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# A COMPARISON OF PARABOLIC AND CIRCULAR ARC PREDICTION


JOSEPH K. WALD
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MARCH 1990



U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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As opposed to the standard second order "parabolic" predictor, the Circular Arc Aimed Munition (CAAM) prediction concept accounts for the rotational motion of targets maneuvering in a circular arc. In this paper we present the results of a simulation study that investigated the difference in effectiveness between the CAAM predictor and a parabolic predictor, installed in a modern air defense gun, against a variety of flightpaths flown by maneuvering aircraft in actual field tests.

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# A Comparison of Parabolic and Circular Arc Prediction

Joseph K. Wald (U.S. Army Ballistic Research Laboratory)
Harold H. Burke (U.S. Army Materiel Systems Analysis Activity)

## I. INTRODUCTION: BACKGROUND AND PURPOSE

The ability of modern fixed wing aircraft and helicopters to perform evasive maneuvers while carrying out their missions has significantly degraded the performance capabilities of gun systems engaging these targets. These evasive tactics have motivated the initiation of programs to improve the effectiveness of conventional gun systems. One way to improve the effectiveness of a gun system engaging maneuvering targets is to increase its delivery accuracy. A new and different fire control solution using a Circular Arc Aimed Munition (CAAM) prediction concept has the capability of doing just that [**1**,**2**].

In this paper we present the results of a simulation study that investigated the difference in effectiveness (measured by hit probability) between the CAAM predictor and a standard conventional second order predictor, installed in a modern air defense gun, against a variety of flightpaths flown by maneuvering aircraft in actual field tests.

In section II, we introduce the CAAM predictor, noting how it differs from the standard (first order) linear and (second order) parabolic predictors; in section III, we describe the methodology used in the simulation study; in section IV, we present the results of the study; and in section V, we present our conclusions.

## II. THE CAAM PREDICTOR

The purpose of the predictor in a gun's fire control system is to estimate the future position of the target, necessary information for the development of proper lead angles. Conventional linear prediction, described by the equation

$$\vec{p_f} = \vec{p_p} + \vec{v_p}\, t_F \;,$$

where $\vec{p_f}$ is the future position of the target, $\vec{p_p}$ its present position, $\vec{v_p}$ its current velocity, and $t_F$ the projectile's time of flight, clearly assumes that the target will be flying along a straight line, at least for the duration of the projectile's flight. Similarly, conventional parabolic prediction, described by the equation

$$\vec{p_f} = \vec{p_p} + \vec{v_p}\, t_F + (1/2)\, \vec{a_p}\, t_F^2 \;,$$

where $\vec{a_p}$ is the target's present acceleration, assumes that the target will be flying along a parabolic arc in the future.

The CAAM predictor makes the assumption that for at least one projectile time of flight (several seconds), an aircraft will fly in a circular arc of fixed radius. This seems to be a reasonable assumption since the laws of aerodynamics and the requirement to maintain a stable operating condition constrain the acceleration vector of the aircraft to remain more or less perpendicular to its velocity vector. In fact, modern fire/flight control systems constrain aircraft to maneuver in sustained (high acceleration) circular arcs during the ordnance delivery portion of the flight profile

[3,4,8]. Compared to straight line ordnance delivery, this tactic clearly increases survivability against engagement from an air defense gun equipped with a conventional linear or parabolic predictor. However, it is equally clear that this tactic conforms to the assumption underlying the CAAM concept, and thus should not offer quite as much improvement in survivability against a gun outfitted with a CAAM predictor. Other studies have shown that the CAAM concept will also give improved accuracy against ground targets [9].

The CAAM prediction concept is given by the equation

$$\vec{p_f} = \vec{p_p} + \vec{v_p}\,\gamma_v\,t_F + (1/2)\,\vec{a_p}\,\gamma_a\,t_F^2\ ,$$

where the factors $\gamma_v$ and $\gamma_a$, which account for the rotational motion of the aircraft maneuvering in a circular arc, are defined by the expressions

$$\gamma_v = 1 - (\Delta\theta)^2/6\ ,$$

and

$$\gamma_a = 1 - (\Delta\theta)^2/12\ .$$

The term $\Delta\theta$ is equal to $|\vec{a_{p_N}}|\ t_F\ /\ |\vec{v_p}|$, the rotation rate of the aircraft (i.e., the magnitude of that component of the acceleration vector perpendicular to the velocity vector divided by the magnitude of the velocity vector) multiplied by the time of flight. This is just the amount of circular arc that the aircraft moves through during the time of flight of the projectile.

## III. COMPARISON METHODOLOGY

The vehicle that was used for the comparison of the two predictors was the Modern Gun Effectiveness Model (MGEM) [5]. MGEM is a time sequenced, Monte Carlo simulation of an engagement between a "state of the art" air defense gun and a single aircraft target. The aircraft target is just that, a target. It does not attempt to attack the air defense gun; neither does it alter its flightpath in response to being fired upon. This methodology tends to give overly optimistic estimates of the performance of an air defense gun in a tactical situation, but is appropriate for a comparative study such as the present one.

In MGEM, the flightpath of the target is fed into a sensor model that provides noisy position information to the fire control computer. A Kalman filter computes smoothed estimates of position, velocity, and acceleration for the target. These estimates, together with the ballistic characteristics of the ammunition, allow the fire control computer to predict the position of the target one time of flight in the future. Aiming commands are issued and bullets are flown out to intercept the target. Since there are many error sources modeled in the steps of this procedure, the bullets will, in general, not pass through the center of the target. Therefore, based on the path of each bullet and the size of the target, a determination is made as to whether that bullet hit the target. This process is repeated for as many Monte Carlo replications as desired, with the resulting probability of hit being simply the fraction of replications in which at least one bullet hit the target. The amount of damage done by a bullet can also be computed, although for our purposes only the probability of hit was calculated.

In the present study we focused our attention on the prediction problem. Since the standard parabolic predictor was already resident in MGEM, we needed only install the CAAM predictor described above as a new option in the prediction subroutine. We then selected several flightpaths from the Library of Digitized Flightpaths [6] in residence at the Ballistic Research Laboratory, and used them, in the manner described below, to compare the two predictors.

The flightpaths in the Library of Digitized Flightpaths were produced not from a mathematical model, but rather from actual profiles flown during technical and operational tests conducted by the U. S. Army in New Mexico and California. The noise superimposed on the flightpaths during the data collection process was removed by an optimal double sweep Kalman smoothing technique [7] that simultaneously produces target positions, velocities, and accelerations. Table 1 contains a list of the flightpaths chosen for the study. These flightpaths are also depicted in figures 1 through 5.

| TABLE 1. The Flightpaths. | |
|---|---|
| Flightpath Number | Flightpath Description |
| 3 | "straight penetrator" |
| 8 | "general turn" |
| 2 | "pop-up, turn, and dive" |
| 16 | "low level attack" |
| 5 | "jinking penetrator" |

The flightpaths are listed in order of increasing severity of maneuver. The peak accelerations of flightpath 3 are about 10 meters per second per second, while the peak accelerations for flightpath 5 are about six times that size. It would be desirable to compare the performance of the two predictors against a sustained high acceleration maneuver, but no such missions were flown during the field tests from which these flightpaths were taken. The sensitivity of sophisticated fire control systems to small "real world" variations in a flightpath makes it dangerous to draw conclusions about effectiveness when using a mathematically derived flightpath. So, as appealing as the idea was, we resisted the temptation to use an analytically produced, high acceleration, circular flightpath in this study.

Flightpaths 3 and 5 would typically be encountered by an air defense gun during the ingress and egress portions of an aircraft's mission, with flightpaths 2, 8, and 16 typical of "vicinity of target" maneuvers. Flightpath 3 was included only to verify that use of the CAAM predictor does not result in a degradation of performance against nonmaneuvering targets, and was therefore included only in table 4.

For simplicity, we chose the presented area of the target to be 10 square meters when viewed from each of the cardinal directions. The maximum intercept range was chosen to be 4000 meters, with the gun firing a series of one second (10 round) bursts with an interburst waiting period of 0.5 seconds while the target was in range. The time of flight of the bullets as a function of range appears in table 2.

| TABLE 2. Time of Flight Versus Range. | |
|---|---|
| Range (meters) | Time of Flight (seconds) |
| 500 | 0.43 |
| 1000 | 0.91 |
| 1500 | 1.43 |
| 2000 | 2.00 |
| 2500 | 2.63 |
| 3000 | 3.33 |
| 3500 | 4.12 |
| 4000 | 5.00 |

## IV. COMPARISON OF HIT PROBABILITIES AND ANALYSIS

We discovered as a result of our initial computer runs that due to the very detailed nature of the modeling of the fire control system, hit probability was extremely sensitive to the geometric relationship between the air defense gun and the flightpath. The hit probabilities appearing in

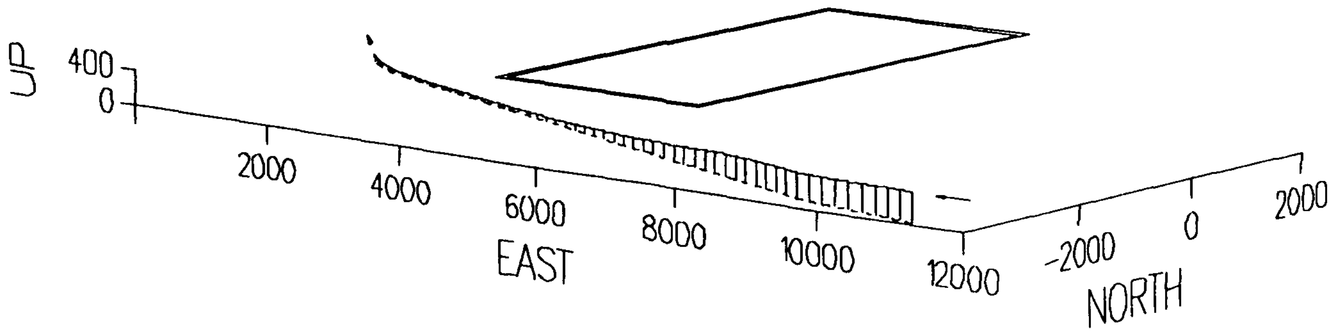


Figure 1. Flightpath 3

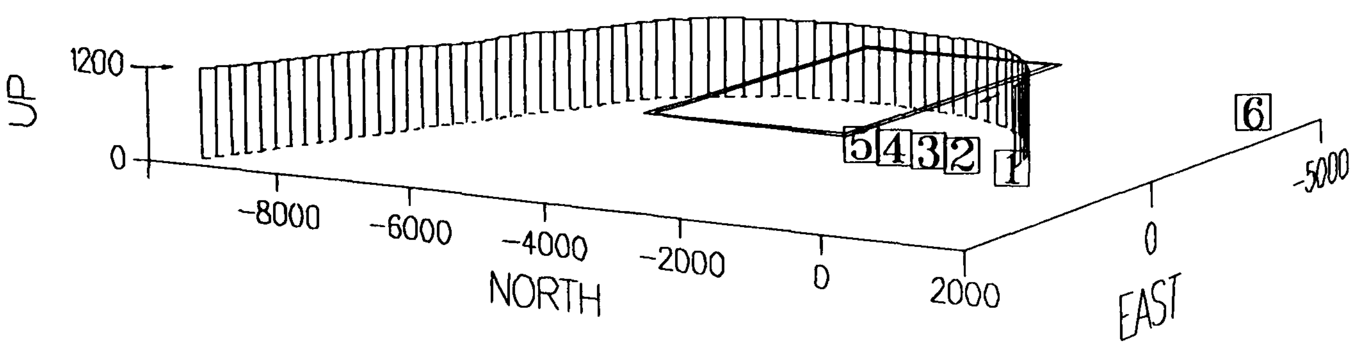


Figure 2. Flightpath 8

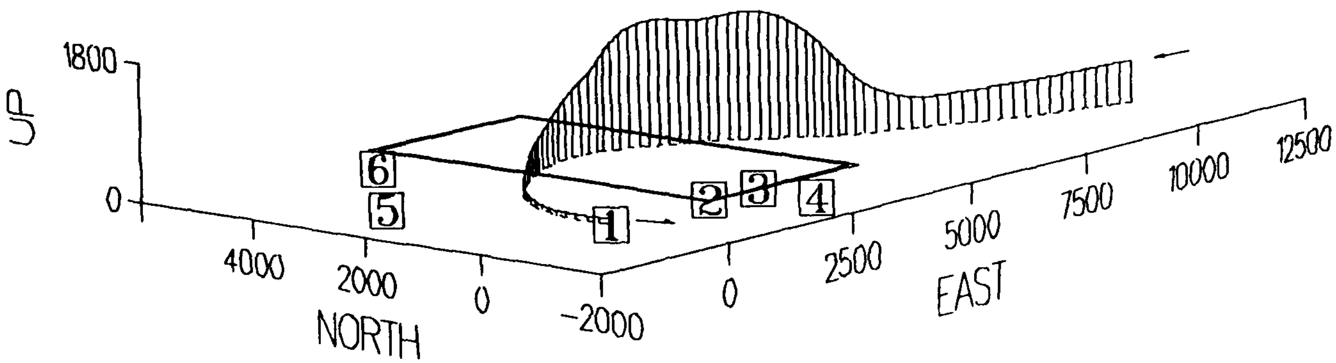


Figure 3. Flightpath 2

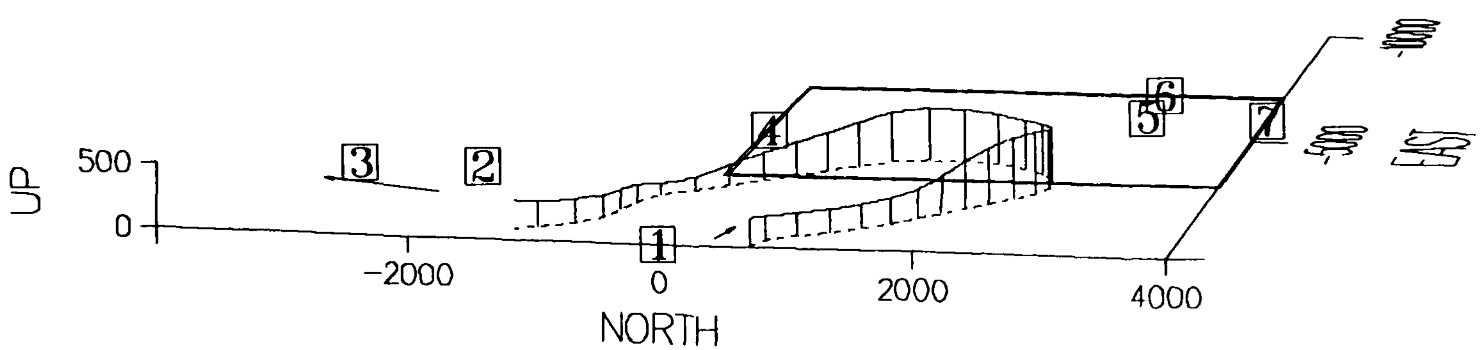


Figure 4. Flightpath 16

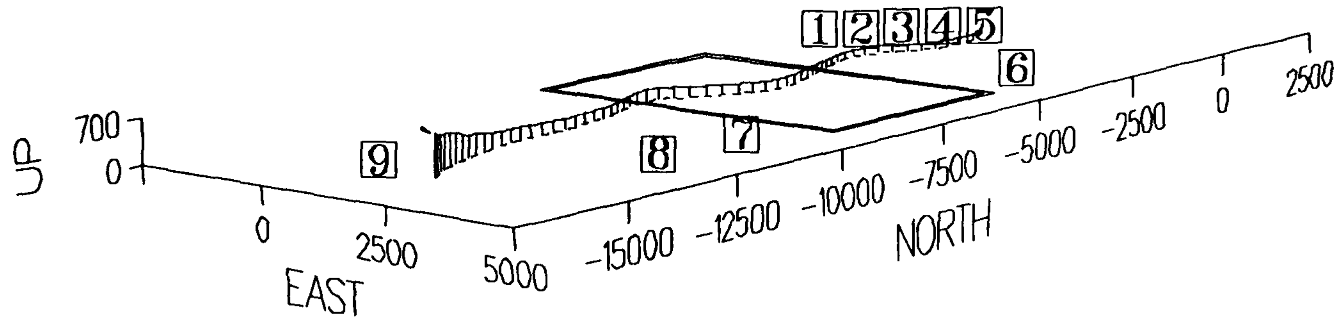


Figure 5.  Flightpath 5

table 3 show that varying the location of the gun relative to the flightpath causes a wide variation in the relative performance between the two predictors. These results were based on 100 Monte Carlo replications. The gun locations are indicated graphically in figures 2 through 5.

TABLE 3. Hit Probability Comparison: Fixed Gun.

| Flightpath | Position Number | Parabolic Prediction | CAAM Prediction |
|---|---|---|---|
| 8 | | | |
| | 1 | .95 | .98 |
| | 2 | .99 | .96 |
| | 3 | .96 | .95 |
| | 4 | .80 | .78 |
| | 5 | .71 | .68 |
| | 6 | .01 | .04 |
| 2 | | | |
| | 1 | 1.00 | 1.00 |
| | 2 | .67 | .75 |
| | 3 | .38 | .40 |
| | 4 | .14 | .13 |
| | 5 | .74 | .71 |
| | 6 | .53 | .50 |
| 16 | | | |
| | 1 | .67 | .68 |
| | 2 | .54 | .53 |
| | 3 | .12 | .15 |
| | 4 | .72 | .79 |
| | 5 | .25 | .32 |
| | 6 | .04 | .03 |
| | 7 | .09 | .19 |
| 5 | | | |
| | 1 | .05 | .08 |
| | 2 | .11 | .21 |
| | 3 | .20 | .31 |
| | 4 | .68 | .72 |
| | 5 | .98 | .96 |
| | 6 | .08 | .14 |
| | 7 | .22 | .32 |
| | 8 | .36 | .61 |
| | 9 | .69 | .65 |

We avoided this dependence of results on the (rather arbitrary) choice of gun location by varying the position of the gun in each replication, and increased to 400 the number of Monte Carlo replications that were run for each predictor against each flightpath. The gun was randomly placed in a two dimensional rectangular "box" as indicated in figures 1 through 5. This approach increases the realism of the simulation in that it is to be expected that the geometric relationship between the aircraft and the gun will change (perhaps drastically) from one engagement to another on a real battlefield. The location and shape of the box was chosen to cause most engagements to occur along the part of the flightpath that contains the most severe maneuvers of the target and to allow the gun to engage the target at all ranges. A summary of the results of these runs appears in table 4.

| TABLE 4. Hit Probability Comparison: Randomly Placed Gun. | | |
|---|---|---|
| Flightpath | Parabolic Prediction | CAAM Prediction |
| 3 | 0.92 | 0.92 |
| 8 | 0.65 | 0.68 |
| 2 | 0.65 | 0.71 |
| 16 | 0.66 | 0.71 |
| 5 | 0.48 | 0.54 |

As mentioned in section III, flightpath 3 was included only as a "control", i.e. to insure that against nonmaneuvering targets the CAAM predictor does not degrade the effectiveness of the gun system. The results here verify that assertion. Note that for 400 Monte Carlo replications, the standard deviation of the hit probability distribution is less than or equal to 0.025. Therefore, considering the differences in hit probabilities for the four maneuvering flightpaths (differences that are consistently in favor of the CAAM predictor), we can say with at least 80 % confidence for flightpath 8 and greater than 90 % confidence for flightpaths 2, 16, and 5, that these differences are not due just to the stochastic nature of the model.

These results lead one to the conclusion that there are more "segments" of these flightpaths that are better approximated by circular arcs than by parabolic arcs. We assert that for any flightpath containing a long circular maneuver at high acceleration, the CAAM predictor will prove superior to the parabolic predictor. This effect is rather mild in flightpath 8, since the relatively low acceleration (about 20 *meters per second per second*) corresponds to a circle of large radius. At any point on such a circle, the corresponding tangent parabola diverges rather slowly. Thus the error in miss distance caused by parabolic prediction will not be too serious. For a much higher acceleration, however, the circle will be "tighter", i.e. it will have a much smaller radius of curvature, and the parabola will be a much worse approximation than the circle for the same projectile time of flight.

Note also that while modern attack helicopters fly at much lower speeds than fixed wing aircraft, they can turn in much tighter circles. Therefore the CAAM concept may be applicable against these targets as well. Helicopters were not included in the study due to the lack of available highly maneuvering helicopter flightpaths.

The advantage enjoyed by the CAAM concept over conventional parabolic prediction can be negated if other error sources in the gun system grow too large. To investigate this effect, we increased the standard deviation of angular noise errors in the sensor model from 0.0015 radians (the value used in the runs documented in tables 3 and 4) to 0.0050 radians, and repeated the above experiment (with the randomly placed gun) with flightpaths 8, 2, 16, and 5. The results appear in table 5. The value of 0.0015 radians is appropriate for an automated tracking device or possibly for a man/machine combination, while the 0.0050 value may be more appropriate for a strictly human tracker.

| TABLE 5. Hit Probability Comparison: Noisy Sensor. | | |
|---|---|---|
| Flightpath | Parabolic Prediction | CAAM Prediction |
| 8 | 0.42 | 0.43 |
| 2 | 0.53 | 0.50 |
| 16 | 0.51 | 0.52 |
| 5 | 0.39 | 0.40 |

As expected, the performance of both predictors decreased. Now, however, the performances of the two predictors are statistically indistinguishable. The reason for this becomes apparent when one considers the expressions

$$\vec{v_p}\,\gamma_v\,t_F\ ,$$

and

$$(1/2)\,\vec{a_p}\,\gamma_a\,t_F^2\ ,$$

the "velocity" and "acceleration" terms from the CAAM prediction equation. When the sensor is degraded, so are the present velocity and acceleration estimates of the target. Since $\gamma_v$ and $\gamma_a$, respectively, are multiplied by these estimates, the accuracy of the product is constrained by the accuracy of the least accurate factor. In this case, the noisy state estimates "overwhelm" the more subtle differences between predictors.

## V. CONCLUSIONS

1. Compared to conventional parabolic prediction, CAAM provides a modest but consistent improvement in delivery accuracy against aircraft executing (available) "real life" maneuvering flightpaths. However, its real value should be seen when it is applied against aircraft flying modern sustained high acceleration circular arc ordnance delivery maneuvers. Whenever we can get high resolution, high data rate (about 20 Hertz), "real life" target position data for such maneuvers, we intend to continue the comparison between parabolic and CAAM prediction. Such stringent restrictions on the flightpath data are necessary, since a model of the sophistication of MGEM is required for the analysis of these rather subtle phenomena.
2. In order to get full benefit from CAAM prediction it is necessary to have a rather accurate target tracking system. A good automatic tracking device or a human aided tracker would probably qualify, but it is doubtful that an unaided human could track highly maneuvering modern fixed wing aircraft accurately enough for this purpose.
3. The benefits of CAAM prediction are available at relatively low cost. In an existing weapon system, a new computer card is necessary, while in a new system, there will be no additional cost in adding CAAM prediction during the design of the fire control system.

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