Uses of Radar 2000 during Projectile Development & Production

What are the benefits of using Doppler radar measurements and fitting the experimental data using RADAR 2000?

Doppler radar provides nearly continuous velocity-time information on the projectile during the flight down range. For fixed radar heads, the data can extend for as long as the projectile remains in the beam; for tracking radar heads, the projectile can typically be tracked to just before impact.

Analysis of Doppler radar provides a table of drag vs. Mach number, which can be read into a trajectory code, allowing the user to accurately model the trajectory of the projectile. In addition, various other flight parameters such as spin rate, tracer burn out, dynamic and structural stability can occasionally be extracted from radar data. Firing a group of projectiles with nearly identical mass properties and exterior shape yields information regarding the average and standard deviation of projectile in flight performance.

Radar 2000 by Arrow Tech Associates allows the Doppler radar data from multiple shots to be analyzed and the flight behavior of a group of projectiles to be analyzed relative to their “mean” performance. Assessments can then be made regarding the projectile flight performance and whether the projectiles are exhibiting expected behavior. Assessment of flight behavior early in a development program reduces the number of design/fabrication cycles required to put a cartridge into production and reduces development risk.

Why are Doppler Radar drag measurements better than just a retained velocity measurement?

Doppler radar works by sending out a high frequency radio pulse and “listening” for the frequency of the return signal compared to the outbound signal. These pulses strike the projectile, bounce off, and are returned to the receiving antenna. By comparing the frequency of the return signal and comparing it to the frequency of the outbound signal, the instantaneous velocity of the projectile in flight can be measured at frequent intervals throughout the trajectory.

If the mass and diameter of the projectile are known (measured prior to launch), and the temperature and pressure of the air is known (to compute air density), and the initial gun elevation with respect to horizontal is known (to subtract out the deceleration caused by gravity acting on the projectile), with a little simple arithmetic, the total drag force acting on the projectile can be computed. Arrow Tech Associates radar reduction software known as RADAR 2000 uses a modified point mass trajectory simulation to generate a velocity-time profile, which is compared to the experimental data. This velocity-time profile is then differentially corrected by user selected methods until the difference (e.g.

error) between the velocity/time profile computed by the point-mass trajectory program and the experimental data is minimized. By using the modified point-mass trajectory approach, the measurement error can be estimated, giving the user increased confidence in the accuracy of the results. Additionally, if the offset between the radar and the gun has been measured, and the experimental data is radial velocity, the muzzle velocity for each shot can be determined, typically to within 0.1 m/sec.

If a statistically significant sample of projectiles is fired during the course of a test series, the drag and muzzle velocity results can be averaged to obtain the "mean" projectile drag vs. Mach number and muzzle velocity. The muzzle velocity and drag variability, also known as standard deviation, about the measured means can also be determined. The measurement of the muzzle velocity and the drag standard deviations are important to determining the expected impact point spread on target at longer ranges. An assessment of the drag and muzzle velocity variability are also important to obtaining good long range precision, because at long ranges variations in these parameters causes vertical pattern elongation, also known as "stringing".

For "well behaved" projectiles, the drag standard deviation should be no more than 1.5-2.0% of the mean drag. Standard deviations this low are in line with those obtained with much more sophisticated measurement techniques (e.g. Spark Range) for identical projectiles. Variability above this level is indicative of some sort of unexpected and undesirable aerodynamic and/or mass properties variability. Occasionally, variations in wind direction and magnitude add to this variability, but this is rather rare in direct fire applications.

With a retained velocity measurement (e.g. two chronographs separated by 100-200m) only a very limited assessment of projectile performance can be obtained because the data consists of two "snapshots" at each chronograph instead of the data being continuously monitored for the whole flight.

Total Drag Force Definition:

The total drag of a projectile is the sum of its zero yaw drag plus any yaw drag that may be present during its flight due to yawing motion. This total drag force acts opposite to the projectile's instantaneous velocity vector during flight. For the vast majority of projectiles flying in the supersonic Mach regime with no internal moving parts, once the yaw motion from any initial launch disturbances have damped, the measured drag is very close to the zero yaw drag. However, as the projectile flies further down range and continues to decelerate and transition from supersonic to transonic and finally to the subsonic regime, aerodynamic forces and moments acting on the projectile typically cause a minor dynamic instability to arise, making the projectile fly at some small, non-zero angle of attack. This motion can arise from any combination of a number of sources, among these are:

1. Surface imperfections on the exterior of the projectile, most notably the interface surface between the projectile and the rifling/bore.
2. The absence of a boattail on the projectile.

3. The presence of a boattail on the projectile in excess of 0.6 calibers (bore diameters) in length.
4. The presence of a boattail with a total included angle in excess of 18 deg. combined with a boattail length greater than about 0.4 calibers.

How Does a Doppler Radar Drag Analysis Reduce Projectile Development Risk?
All types of tube launched munitions can benefit from Doppler Radar Drag Analysis because the total drag as a function of Mach number will be known prior to committing the design to production, and the flight behavior will have been characterized.

Early in development and occasionally, well into production, extended range testing with Doppler radar has been used to spot the following problem projectile behaviors:

- Moving parts
- Spin-yaw resonance
- Structural resonance
- Excessive muzzle velocity variability
- Aerodynamic trim/Mass Asymmetry
- Variable Tracer Burn Out Time

Depending on program requirements, each of these problems has the potential to cause the projectile to fail to meet specific performance criteria. Fortunately, each of the above mentioned problem behaviors has a distinct radar “signature”, which will be discussed briefly below:

Moving Parts
Projectiles which have internal or external components which can move relative to the projectile body can exhibit a dynamic instability the magnitude of which is related to the magnitude of the mass of the moving part, the oscillation radius of the part relative to the rest of the projectile body, and the distance between the projectile center of mass and the center of mass of the moving part. This condition can be caused by inadequate swaging or staking of components, assembly clearances between threaded parts, or failure to restrain components relative to the projectile body. Figure 1 shows the effect of moving parts on the total drag coefficient vs. time behavior.

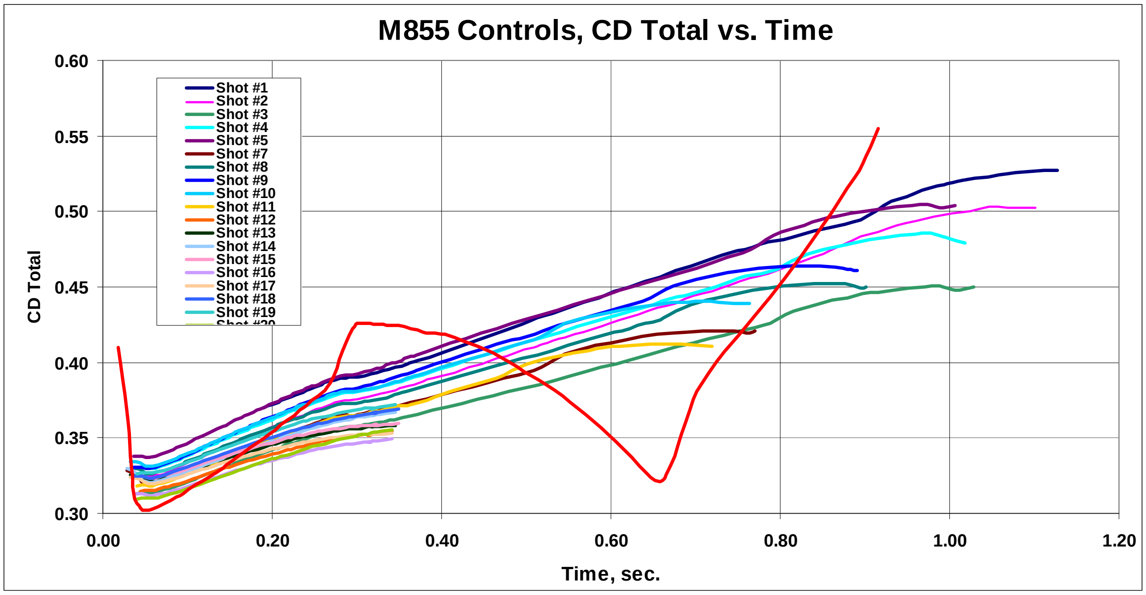

Figure 1: Effect of Moving Parts

RADAR 2000 has been able to examine the mean and standard deviation of drag behavior and has found indications of loose parts on 5.56mm, 30mm, and 40mm projectiles on various occasions. Indications can be as subtle as an unexplained, random increase in drag for a percentage of the examined projectile population, or it can be quite dramatic, as shown in Figure 5.

The ability to critically examine the drag performance of a single or several projectiles in group of projectiles relative to the “normal” performance gives users of RADAR 2000 the ability to reduce development risk.

Aero Trim / Mass Asymmetry

Aerodynamic trims and/or mass asymmetry are the “driving force” behind the spin-yaw resonance condition. If the trim angle of the projectile is small and the projectile rolls through the resonance frequency, the flight behavior of the projectile may be largely unaffected and hence unnoticed. However, it is exceptionally difficult to build statically stable projectiles with much less that 0.15 deg. of trim, and depending on the static margin of the projectile, this may be sufficiently large to cause a serious flight dynamic problem if the bullet rolls through the resonance frequency. Aerodynamic trims would cause the projectile to fly at a constant, non-zero angle of attack if the projectile roll rate were zero. Figure 2 shows a long rod projectile flying with a trim.

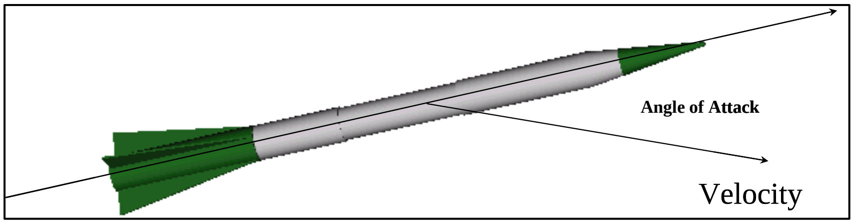

Figure 2: Aerodynamic Trim

Spin-Yaw Resonance

Spin-yaw resonance is a condition occasionally experienced by statically stable projectiles when the roll frequency of the projectile is equal to the pitch frequency. Under such conditions, any aerodynamic trim the projectile possesses is multiplied by the trim amplification factor, causing the projectile to fly at a potentially large angle of attack. This leads to significant loss of velocity, as well as the projectile arriving at the target at a large angle of attack, which may impede intended function. Depending on various projectile parameters, it is possible for this condition to occur near the gun or be delayed until the projectile is well down range. Figure 3 shows the angle of attack vs. range for a projectile experiencing spin-yaw resonance.

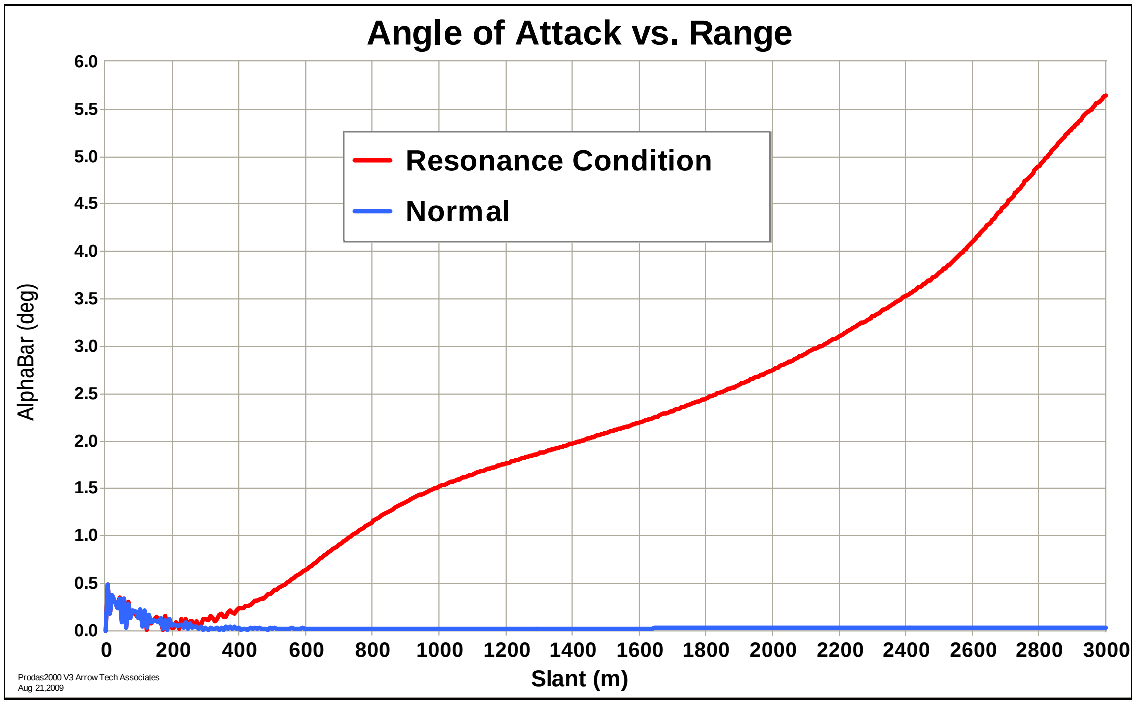

Figure 3: Angle of Attack for Spin-Yaw Resonance

Figure 4 shows the experimental velocity-range behavior for a projectile experiencing spin-yaw resonance, along with the expected velocity-time behavior.

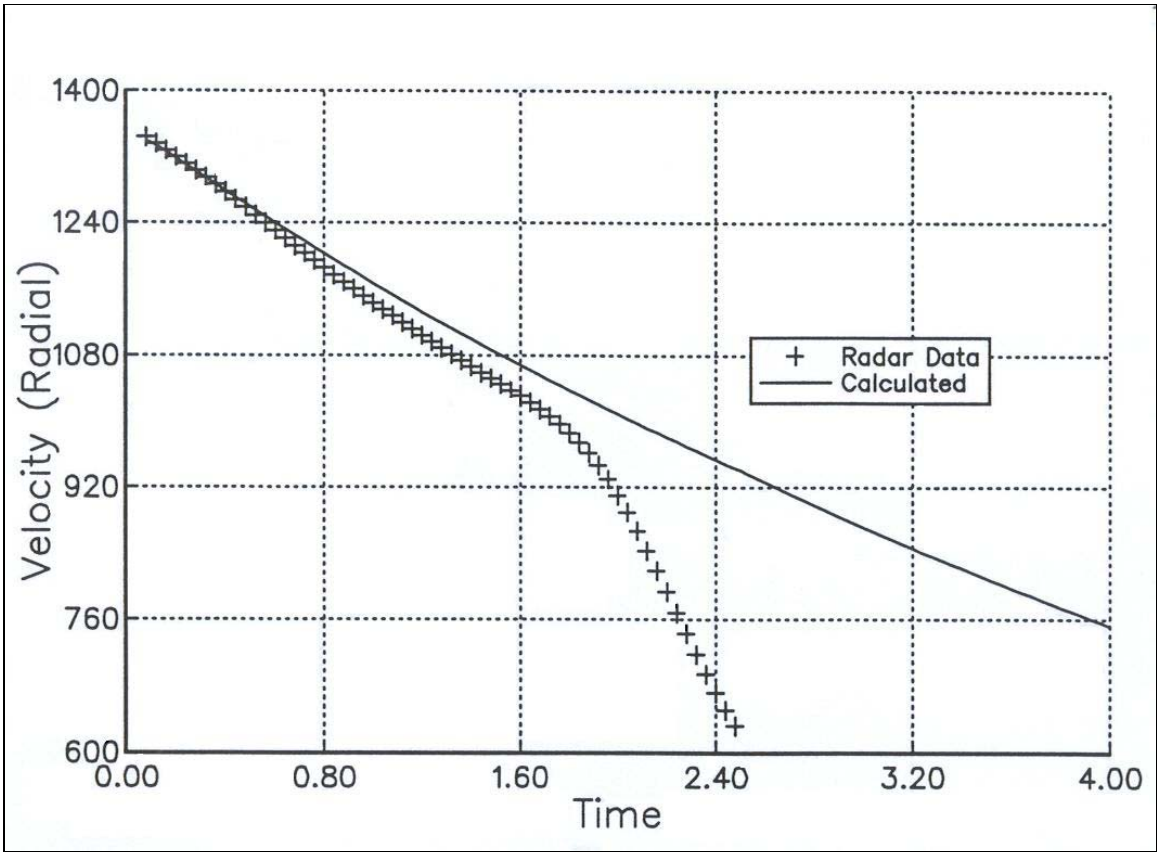

Figure 4: Experimental vs. Calculated Velocity-Range Behavior for Spin-Yaw Resonance

The velocity behavior in is characteristic of spin-yaw resonance in that it takes some time to develop. Statically stable projectiles are susceptible to this sort of dynamic instability, while spin stabilized projectiles are not. Analysis of radar data is clearly able to determine the presence of this sort of instability.

Structural Resonance

Structural resonance is a condition occasionally seen by statically stable projectiles where the roll frequency is equal to the first bending mode structural frequency of the projectile. This can occur at very high spin rates if the projectile is launched at full spin from a rifled barrel, or at much lower spin rates if the projectile is launched from a smooth bore barrel, is constructed from materials with low elastic modulus, and the roll producing surfaces on the projectile spin up the projectile to or through the structural resonance frequency. The bad thing about this sort of condition is that it is usually catastrophic for the projectile structure, as well as the flight trajectory. An example of a projectile suffering from structural resonance is shown in Figure 5 below:

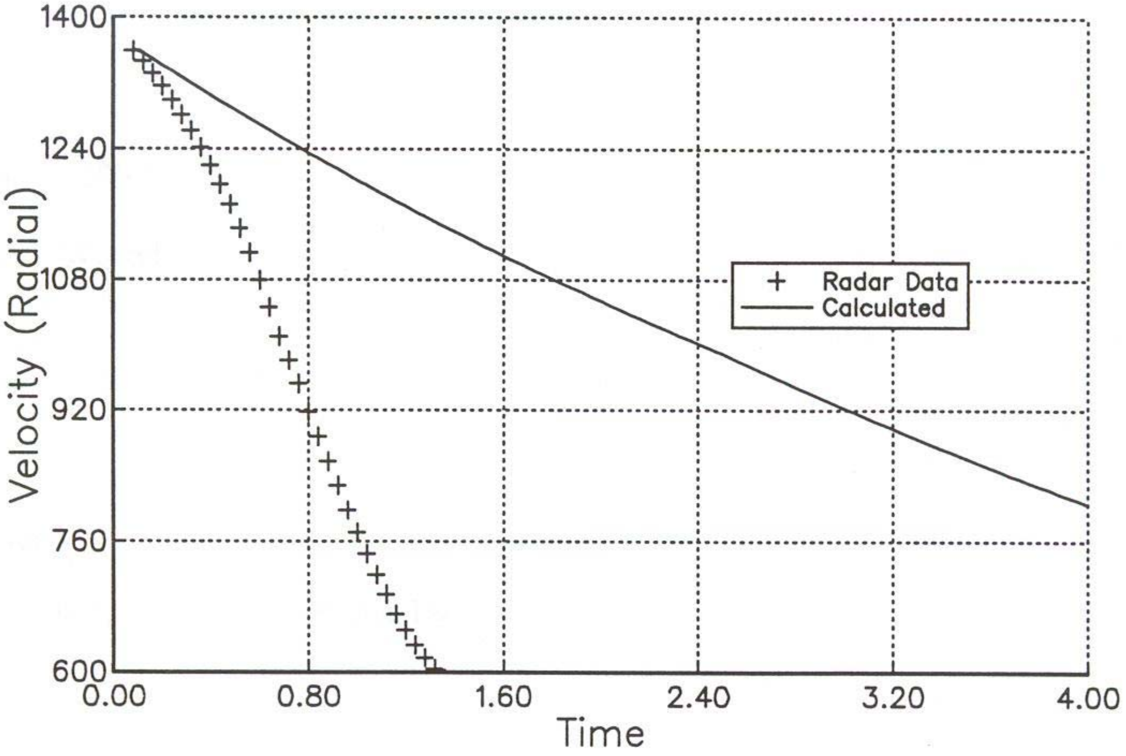

Figure 5: Structural Resonance Velocity vs. Time Behavior

In this particular instance, the statically stable projectile emerged from the muzzle rolling just above its structural resonance frequency. In short order, the projectile spin decayed to the point where the spin frequency equaled the structural resonance frequency, and the structure failed, indicated here by the immediate onset of a high drag and high deceleration behavior. While it is more likely for a statically stable projectile to experience this condition, it is possible for both fin stabilized and spin stabilized projectiles to experience this sort of instability. Analysis of Doppler radar data is clearly able to identify this sort of structural dynamic problem.

Excessive Muzzle Velocity Variability

Excessive muzzle velocity variability can be caused by a number of sources; propellant load variability, engraving pressure variability, deposition of projectile material in the forcing cone of the barrel, variability in engraved surface length and dimension, etc. Typically, the muzzle velocity standard deviation will be about one-half of one percent of the muzzle velocity or less. Depending on the application, this amount of variability may or may not be acceptable for a reasonable dispersion error budget. Figure 6 shows the effect of muzzle velocity variations on vertical impact point.

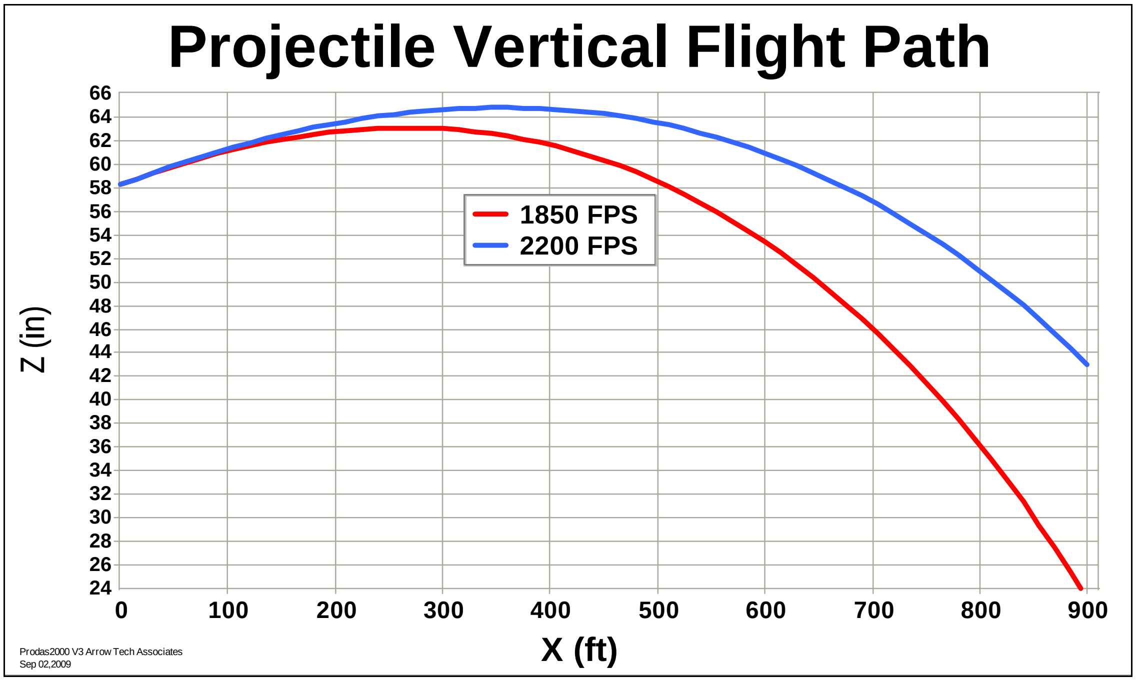

Figure 6: Effect of Muzzle Velocity Variation on Vertical Impact Point

The aim point is the same for the two initial velocity cases shown in Figure 6; by the time this projectile has traveled 800 feet, the difference in drop is nearly 15 inches. Assessment of muzzle velocity fitted from Doppler radar data analysis is able to identify this dispersion cause.

Variable Tracer Burn-Out Time

If the projectile of interest has a pyrotechnic tracer element, the gas emitted from the base of the bullet during flight tends to reduce the drag force operating on the bullet. The drag of the basic aerodynamic shell of the projectile can be determined if untraced versions of the projectiles are fired. Using the results of this data reduction, the effect of the tracer can be solved by using only time varying solution parameters. The tracer “off” time can be parametrically varied for each unique shot until a dramatic reduction in experimental fit error occurs when the tracer burn out time is entered. This “study” is solving for the tracer burn out time, and analysis of the statistics of the tracer burn out can indicate if the tracer consolidation process is well controlled or needs refinement. Analysis of Doppler radar data can determine if the tracer burn time meets the requirements, and by using the “flyout” routine in Radar 2000, the user can determine the effect tracer burn out has on ground impact distance.

Is Doppler Radar Drag Analysis Time Consuming?

Early in the history of Doppler Radar Drag Analysis, computer computation speeds were slow and hence radar data reductions were quite time consuming. With today’s computing speeds and storage capabilities, radar data reductions have become easier and can typically be completed in short order once the atmospheric and other launch conditions have been identified.

How is Drag and Drag Variability evaluated via RADAR 2000?

Radar 2000 uses a modified point mass trajectory simulation to generate a velocity-time profile for the projectile, which is then compared to the experimental data. The user selects the Mach regime of interest to be fit as well as the analytical degrees of freedom which enables one to modify the baseline drag coefficient vs. Mach Number. If the samples are gun launched projectiles using tracer or rocket elements, it is recommended to fire some samples with inert elements, solve for the drag vs. Mach number of the baseline shape without the active elements, and use those results as "starting solutions" for the reductions with active elements, solving only for the drag reduction contribution of the active items.

As the data reductions are completed on each individual projectile, the data results of identical configurations are collected into groups, allowing the user to pass judgment on the performance of the group. If the standard deviation in drag is on the order of about 1%-1.5%, the drag variability is about as good as can be attained. If the drag variability is moderately higher, say 2.0%-3.5%, variability in some external condition (e.g. driving band condition) is the most likely explanation. If the drag variability is higher than about 4%, it may be time to start considering the potential for loose parts or flight dynamics being a contributor to the drag variability. Figure 7 shows the raw drag vs. Mach number for several shots of two different configuration projectiles before processing with RADAR 2000.

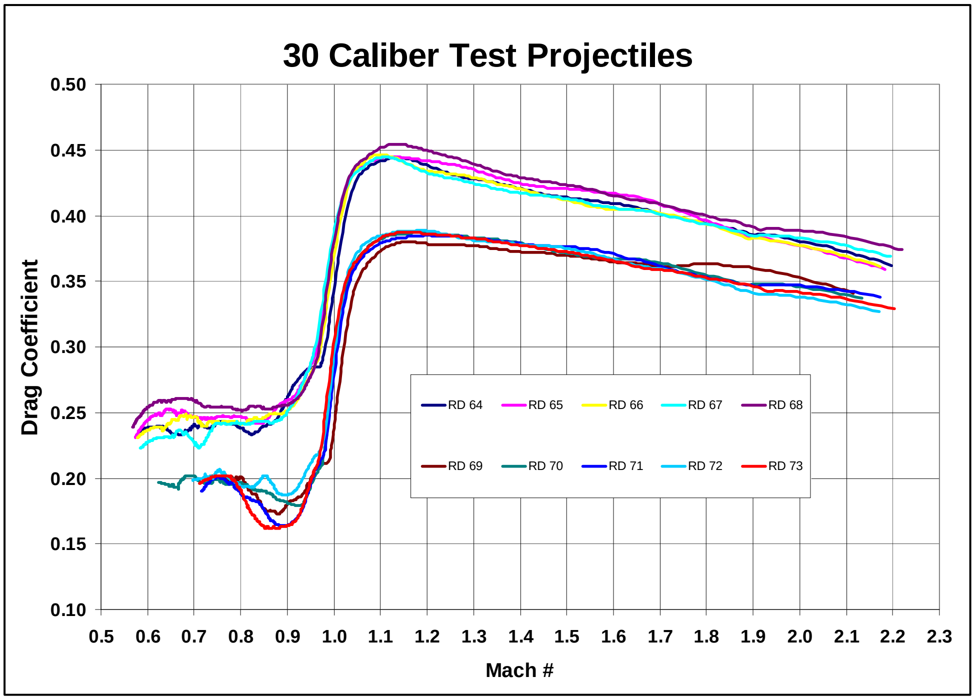

Figure 7: Raw Drag vs. Mach Number from Doppler Radar

The rapid changes in drag shown in the lower group between Mach 2.1 and Mach 1.7 are as a result of projectile yaw motion, and the rapid drag coefficient changes seen below Mach 1.0 are the result of a dynamic instability caused by the projectile aerodynamic properties.

***Data Fusion*: Recent Advances in Data Reduction and Trajectory Reconstruction**

In recent years, Arrow Tech Associates, Inc. has been involved in the development of advanced algorithms for the data reduction and trajectory reconstruction using multiple sources of test data. This *data fusion* concept has the ability to bring together multiple sources of data regardless of whether the data sources are ground-based systems such as multiple Doppler and/or Position radars or the data sources are from on-board systems such as GPS and/or other electronic sensors.

For example, test programs are now using the following three ground-based systems:

- Primary Doppler Radar (i.e., behind the gun)
- Secondary Doppler Radar (i.e., downrange)
- Position Tracking Radar

Developments are being made where all three sets of data are being used in the data reduction and trajectory reconstruction of each individual shot. The data reduction procedures take advantage of the fact that not all data sources have the same level of accuracy during the complete flight.

For those test programs that have on-board telemetry, radar data is being coupled with the on-board telemetry.

Radar Data Reduction History:
Arrow Tech has used RADAR 2000 to analyze the expected dispersion behavior of a number of projectiles. A list of the projectiles analyzed with this technique is shown in Table 1.

Table 1: 5.56mm-155mm Radar data reductions Analyses & Year of Performance

Caliber/CTG	Year
5.56mm/M855	2008
7.62mm/ Various	2008
0.50 Cal SLAP	2003
20x102mm/Mk149, Mk244	1995
20x102mm PGU-28/B	2001, 2003
20x102mm HEI	2005
25x58mm/ACSW	2005 - 2007
25x137mm/M919	1997 - 1999
25x137mm/M910	2004
25x137mm/M791	2000
25x137mm/M910E1	2003-2004
27x145mm/DM33	2001
30x113mm TP-T	1989-1990
30x173mm/Mk239, Mk258	1999-2004
30x173mm/Mk310	2007
30x173mm TPDS	2009
30x173mm/PGU-13	2007
40x46mm/NL	2008
40x51mm Mk281Mod1	2005
40x51mm/Mk285	2009
57x438mm/PPHE	2004
105x371mm	2006-2009
120mm/M934	1998
120mm PGMM	2004
120mm/M831A1	1994
120mm/M1002	2001
155mm M549A1	2006
155mm	2009
155mm PGK	2001-2004
Various (Army Test Range)	2001-2009