Electromagnetic Guns versus Conventional Guns - a performance comparison

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Abstract - **Performance improvement is one of the key issues of Electromagnetic gun systems compared to conventional gun systems. Due to higher muzzle velocities, the gun's fire control computer will be able to predict the target's future position more accurately because prediction time will be smaller. In this paper, an investigation is done for the expected performance increase due to the higher muzzle velocities in air defense applications using a parametric as well as a Monte-Carlo approach. The Monte-Carlo approach was used for the evaluation of the performance difference between 'Conventional' and 'Electromagnetic' (EM) versions of naval air defense gun systems. Because present day operational EM guns do not exist, the majority of the gun system parameters were kept equal to their conventional version. Parameters that were varied were of course the muzzle velocity but also the gun dispersion. The dispersion is also a very important parameter influencing system performance.**

Both systems were generic. The first system is a gun, firing proximity fused ammunition at a low fire rate. The second system is a rapid fire gun in a Close In Weapon System (CIWS) role. The two systems were evaluated against several types of missile target trajectories. These trajectories were generated with 6-Degrees of Freedom Simulation models with realistic generic parameters. The hit probability was used as a performance figure. The results show that considerable improvements can be obtained with EM guns and that more profound analysis requires more insight into gun dispersion characteristics.

1. Introduction

One of the disadvantages of ordinary gun systems for air defense is that, the projectile, once in flight, can not be corrected when the target manoeuvres. It is clear that the longer the time of flight to the intercept point of the projectile and target, the more influence target manoeuvres will have and the lower the performance will be. A solution to this problem seems obvious; upgrade the accuracy of the prediction of the trajectory that is flown by the target during the time of flight of the projectile. A problem that rises is that ideal prediction is not feasible because it would require exact knowledge of every disturbance that every subsystem of the target experiences during the projectile's time of flight including the structure of the target's guidance and control system and the exact state at the starting moment of prediction. Despite this problem it pays to make the prediction as accurate as possible.

A different, more revolutionary, solution is to reduce the projectile's time of flight. This can be done by increasing the muzzle velocity. Conventional guns have a physical limit in the initial velocity that can be given to a projectile; EM guns do not have such limitations. Not more than a couple of years ago, EM guns were viewed as nothing more than a curiosity. Today, although a lot of work has yet to be done, researchers have proven under laboratory conditions that considerable masses can be fired at several kilometres per second.

The flight time reduction is just one of the advantages, others are for instance electronically controllable muzzle velocity allowing the fire control computer to choose the optimal muzzle velocity for every specific air defense task. Another aspect concerns the vulnerability of the target; targets are expected to be more vulnerable for higher impact speeds simply because more energy is delivered to the target. This holds for impact (KE) munition, but on the other hand, the effectiveness of proximity fused, (HE) munition is expected to be more sensitive for the exact fuse point when higher intercept speeds are considered.

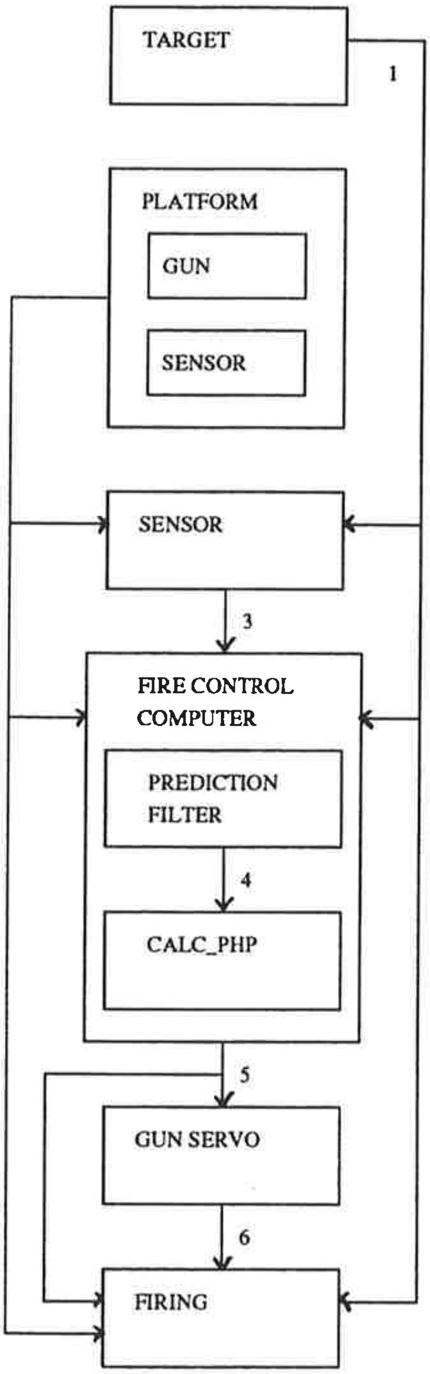
First, an analytic model is presented which introduces some important parameters and parameter sensitivities. The purpose of this parametric approach is purely to gain insight. Monte-Carlo simulation models are then used to obtain more realistic results. Performance results are presented for two gun types against three (missile) target types; two seaskimmers and one so-called high-diver. For the guns, 'conventional' as well as EM versions were used.

References [1] and [2] are the (classified) final examination reports of the second author, forming the basis of this paper.

2. Air Defense Gun Systems

Several subsystems and processes have to be distinguished when simulating air defense gun system engaging targets. These are: (see figure)

TARGET:
    Determining target position, velocity and attitude.
PLATFORM:
    Determining gun servo and target sensor platform position.
SENSOR:
    Measuring the target's position.
FIRE CONTROL COMPUTER: to be divided into:
    PREDICTION FILTER:
        This determines target quantities such as estimated position and velocity for the prediction of the target trajectory in the future
    CALC_PHP:
        Predicted Hitting Point calculation process, usually iterating towards a predicted hitting point (PHP) using firing tables and trajectory derivatives from the prediction filters.
GUN SERVO:
    Gun Servo, steering the gun into the right direction
FIRING:
    In the simulation this process represents the actual firing and projectile trajectory calculations. The result of the firing process, namely a real intercept geometry of target and projectile is determined given gun direction, the target's position, velocity and attitude at the moment of intercept and disturbances influencing the projectile's trajectory.



The above processes interrelate as shown in the figure on the right. This layout is used as a basis for the parametric study as well as the simulation approach.
The numbers in the figure refer to the following quantities:

1. Target trajectory; position, velocity and attitude.
2. Gun- and Sensor platform position.
3. Measured target position
4. Prediction filter tracking state; this depends on the filter method chosen, for instance when the filter is an $\alpha\beta$ filter the state consists of the estimated position and velocity.
5. Calculated predicted hitting point and gun aiming angles
6. Gun servo angles

3. Parametric performance assessment

Two error sources that play a major role in determining the single shot hit probabilities are D and EPHP. D is the deviation of the shell's position at the predicted intercept point with respect to the desired position (i.e. the position which is aimed at). To be more specific this deviation is composed into three directions, namely two directions perpendicular to the gun aiming direction and one in the gun aiming direction. This error generally has zero mean. EPHP is the deviation of the predicted target position at the predicted moment of intercept (called the Predicted Hitting Point or PHP) with respect to the real target position at that moment. The EPHP may not have zero mean.

The relation between these two quantities on the one hand and the hit probability on the other is not straightforward. It depends on the mean of EPHP which in its turn depends on target trajectory characteristics and prediction tracking filter characteristics. In the appendix the hit probability is first derived for the zero mean case. Further, it is made plausible that for the non-zero mean case that there exists an optimal choice for the variance of EPHP when the mean is given. Unless it is estimated, the problem is that the mean is not known. Often, a more or less 'averaged' optimal variance is chosen. How this is done, depends on the design of the fire control system.

When using the formulas obtained in the appendix we are now able to obtain (rough) estimates for impact of muzzle velocity increase on the performance. The Single Shot Hit Probability (SSHP) is equal to:

$\mathrm{SSHP}=1-\exp(-0.5\cdot(RH/\sigma)^2$ with

$\sigma^2 = \sigma_{bal}^2 + \sigma_{pos}^2 + (ts\cdot\sigma_{vel})^2 + \sigma_{man}^2$

With RH, the so-called hit radius and σ the total dispersion. The meaning of these quantities is further explained in the appendix.

To determine for instance the SSHP at a range of 1 km assume that:

σ_{pos} = 1 m σ_{vel} = 1 m/s
G_{max} = 10 m/s^2 σ_{bal} = 1 m

Then it follows that :

$$\sigma^2 = (1)^2 + (1\cdot ts)^2 + (0.5\cdot(10/3)\cdot ts^2)^2 + (1.5)^2 = \\ = 3.3 + ts^2 + 2.8\cdot ts^4$$

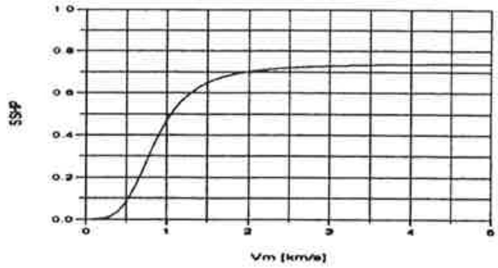
Call V_m the mean velocity over the first kilometre that the projectile travels. So:

$ts = 1/V_m$, the dimension of V_m is : [km/s].

and so :

$\mathrm{SSHP}=1-\exp(-0.5\cdot RH^2/(3.3+1/V_m^2+2.8/V_m^4))$

The following figure shows the SSHP as a function of V_m with RH = 3 m.



It should be noted that the only parameter that is varied is the projectile velocity. So no influence of other parameters that will change because of the fact that EM guns are used are taken into account. Especially the ballistic dispersion is expected to be different in EM gun systems.

4. Performance assessment via simulation

The analytical description of the former section shows which variables play an important role in determining the performance bounds that can be obtained when the muzzle velocity varies.

Unless it is studied which influence the dispersion due to prediction has for specific threat trajectories the results should not be used in the absolute sense. Especially the error due to target manoeuvring is very critical to miss-estimation. For these reason, the so-called Monte-Carlo simulation approach is desirable.

Two gun systems are evaluated against three threat types and compared with EM versions of these systems. In the EM version simulations, the only parameter that was changed was the muzzle velocity. In this section the simulation method, the target trajectories and the gun systems are described.

4.1 Monte-Carlo simulation

A computer model has been built for every subsystem of an air defense gun system to perform a simulation of the gun system engaging a target. The layout of such a computer model resembles the layout as displayed in section 2. In this way, for a given target trajectory, the geometry of the intercept of the projectile and the target can be determined for every projectile fired. In [3] a description of FELGUN is given which is the computer model for doing air defense gun Monte-Carlo simulations. FELGUN has been used to perform the simulations for this study.

When the end geometries for each projectile shot at a given target trajectory are known, statistical results must be derived for the performance figures. This is called the problem of statistical inference. It amounts to estimating a parameter from a distribution of which samples are taken. The performance figure of interest here is the single shot hit probability (SSHP) at a given range in the trajectory.

The so obtained SSHP can subsequently be used to determine the Cumulative Hit Probability. Say that this cumulative hit probability for projectile n in a burst is called CHP_n.

The following relation holds when the single shot hit probability for projectile i is called $SSHP_i$ (i=1,..,n) :

$$CHP_n = 1 - \prod_{i=1}^{n} (1-SSHP_i)$$

4.2 Target trajectories

The two gun systems are both (fictitious) naval systems. Therefore so-called ASSMs (Anti Surface Ship Missiles) are used as targets. Three types of ASSMs covering a fairly wide range of possible threats are used, namely a Subsonic Sea Skimmer (SBS), a Supersonic Sea Skimmer (SSS) and a Supersonic High Diver (SHD). All trajectories were generated with the missile simulation program WASP, see [4].

Only straight incoming trajectories are assumed, so no Anti Close In Weapon System manoeuvres were considered. The sea skimmers all fly at an altitude of 10 m. The SHD was simulated with a 45° dive angle.

The following table lists some characteristics of the threats that were found in the open literature. The speeds were chosen arbitrarily, but in accordance with expectations. The SBS and SHD diameters used were those from the Exocet and AS-6 (Kingfish) respectively, they can be found in [6] and [7]. The diameter of the SSS is an estimated value. The figures used are given in the table below.

Threat	Speed [m/s]	Diameter [cm]
SBS	300	35
SSS	900	50
SHD	1000 (initial) 700 (terminal)	90

4.3 Gun system description

Two naval air defense gun systems were evaluated against the threat types, mentioned in the previous section. The characteristics of the two systems were chosen to give a fair amount of variability. The systems chosen were generic versions of the OTO/MELARA 76mm gun system and the Goalkeeper CIWS. Both systems are described in [5]. So the simulated systems could be described as OTO/MELARA 76mm-like and Goalkeeper-like. The results therefore merely indicate possible trends, which is enough to serve the purpose of this study. The guns will be denoted with the names 'Conventional-76mm' and 'Conventional-30mm'. These names were chosen to differentiate them from the Electromagnetic version. They are denoted 'EM-76mm' and 'EM-30mm'.

The error parameters, determining ballistic - and sensor noise were chosen equal for both the 30mm and 76mm. They are:

Sensor: $\sigma_{elevation}$ = 1.0 [mrad]
$\sigma_{azimuth}$ = 1.0 [mrad]
σ_{Range} = 2.0 [m]
Gun: $\sigma_{el\_dispersion}$ = 1.0 [mrad]
$\sigma_{az\_dispersion}$ = 1.0 [mrad]
$\sigma_{tof\_dispersion}$ = 0.005 [s/km]

The time of flight dispersion is denoted with tof_dispersion.

4.3.1 Conventional- and EM-76mm

As described in section 2, an air defense gun system is characterised by the parameters of the target sensor, fire control (gun prediction) and gun dispersion.

For the Conventional 76mm these are the following:

Gun:	V_0 (muzzle vel.) = 800 [m/s] Fire rate = 2 [shots/sec]
Munition type:	High Explosive with proximity fuse, fuse trigger diameter = 6.0 [m]. This figure is used for all threats.
Fire control	linear prediction

The only parameter that was changed for the EM version of the 76 mm gun was the muzzle velocity. So the same munition is used. The muzzle velocity was chosen to be: V_0=1600 [m/s].
This increased EM muzzle velocity number was based on realistic assumptions concerning electrical power supply possibilities.

4.3.2 Conventional- and EM-30mm

The CIWS that is simulated can be described as Goalkeeper like because not all Goalkeeper system data is implemented, especially in the area of the fire control computer. So the results do not pretend to represent the absolute performance of the Goalkeeper system but should be used to compare the conventional and EM gun systems. The character of this study is such that this is allowable.

Gun:	V_0 (muzzle vel.) = 1150 [m/s] Fire rate = 70 [shots/sec]
Munition type:	Armour Piercing, requiring impact
Fire control	Curved path prediction (i.e. taking into account acceleration)

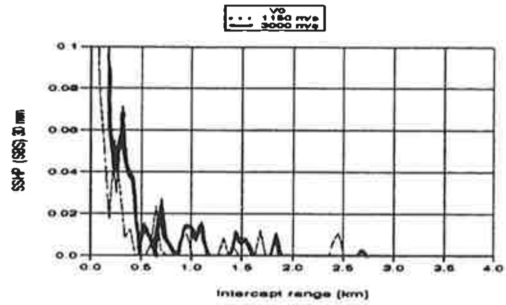
The only parameter that was changed for the EM version of the 76 mm gun was the muzzle velocity. So the same munition is used. The muzzle velocity was chosen to be: V_0=3000 [m/s].
This increased EM muzzle velocity number was based on realistic assumptions concerning electrical power supply possibilities.

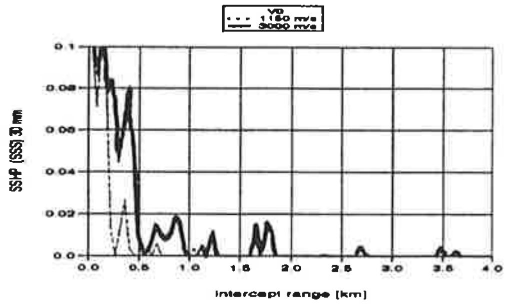
5. Simulation Results

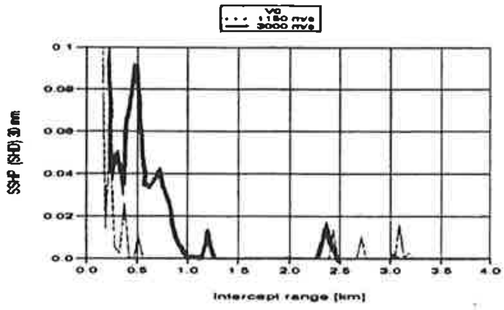
In this section, the results for the 30mm and 76mm are presented.

5.1 Simulation results for the 30mm guns

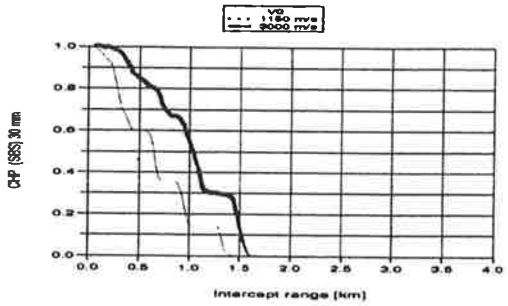
First the Single shot results are given. From top to bottom, the performance against SBS, SSS and SHD are shown. As can be seen the EM version performs better on the average. The occasionally higher values for the conventional version are due to the fact that the results are in fact a Monte-Carlo sample.

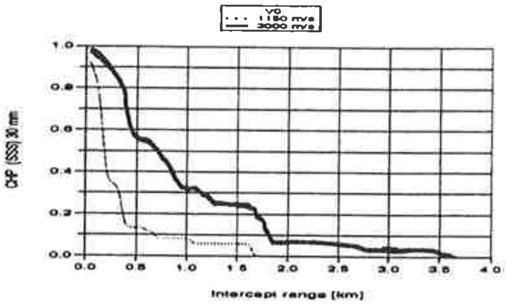


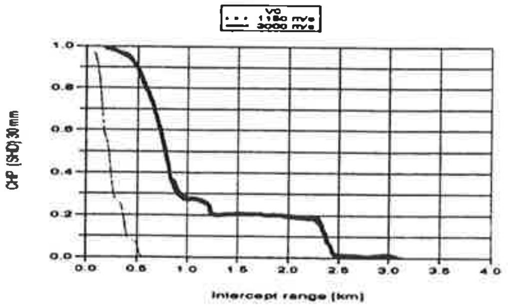




Actually guns fire in bursts, so it is interesting to see what the Cumulative results are. To do this, a burst length of 5 second was chosen. This is the reason why the cumulative graph starts at a longer range for the EM version. At the next page, these cumulative results are shown



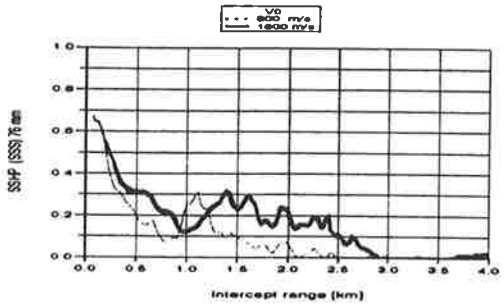


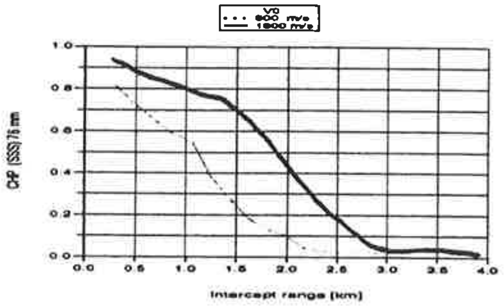


5.2 Simulation results for the 76mm guns

The 76mm results are only given for the SSS and SBS case. The performance against the SHD was too small to give a sensible comparison between the conventional and EM version.

Below the SSS performance is given, first the Single Shot results (SSHP) and then the cumulative results (CHP). The CHP was made with a burst length of 8 seconds.

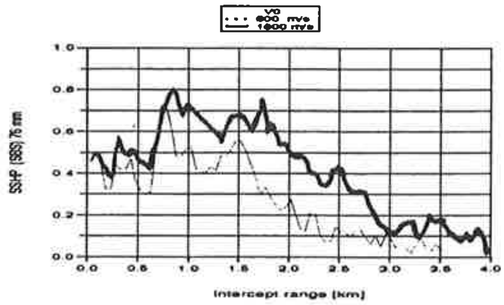




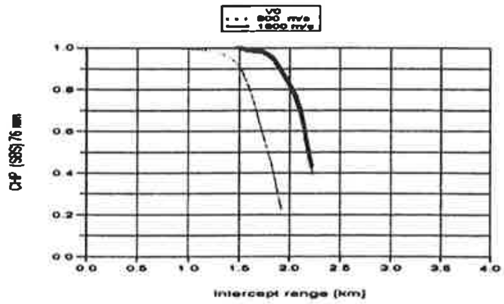
To get some idea of the influence of the ballistic dispersion, simulations were performed with the nominal gun dispersion figures, but also with half these sigma values as well as twice these sigma values. The nominal values are the values given in section 4.3. The simulations were done for the SBS case.

On the next page, the results are shown subsequently for the half sigma, nominal sigma and two sigma case. On the left, the single shot results are plotted and on the right, the cumulative results. The cumulative results were again made with an 8 seconds burst length.

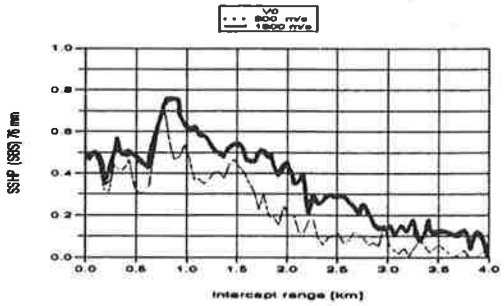
SSHP results for the half sigma case.



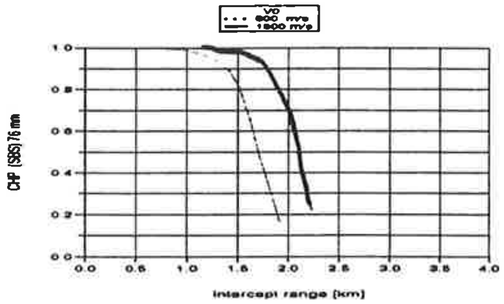
CHP results for the half sigma case.



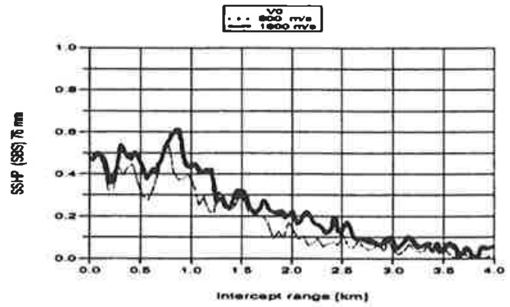
SSHP results for the nominal sigma case.



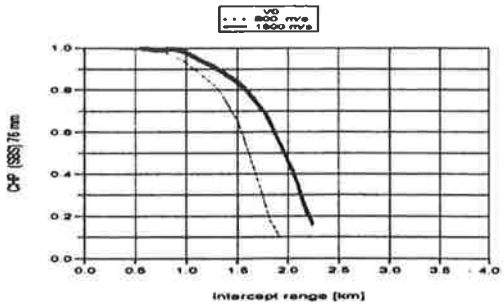
CHP results for the nominal sigma case.



SSHP results for the two sigma case.



CHP results for the two sigma case.



As can be seen, the results clearly show a performance gain increasing with decreasing ballistic dispersion.

The overall results show a relatively small improvement in the single shot hit probabilities but this amounts to a reasonable performance gain for full bursts. When the burst length increases, the results all tend to 100% as is to be expected. This is an indication that increasing muzzle velocity is one of the tools gun designers have in boosting the performance, also longer burst length may improve the gain to an acceptable level.

Conclusions

In this study insight into the relation between air defense gun performance, system parameters and threat parameters is given, first parametrically and then by means of simulation. This relation was especially studied for the muzzle velocity parameter. It is shown that considerable performance gain can be obtained when muzzle velocities in the EM gun range are used. It is also shown that the EM gun performance gain not only depends upon the prediction errors that will be smaller but also on the gun dispersion. Further study in the area of dispersions that can be expected in operational systems is desirable when more realistic performance gain figures are needed. It is noted that the design of an air defense gun systems requires careful tuning of all the system components and parameters. Important parameters, apart from the muzzle velocity, are ballistic dispersion, prediction tracking filter accuracy, burst length and rate of fire. Especially the prediction tracking filters need tuning when other parameters, like muzzle velocity, change. Tuning was not done in this study. The obtained performances may therefore be increased when all parameters are completely matched.

Appendix

Call the gun dispersion error D and the PHP error EPHP. Assume that these errors are one-dimensional with Gaussian distribution. Let μ_{EPHP} and σ_{EPHP} be the mean and standard deviation of EPHP and let σ_D be the standard deviation of D, assume that D has zero mean. The gun aiming direction is chosen in the PHP direction, so the total error of the shell with respect to the target is:

$$E = D + EPHP$$

The mean and standard deviation of E then become

$$\mu_E = \mu_D + \mu_{EPHP} = \mu_{EPHP} \quad \text{and} \quad \sigma_E = \sqrt{(\sigma_D^2 + \sigma_{EPHP}^2)}$$

And the probability density function of E is given by:

$$f_E(E)=(1/(\sigma_E\sqrt{(2\pi)}))\cdot\exp(-0.5\cdot(E-\mu_E)^2/(\sigma_E^2))$$

When a target dimension of $2\cdot\varepsilon$ is assumed then the Single Shot Hit Probability is given by

$$SSHP = \int_{-\varepsilon}^{\varepsilon} f_E(E)\cdot dE \approx 2\cdot\varepsilon\cdot f_E(0)$$

Assume that μ_E is given and that σ_{EPHP} is under control of the designer of the fire control system. An optimal choice for σ_{EPHP} can then be obtained from:

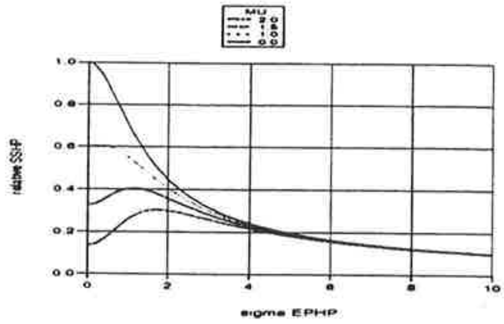
$d(SSHP)/d(\sigma_{EPHP}^2)=0$ which results in $\sigma_{EPHP}^2=\mu_E^2-\sigma_D^2$

A variance must always be positive, so this means that the above only holds for the case $\mu_E > \sigma_D$.
When $\mu_E \leq \sigma_D$ the optimal choice is $\sigma_{EPHP}=0$.

The maximal SSHP that can be reached for given σ_D is found for $\sigma_{EPHP}=0$ and $\mu_E=0$. So:

$$SSHP_{max} = 2\cdot\varepsilon\cdot(1/\sqrt{2\pi})\cdot(1/\sigma_D).$$

When the SSHP is divided by $SSHP_{max}$, the relative SSHP is obtained. In the figure below, the relative SSHP is shown as a function of σ_{EPHP} for several values of μ_E.



The above relations hold for the one dimensional case but can easily be transformed to two dimensions when the mean is zero. In [8] the following formula for the single shot hit probability is given in two dimensions:

$$SSHP=\sqrt{((1-\exp(-0.5\cdot(RH/\sigma_h)^2)\cdot(1-\exp(-0.5\cdot(RH/\sigma_v)^2))}$$

Where :

SSHP	Single shot hit probability
RH	Total hit radius, so in the case of impact munition this is the target radius and in the case of proximity fused munition this is the sum of the target radius and the effectiveness radius of the fuse.
σ_h	Standard deviation of the total error in horizontal direction.
σ_v	Standard deviation of the total error in vertical direction.

When $\sigma_h = \sigma_v = \sigma$ this reduces to :

$$SSHP=1 - \exp(-0.5\cdot(RH/\sigma)^2$$

The σ can be approximated using the following relation:

$$\sigma^2 = \sigma_{pred}^2 + \sigma_{bal}^2$$

Where :

σ_{pred}	Standard deviation of the prediction error
σ_{bal}	Standard deviation of the error due to ballistic dispersion.

Reference [9] elaborates on tracking filters, so-called $\alpha\beta$ filters are often used for linear prediction. When the prediction is linear, the prediction error can be described as follows:

$$\sigma_{pred}^2 = \sigma_{pos}^2 + (ts\cdot\sigma_{vel})^2 + \sigma_{man}^2$$

Where :

ts	Time of flight (shot time) of the projectile to the intercept point.
σ_{pos}	Standard deviation of the filtered position used for prediction
σ_{vel}	Standard deviation of the filtered velocity used for prediction.
σ_{man}	Standard deviation in the predicted position due to target manoeuvring.

Note that the incorporation of target acceleration as a variance is a different way of approximating the SSHP.

When it is assumed that the target will have a certain mean acceleration then σ_{man} can be determined. This mean acceleration depends on the threat trajectory but a reasonable estimate is that straight incoming missiles performing no intentional manoeuvres have a mean acceleration of 1/3 of the maximal acceleration (G_{max}). The standard deviation then becomes :

$$\sigma_{man} = 0.5\cdot(G_{max}/3)\cdot ts^2$$

Now the total sigma is known as a function of ts. So it is clear that there is an upper boundary for SSHP when ts tends to zero (by letting the muzzle velocity tend to infinity).

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References

1. *'Elektrische Energievoorzieningen voor Elektromagnetische Kanonsystemen' (Electrical Power supply for Electromagnetic Gun systems)*, J. van der Weijden, Prins Maurits Laboratory (TNO-PML), Rijswijk, April 1992, PML 1992-IN11, Confidential.
2. *'Vergelijking van de trefkans van munitie verschoten met elektromagnetische kanonsystemen en conventionele kanonsystemen' (Hit probability comparison of EM-guns and 'conventional guns')*, December 1992, LTZE2. J. van der Weijden, Prins Maurits Laboratory (TNO-PML), Rijswijk, PML 1992-119, Confidential.
3. *'Design requirements for the Gun Defense Simulation Model "FELGUN"'*, Ir. N.M. de Reus, TNO Physics and Electronics Laboratory (TNO-FEL), The Hague, February 1992, FEL-91-A439.
4. *'WASP, the Weapon Analysis and Simulation Program'*, Ir. H.G.M. Janssen, Ir. N.M. de Reus, Ir. P.F. Ruizendaal, Ir. A. Wijbenga, TNO Physics and Electronics Laboratory (TNO-FEL), The Hague, March 1991, FEL-90-A322.
5. *'Janes Weapon systems'*
6. *'World Missile Directory'*, 'Flight International', February, 1985
7. *'An illustrated guide to modern airborne Missiles'*, B. Gunston, 1983, Arco Publishing, Inc. New York
8. *'Engineering design handbook'*, US army materiel development and readiness command, DARCOM-P 706-101, november 1977
9. *'Synthesis of an Optimal Set of Radar Track-While-Scan Smoothing Equations'*, T.R. Benedict and G.W. Bordner, July 1962, IRE Transactions on Automatic Control.

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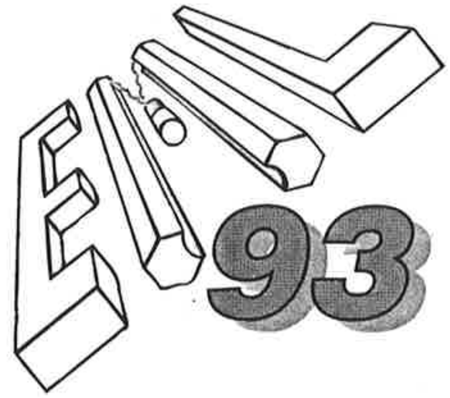

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