | 0.0323423 | 11.4123 | 0.0314505 | 11.4001 | 0.0326443 | 11.4004 | 0.0317180 | 11.3959 |

| | a3 | a2 | a1 | a0 | V0 | CD | dV/dx |
|---|---|---|---|---|---|---|---|
| **Test 1** | 1.5761E-08 | 1.9406E-06 | 4.1023E-04 | 2.8439E-02 | 2437.6 | 1.79 | 23.062002 |
| **Test 2** | 5.4435E-08 | 1.7083E-06 | 4.1568E-04 | 2.7835E-02 | 2405.7 | 1.55 | 19.77285 |
| **Test 3** | 2.9361E-08 | 1.9223E-06 | 4.2280E-04 | 2.7223E-02 | 2365.2 | 1.72 | 21.507083 |
| **Test 4** | 6.6191E-09 | 1.7185E-06 | 4.1697E-04 | 2.6464E-02 | 2398.2 | 1.56 | 19.76768 |
| **Test 5** | 5.7707E-09 | 1.9215E-06 | 4.2105E-04 | 2.7585E-02 | 2375.0 | 1.73 | 21.677254 |
| **Test 6** | 1.8829E-08 | 1.9283E-06 | 4.2235E-04 | 2.6626E-02 | 2367.7 | 1.73 | 21.620883 |

Seems high!

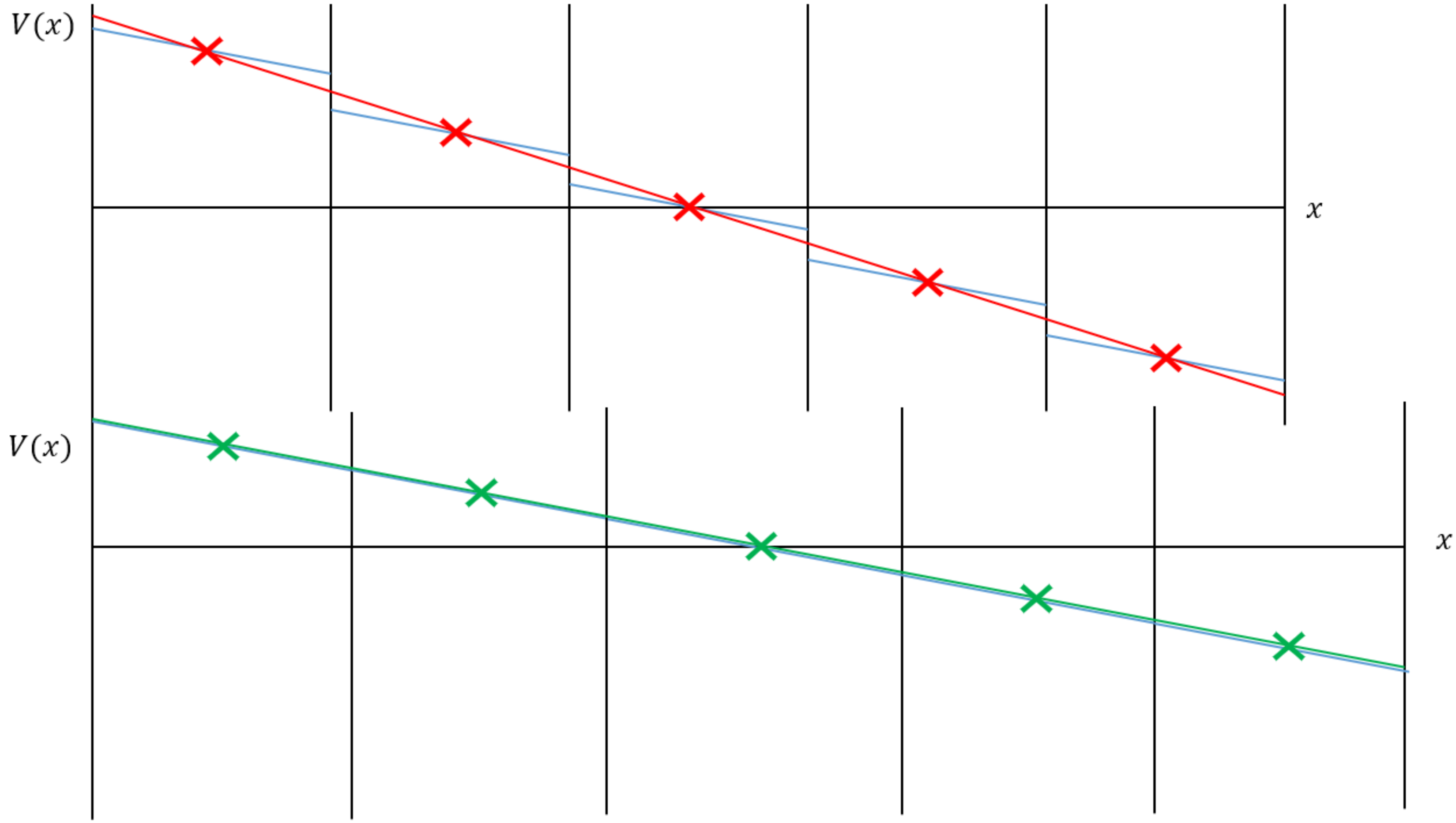
# DRAG COEFFICIENT CALCULATION



| | | |
|---|---|---|
| | TOA Gauges | |
| | 15in x 15in | |
| | 657 grains | |
| | ~0.010" thick | |
| lb | 0.093857143 | TOA mass, lb |
| kg | 0.042572849 | TOA mass, kg |
| S | 0.000160606 | Fragment Presented Area, m^2 |
| m1 | 0.0186 | Fragment Mass, kg |
| v1 | 2367.7 | Measured Midpoint Velocity, m/s |
| A | 0.145161 | TOA Total Area, m^2 |
| m2 | 4.71026E-05 | Mass of Punched Out TOA, kg |
| v2 | 2361.71919 | Residual Velocity, m/s |
| dv | 5.980810401 | Velocity Reduction, m/s |
| dVdx | **18.907529** | m/s per m |
| dx | 0.316318986 | Equivalent Distance, m |
| dxin | 12.45351011 | Equivalent Distance, in |
| dt | 0.133597578 | Equivalent Time, ms |

Velocity drop equivalent to ~12” of travel!

# DRAG COEFFICIENT CALCULATION




TOA gauge velocity drop acts as equivalent range length and time delay

# DRAG COEFFICIENT CALCULATION

| | dtms | dxin | dtms | dxin | dtms | dxin | dtms | dxin | dtms | dxin | dtms | dxin |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.1342937 | 12.887973 | 0.1626238 | 15.402528 | 0.134371 | 12.5124 | 0.1485344 | 14.02423 | 0.1332225 | 12.45684 | 0.1335976 | 12.45351 |

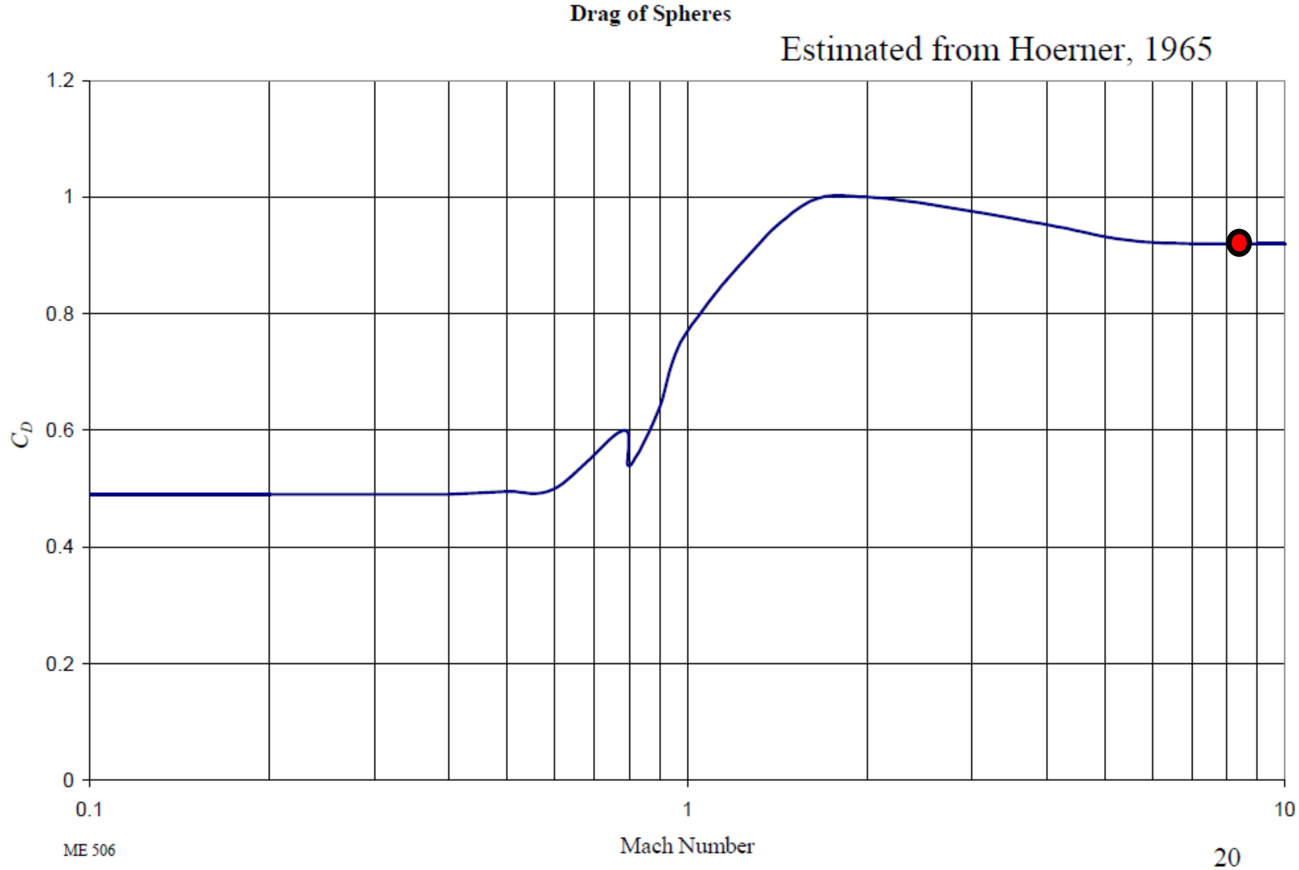
| | Test 1 (RT21463) | | Test 2 (RT21464) | | Test 3 (RT21465) | | Test 4 (RT21466) | | Test 5 (RT21467) | | Test 6 (RT21468) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TOA (ms) | X (in) | TOA (ms) | X (in) | TOA (ms) | X (in) | TOA (ms) | X (in) | TOA (ms) | X (in) | TOA (ms) | X (in) |
| GUN-TOA1 | 25.4180 | 120.0000 | 24.7467 | 120.2500 | 22.6041 | 103.5000 | 21.9282 | 104.0000 | 23.0228 | 104.0000 | 22.0304 | 104.0000 |
| TOA1-TOA2 | 26.7387 | 132.8880 | 26.1217 | 134.6525 | 24.5416 | 191.8874 | 23.8400 | 193.3992 | 24.9287 | 192.7693 | 23.9640 | 193.3285 |
| TOA2-TOA3 | 28.0863 | 132.8880 | 27.5212 | 134.6525 | 26.5340 | 192.6374 | 25.8179 | 192.8992 | 26.8985 | 191.3318 | 25.9359 | 190.7035 |
| TOA3-TOA4 | 29.4689 | 132.8880 | 28.9561 | 136.2775 | 28.5974 | 191.6374 | 27.8563 | 193.0242 | 28.9500 | 191.5818 | 27.9926 | 191.3910 |
| TOA4-TOA5 | 30.8969 | 132.8880 | 30.4339 | 136.2775 | 30.7655 | 193.6999 | 30.0026 | 195.2117 | 31.0982 | 193.6443 | 30.1532 | 193.7660 |
| TOA5-TOA6 | 32.3552 | 132.8880 | 31.9459 | 135.4025 | 33.0142 | 191.3249 | 32.1932 | 192.8367 | 33.3104 | 191.0193 | 32.3860 | 190.9535 |

| | a3 | a2 | a1 | a0 | V0 | CD | dV/dx |
|---|---|---|---|---|---|---|---|
| Test 1 | 1.1606E-08 | 1.5824E-06 | 4.1023E-04 | 2.8775E-02 | 2437.6 | 1.46 | 18.805598 |
| Test 2 | 3.7964E-08 | 1.3419E-06 | 4.1568E-04 | 2.8241E-02 | 2405.7 | 1.22 | 15.532698 |
| Test 3 | 2.3976E-08 | 1.6802E-06 | 4.2280E-04 | 2.7559E-02 | 2365.2 | 1.50 | 18.79808 |
| Test 4 | 5.2756E-09 | 1.4784E-06 | 4.1698E-04 | 2.6836E-02 | 2398.2 | 1.34 | 17.005553 |
| Test 5 | 4.6791E-09 | 1.6804E-06 | 4.2106E-04 | 2.7918E-02 | 2375.0 | 1.51 | 18.956255 |
| Test 6 | 1.5344E-08 | 1.6863E-06 | 4.2235E-04 | 2.6960E-02 | 2367.7 | 1.51 | 18.906947 |

Iterative procedure corrects for velocity drops across thick TOA gauges – $C_D$ appears to be 1.2-1.5

# RESULTS AND DISCUSSION

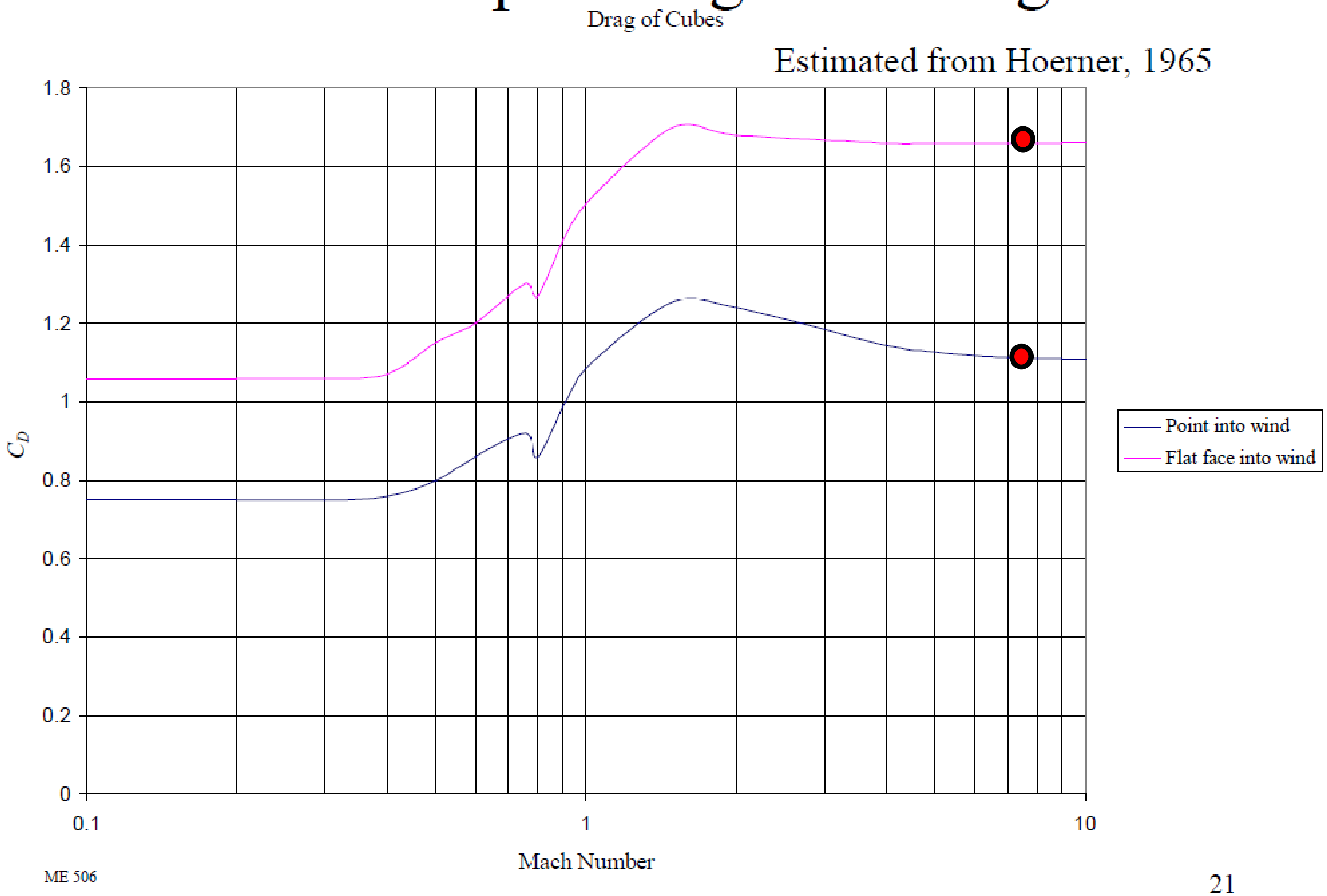
## Spherical Fragment Drag




Spherical fragment expected $C_D$~0.9

# RESULTS AND DISCUSSION

## Cube Shaped Fragment Drag




Cube shaped fragment $C_D$ expected to be 1.1-1.65

# SUMMARY AND CONCLUSIONS, FUTURE WORK

- 6 drag coefficient measurements performed for NATO IM fragment at approximately 2530 m/s
- ~80ft (~25m) range length with 6 TOA gauges
- Drag coefficient measured to be 1.22-1.51 when corrected for TOA gauge thickness
- Looks to be about what we expected; agrees with Dunn and Porter too
- Possible sources of error: TOA spacing error, trajectory curvature, fragment yawing motion, deformation from TOA gauge impacts
- Future work: perform measurements with rifled gun, thinnest possible TOA gauges, and more optimized timing station distribution

# QUESTIONS

# REFERENCES

[1] Murphy, C. H. “Free Flight Motion of Symmetric Missiles”. BRL-R-1216, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1963.