Development of model-based system engineering methodology to predict modular artillery charge system performance

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Abstract

KEYWORDS: Weapon system, system effectiveness, modular artillery charge system, model-based system engineering, muzzle velocity variability, probable error.

The performance measures of modular artillery charge system (MACS) are problematic during the early development phases since the ballistic effect of all possible variations of the input variables cannot be validated through testing. This lack of prediction rises a pressure on the MACS system engineers in the integration and verification phases of the system during the development lifecycle.

The research identifies the sources of error that determine the performance of MACS in both launch phase and in-flight phase of the projectile. The research derives the errors in the launch phase and investigates their implication to the overall performance (in form of dispersion and accuracy). Therefore, the research methodology gathers variations of MACS components (charge and projectile) and executes simulation of overall system performance. Thus, such a methodology would be used to serve as a tool to provide the capability for the system engineers to predict and determine MACS performance parameters and develop IB and EB specifications.

The study resulted in that the first stage of the methodology, which is IB specification modelling shows inadequate tolerances in charges muzzle velocity (MV) values for all MACS configurations. The muzzle velocity variability (MVV) and projectile mass variations lead to generate dispersion and inaccuracy in firing as they are performance measurement of MACS.

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Abbreviations

0-D:	Zero dimension
1-D:	One dimension
AB:	All-burnt
ARL:	Army Research Laboratories
CEP:	Circular error probable
CFD:	Computational fluid dynamic
CI:	Configuration item
CMD:	Charge mass determination
CMS:	Charge mass subtraction
DoD:	Department of defence
DRS:	Development requirement specification
EB:	External ballistic
EBM:	External ballistic model
ECEP:	Equivalent circular error probable
IB:	Internal ballistic
IBM:	Internal ballistic model
MACS:	Modular artillery charge system
MBSE:	Model-based system engineering
MET:	Metrology
MPI:	Mean point of impact
MPMM:	Modified point of mass model
Multi-D:	Multi dimension
MV:	Muzzle velocity
MVV:	Muzzle velocity variability
NATO:	North Atlantic treaty organisation
ORS:	Operational requirement specification
PE:	Probable error
RNG:	Random number generator
RSS:	Root sum of square
SRS:	System requirement specification
STANAG:	Standardisation agreement

TB: Terminal ballistic

TLE: Target location error

TPI: True point of impact

TPM: Technical performance measure

Nomenclature

DP_3: Zone 3 delivery performance [-]

DP_4: Zone 4 delivery performance [-]

DP_5: Zone 5 delivery performance [-]

DP_6: Zone 6 delivery performance [-]

MV_3: Charge 3 muzzle velocity [m/s]

MV_4: Charge 4 muzzle velocity [m/s]

MV_5: Charge 5 muzzle velocity [m/s]

MV_6: Charge 6 muzzle velocity [m/s]

CM_3: Charge 3 mass [g]

CM_4: Charge 4 mass [g]

CM_5: Charge 5 mass [g]

CM_6: Charge 6 mass [g]

PE_R: Probable error [m]

S_i: Source of error [-]

α_0 and α_1: Empirical coefficients of deflection determining [-]

ε_B: Ballistic efficiency [-]

ε_P: Piezometric efficiency [-]

σ_{AZ}: Azimuth estimation variation [mils]

σ_D: Standard deviation of total error in deflection [m]

σ_{Fuze}: Fuze functioning variation [-]

σ_{MV}: MV variation [m/s]

σ_{Met}: Metrological components variation [-]

σ_{Proj}: Projectile properties variation [-]

σ_{QE}: Quadrant elevation variation [mils]

σ_R: Standard deviation of total error in range [m]

σ_{Sub}: Submunition clustering variation [-]

σ_{WL}: Weapon location variation [m]

CEP: Circular error probable [m]

$ECEP$: Equivalent circular error probable [m]

P: Pressure [MPa]

QE: Quadratic elevation [mil]

n: Burn rate exponent [-]

r: Burn rate [m/s]

α: Elliptical distribution coefficient [-]

β: Burn coefficient (or pressure index) [mm/s/MPa]

CHAPTER 1 : INTRODUCTION

1.1 Background

1.1.1 Application of ballistics

Ballistics is the field of mechanics concerned with the launching, flight behaviour and impact effects of projectiles. It is the science of designing and accelerating projectiles so as to achieve a desired effect on the target. The study is theoretically branched, based on the nature of these phenomena, into three primary disciplines, IB, EB and terminal ballistics (TB).

IB is the study of propelling the projectile in the enclosure of the gun/mortar barrel. Forces are exerted due to pressure build-up behind the projectile due to energy released from propellant ignition. This movement requires dynamic interactions between the weapon, the projectile and the combustion agent (propellant). The purpose of IB is to design for an efficient propulsive process inside the gun, take to mean the movement behaviour of the projectile along with the weapon and determine the velocity of the projectile when it leaves the gun (Carlucci & Jacobson, 2007). This reciprocal relationship should be incorporated by taking into consideration the safe operating conditions to prevent the weapon from the extreme pressure that resulted from the generation of the combustion gases. The principal outcomes, (Artillery Manual, 1999) of such systems as integrated to the whole ballistics are:

I. MV which is the magnitude of projectile speed when it leaves the muzzle of the gun. The value of MV with other parameters will determine the range of the projectile.
II. Spin rate that indicates the twisting motion of the projectile after it leaves the gun. By spinning the moving projectile in the air, it will be stabilised, and facilitate more accurate impact on the target. In some applications, the projectile is stabilised by fins instead of spinning motion.
III. Launch elevation, which is an operation parameter that represents the angle of firing that limits the projectile to its trajectory.

After the projectile leaves the gun tube, there are no more propulsive forces acting on the projectile to project it toward the target, and all the forces that propel the projectile to its destination are external forces. The momentum that is transferred during the internal ballistic process propels the projectile forward. Other retarding forces, such as drag, acts externally on the projectile. The values of IB outcomes side by side with projectile dimension (which determine the aerodynamic coefficients such as drag and lift) are now considered as inputs to the EB. The study of EB is the study of the projectile in flight from the time it leaves the muzzle until it impacts on the target. Generally, as a concern of EB, the angle, the velocity and the location of impact are the design outcomes. The satisfactory results of these parameters would be achieved by improving the projectile dynamics and stability and predicting the path and the time of the flight (Horn, 1982).

The TB is the field of study that deals with the behaviour of a launched body and its parts or fragments thereof from the moment of impact or placement at the target. In designing weapons and ammunition systems, the defined terminal effect is the desired objective (Rosenberg & Dekel, 2012). To this point, a proper balance among many factors, including internal and EB is essential to accomplish this desired objective.

In short, the layout, shown Figure 1-1, illustrates the most outcomes of each branch and shows the linkage between them. Unquestionably, there are substantial factors which affect each outcome leading to more sophisticated ballistic systems (the sum of IB, EB and TB sub-systems).

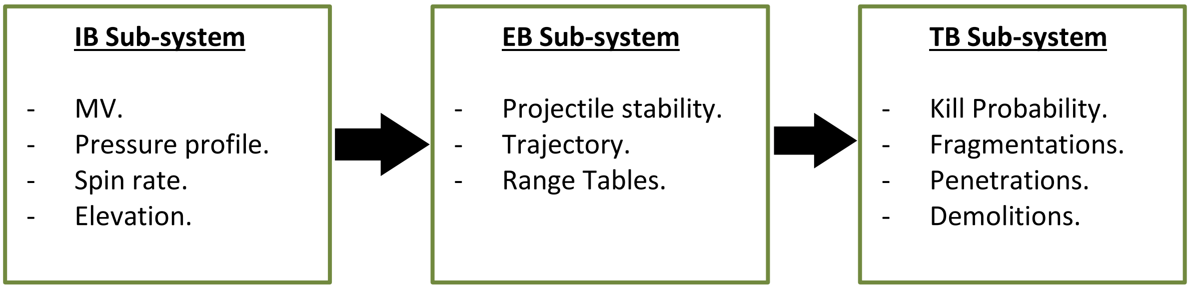


Figure 1-1 Roles of ballistics branches

This study explores the design mode of the IB sub-system in detail and identifies the valid parameters that are critical for which the design may be unreliable. In particular, the increase of the uncertainty of the IB design factors results in weapon system failure or the weapon system not being reliable for use (Artillery Manual, 1999). Typical reasons behind the design factors uncertainties are:

I. The ambiguity of the ballistic events inside the gun may result in uncleared consideration of the system explanation. These hidden events are resulted because of that all it occurs in a concise period, i.e. in some weapons, it may reach six milliseconds.
II. The number of gun-projectile-charge combinations is infinite, and there is no “optimum gun” which be referred to be an ideal system. In other words, different configurations of projectiles and charges can be fitted to the same gun. As a result, an infinite number of tests are required to assure that the weapon system is reliable and safe.
III. The above-mentioned leads to stochastic behaviour of the design parameters, (Carlucci & Jacobson, 2007), that affect the IB output. For example, one of the critical parameters that influence the MV is the propellant geometry which always relies on the manufacturing variations, (Hunt, 1951).

Numerous complex components and systems are combined to result in a ballistic system with the aim of delivering an effective weapon system. The weapon system mainly consists of three parts; the gun, the propellant, or in some applications called charge, and the projectile. Figure 1-2 shows the main setup of an artillery weapon system. The agreement and interaction amongst these components result in what is termed as the “Ballistics Specifications”.

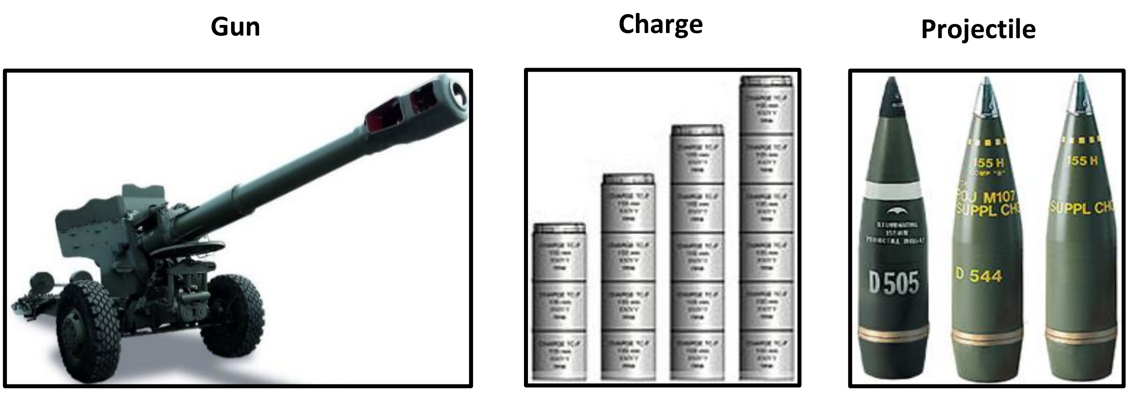


Figure 1-2 Setup of gun-launched weapon system

1.1.2 Performance of weapon system

The ballistic specification is the property of the weapon system where its components (the weapon, the charge, and the projectile) are designed to perform the firing mission that agrees with the user's requirement expectations (Driels, 2013). According to the ballistic specification, as defined previously, the TB properties define the mission objectives as damage mechanism while the IB and EB ensure the delivery of the system and its consistency. To elucidate the weapon system in this study, the significant objectives will focus only on the field of IB and EB as the system deliverables will define the firing range and firing accuracy.

Different weapon systems analysis applies different delivery performance measures and methods of their determination. It is essential to realise the application of a particular weapon system to derive its performance calculations (Erichson, 1973). Thus, there are several methods of system delivery that categorise weapons by their applications leading to numerous firing system varieties starting from the small manual handgun to the self-propelled artillery howitzer. Still, the majority of these types share the same fundamentals of operation except for some applications such as recoilless guns which are outside of the scope of this study.

These fundamentals of operation include mounting, loading, aiming and firing of the gun system (Moss, Lemming, & Farrar, 1995). First, the mounting of a gun is the placement of the arm for operation; for example, a handgun is mounted by hand. Then, to accurately hit a target, it needs a proper aiming process which is the use of sights in handguns. This is designated as direct firing as shown in Figure 1-3. Likewise, another way is to use indirect aiming, such as the use of range tables to point the target in artillery applications. Figure 1-3 disaggregates delivery techniques into different applications.

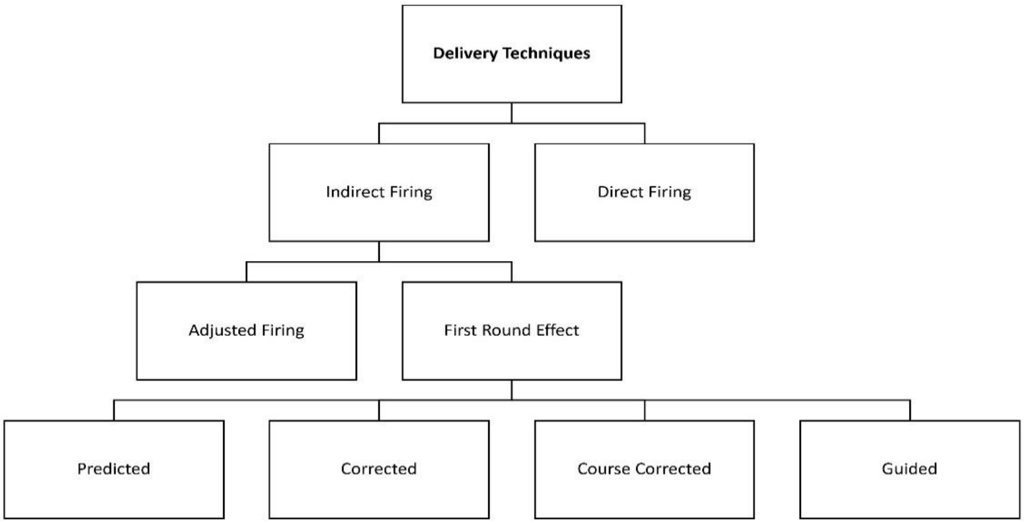


Figure 1-3 Weapon system delivery techniques

The adjusted firing type relies more on the tactical procedures where the user gathers information from the previous missions in the operation theatre to account correction factors to bring the impact point to the designated target. On the other hand, first-round effect firing uses current information such as metrological parameters, time of flight, as well as the weapon system and target location to generate an aiming solution (STANAG 4635, 2008).

This research study will focus on the predicted firing technique by developing a systematic model that uses artillery component specifications to determine system performance and its dependency under a wide variety of specification tolerances.

1.1.3 Function of modular artillery charge system

To improve the mobility and range control of weapon systems in the operational theatre, MACS was introduced. This system has been established by accomplishing the correct combination of gun-charge-projectile to impact the target accurately. After determining the correct combination, the charge is split into incremental parts in order to maintain different target locations (zones) (Dickinson, 1987). As mentioned early in Figure 1-1, the requirements by EB sub-system is to generate range table are MV, spin rate, elevation. Thus, by defining different MV of the weapon system, the gunnery operator will be able to cover a spread of different zones, and this can be accomplished by splitting the charge to different weights and giving different muzzle velocities.

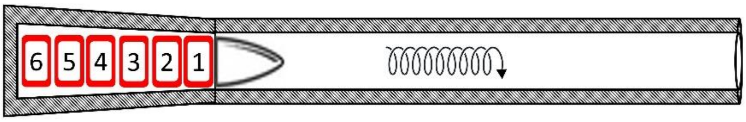


Figure 1-4 MACS configuration

The charge configuration of the multizone artillery system is schematically illustrated in Figure 1-4. A specific MV can be achieved by choosing the number of the split charges loaded into the weapon chamber. As a result of the selected velocity coupled with different weapon launched angles, a wide range can be covered by a indirect fire weapon system (Ruth & Minor, 1985).

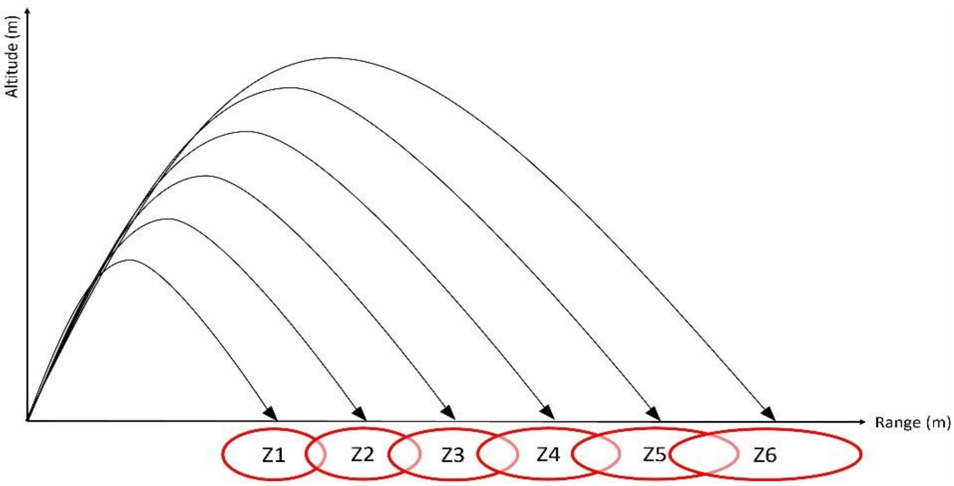


Figure 1-5 Zoning layout of MACS

Figure 1-5 shows the distribution of different zones and their overlap. The overlap is the standardised intersect area between two defined ranges, and it is usually 10% of each zone (Dickinson, 1987). It can be seen from the previous figure that the range band of top zones is wider than the bottom zones. From the perspective of the functionality of the weapon system delivery, a narrower zone band is desirably required since it is more accurate and economical. However, a wider zone may be preferred in several applications to achieve a higher angle of attack, which gives better fragmentation and thus a more significant area of effect (Muller, 2019).

The delivery performance defines a maximum range that is achieved by designing ballistics parameters of MACS for the top zone (Z6) (Field Artillery, 1992). Nevertheless, because of the degree of influence of these parameters differs on the remaining zones, (Field Artillery, 1992), and rise of independent parameters uncertainty result in different performances which are investigated in this study.

1.2 Problem statement

MACS presents a challenge to the ballistic systems engineer in terms of determining the ballistic specifications over all the operational zones. Normal variations in charge specification (MV) and projectile specification (projectile mass) during production may result in varying sensitivities in the lower operational zones. This practice could result in the product moving outside the required charge and projectile specifications leading to reduction in MACS performance. The anticipation of these variations may not have been covered during the development phase, due to the requirement for elaborate testing, which places pressure on development costs.

To predict variations in ballistic performance over all the MACS zones, inputs variability within the typical specification limits should be covered. This prediction will enable the design team to predict weapon system ballistic specifications, in manufacturing (input) as well as performance (output), during the development phases of a charge and projectile lifecycle. This capability will reduce the risk of possible failing ballistic performance specifications during the product lifecycle and may lead to a saving of cost and time. Thus, the research problem to be investigated is to reduce the load on the MACS qualification by adding ballistic specification prediction capability under the MACS design workflow. This prediction capability uses a stochastic tool to observe the influence of different inputs variations to the MACS specifications and performance.

1.3 Research objectives

The performance measures of MACS are problematic during the early development phases since the ballistic effect of all possible variations of the input variables cannot be validated through testing. By employing a stochastic input procedure to a reliable ballistic simulation models (IB as well as EB), the ballistic variation in output can be determined for the complete MACS, and the ballistic input and output specifications can be derived from these simulations early in the development cycle and provide reliable results for the development effort.

The investigation of the effects of the MACS parameters in both stages of charge characterization and system configuration will assign system limitation and reliability to the manufacturing capability. Besides, this effectiveness study will create a direct linkage between the manufacturing capability and the ballistics requirements, such as consistency in range.

1.4 Method of investigation

Figure 1-6 MACS ballistics framework

The research will focus on the formulation of an appropriate stochastic method to be applied on IB sub-system then derive the system delivery outcomes through EB sub-system simulation models. The system input variables and limits will be identified from experimental and manufacturing data and specifications. The ballistic simulation model code will be adapted and applied to determine the relevant ballistic outputs, as shown in Figure 1-6, namely, MV tolerances, system pressure budget, as well as range and consistency in the firing.

To successfully complete this study, the following method will be applied:

Firstly, a critical literature study is conducted. Most of the previous studies have been contributed to the field of the EB only by connected the performance of MACS to the influencers of the EB sub-system outputs. Influencers of EB outputs are metrological message, aerodynamic characteristics of the projectile in flight and operation conditions such as elevation angle of firing.

Secondly, MACS development process is covered. MACS is handled through the development lifecycle; it is treated as two separate sub-systems (IB and EB sub-systems). Then, the performance of the two sub-systems is defined (in MV and projectile mass variations) and verified to produce the overall MACS performance (in impact consistency). Throughout the research, it will be seen that following-up such practice will not ensure the desired MACS performance because the process of lumping the IB and EB sub-system together is not convenient to generate a realistic system performance. It will be seen through the discussion section of this research that the MACS is unsteady system when the charge is split into different small modules leading to a weak correlation between charge design and MACS performance outputs.

1.5 Limitations of the study

The scope of the research links the performance of MACS only to the manufacturing capability (quality limits) of the charge and projectile. The correlation to the system output is done on the charge dimensions and weight where chemical property variations are not included. In addition, on the projectile side, the output of the system is limited to the variations in the weight of the projectile and the relationship to aerodynamic properties is not considered in this research.

Also, the study is limited to the lack of previous studies and experiments that investigate the performance of the lower zones for MACS caused by the dissimilarities in its components. Nevertheless, establishing a baseline for the research contribution may help to prevent this unobservable reduction in system performance.

1.6 Contributions of this study

It will be seen in the literature that they are not comprehended to both IB and EB fields. The research combines the branches of IB and EB and structures a direct prediction framework that helps to ensure the desired system performance measures. This prediction framework can enlighten the artillery systems designers about the performance of the MACS system in early stages in the development lifecycle. Thus, it may introduce “best practice” design activities in the development of MACS systems.

1.7 Summary

The science of ballistics was introduced, and design parameters were defined to shape the characteristics of a weapon system, particularly, the MACS. This study submits the key parameters to define the performance of MACS for all its configuration and operation conditions. In the next chapter, non-standard conditions of configuration and operation are introduced in order to define the effective parameters that cause changes in the MACS performance. Also, research is conducted to determine the best model to be used in this study to calculate ballistic performance.

CHAPTER 2 : LITERATURE SURVEY

2.1 Objectives of the literature survey

The first part of the literature survey introduces the definition of the weapon in the form of system effectiveness where the weapon is characterised to generate functional requirement of engaging the target. The delivery performance of the weapon system figures dimensions this function. The figures of weapon system delivery performance are exclusively accuracy and consistency of firing. In this chapter, most of the delivery performance effective parameters are introduced in both ballistic phase and in-flight phase. A good remark can conclude that to study the effect of particular parameters to the weapon delivery performance can be isolated, and the other parameters can be neglected. Also, different methods of calculating the delivery performance of the weapon system are introduced to find out the situation where the suitable method is implemented in this research results.

The second part of the literature survey studies the ballistic parameters that cause changes in system performance in more details. As described in the next sections, the ballistic parameters that have variations and caused by manufacturing variations are examined separately. These ballistic parameters are charge weight, propellant grain size, propellant dimensions and projectile weight. The examination defines the effect of these ballistic parameters to the IB sub-system causing variations in MV. Also, this part of the literature survey defines the propellant and its method of characterisation by its chemical properties and its burning behaviour. Next, different efficiencies for the IB sub-system were introduced as preliminary figures to design IB parameters. In addition, this part of the literature survey examines different IB models. As the technology in the ordnance sector developed, a wide range of theoretical and applied studies have been published. Especially the analytical and numerical models in IB that represents the science behind the projectile launching have been improved in order to get optimum results. One challenge of the proposed study is to select an IB model with minimal shortcomings and higher accuracy, which can be applied to MACS. Therefore, a survey of different types of IB models has been conducted. Most of the modern IB simulation models use a set of simplified mathematical equations to be solved by a set of algorithms on a computer using numeric methods to solve the entire ballistic cycle in incremental time steps. Many numeric codes were developed during the past 50 years, and the background description and definition of most of these are available. The accuracy of IB sub-systems is categorically enhanced by studying the effect of each input on the MV, the maximum pressure and the exit shot time. These inputs are categorised and reviewed in the literature study, and their degree of influence to the IB sub-system is determined. When studying any parametric sensitivity, the correlation of the input parameter to the output defines the degree of its influence. As a result of defining the corresponding effects, variations of the parameters can be manipulated to limit the boundaries of the IB sub-system.

The last part of the literature survey illustrates the importance of constructing a rigid system engineering model. The complexity of MACS by its nature that has different sub-systems (TB, EB, and IB) and each one has different ballistic parameters needs to establish a well-structured framework. The process of constructing MBSE methodology is based on splitting different phases which lead to meeting the ballistic specifications of MACS. These system phases are system definition, system implementation, system integration and system verification.

2.2 Weapon system delivery performance

To define the system performance, the designer must conceptualise the main areas of interest where the performance is associated with increasing weapon system effectiveness. The term system effectiveness permanently outlines the overall system objectives by which and how the target is engaged and neutralised under specified condition (Sherif & Kheir, 1981), (US Army, 1986). Hence, the areas that integrate the system effectiveness are as described by (Driels, 2013) weapon characteristics, weapon delivery performance and target vulnerability.

First, weapon characteristic is the practice where the weapon system components are designed to perform the military mission. It includes the processes of development, integration and verification of system specifications. Second, weapon delivery performance is the measure of the ability to deliver the weapon to the target (range). It depicts the target hitting by accuracy and precision (consistency) of weapon firing. Third, target vulnerability is an assessment tool that investigates the destructive effect that the weapon has on the target. It calculates the damage criteria in terms of lethality index and kill probability (Driels, 2013). The methodology of system engineering modelling of this research is to create a framework that defines system specifications and limitations as weapon characteristic to predict the required delivery performance.

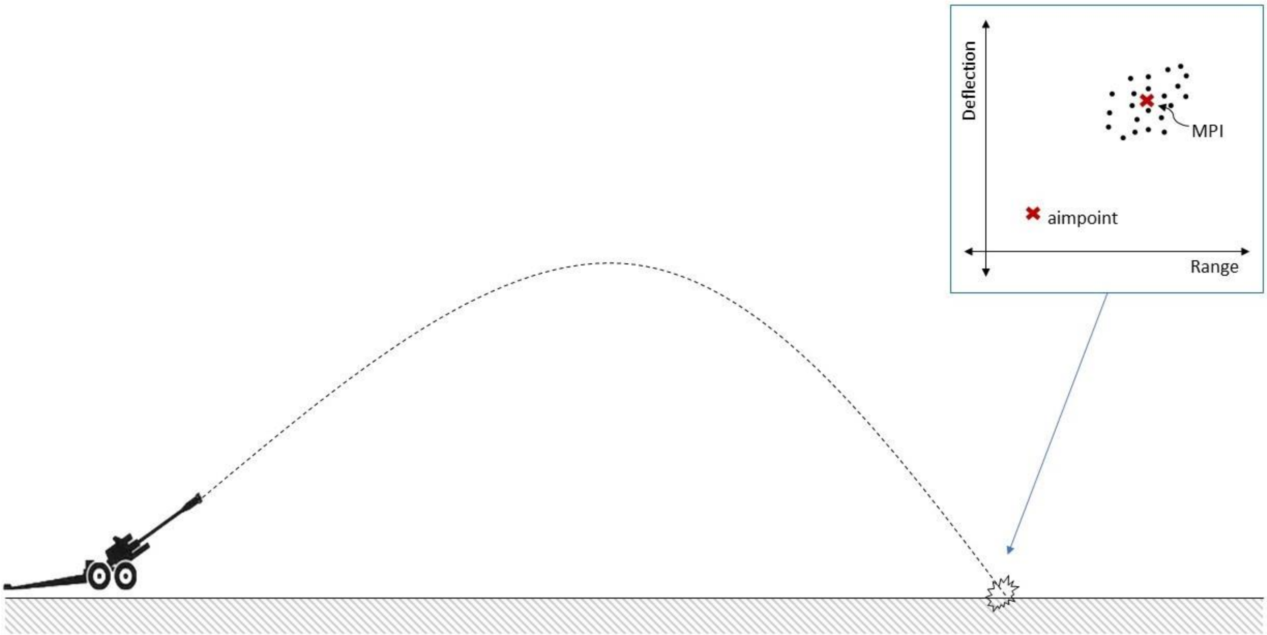


Figure 2-1 Delivery performance representation

The delivery performance as represented in Figure 2-1 is the accuracy of hitting which is the measured distance between aimpoint and mean point of impact (MPI) and the consistency of hitting which is the spread (dispersion) from MPI (Fann, 2006). The standardised NATO unit of measure of consistency is termed as circular error probable (CEP) which is the radius of the circular that contains 50% of the hitting points centred by MPI (STANAG 4635, 2008). For the sake of performance calculations, the area of the plate where the shot falls is coordinated by range as X-axis, height as Y-axis and deflection as Z-axis. Similarly, target location error (TLE) is the distance between the aiming point and the true target location and is assumed that this error is independent of the weapon MPI and can be added or removed to derive the delivery accuracy for the system. The magnitude of the TLE will vary according to the procedures used in the field.

2.2.1 Delivery performance errors

As mentioned in (Artillery Manual, 1999), for a standard shot, the influencer parameters that cause deviation in the range are MV, projectile weight, range wind, air temperature, air density and rotation of the earth while the parameters that affect deviation in deflection are drift, crosswind and rotation of the earth. Accordingly, when these parameters are equalised to the nominal values, the firing table is computed and corresponded to the standard conditions. The variation of standard condition is caused by two types of errors; firing condition error and ballistics error.

The indirect predicted delivery technique type, as described in Chapter 1, uses these error values to calculate firing data needed for the firing mission. The ballistics errors are controlled by the weapon characterisation practice, as described in paragraph 2.2, by reducing the variation in system components specifications. While, on the other hand, the firing condition errors are an unavoidable source of error that is dependent on firing situation, e.g. if the target is moving, weapon location error will occur.

Table 2-1 Types of performance errors

Source of Error	Type of Error	Symbol	Ballistic Phase
Ballistics error	MV variation	σ_{MV}	Launch
	Projectile properties variation	σ_{Proj}	Launch, In-flight
	Fuze functioning variation	σ_{Fuze}	In-flight
	Submunition clustering variation	σ_{Sub}	In-flight
Firing condition error	Weapon location variation	σ_{WL}	Launch
	Quadrant elevation variation	σ_{QE}	Launch
	Azimuth estimation variation	σ_{AZ}	Launch
	Metrological components variation	σ_{Met}	In-flight

Table 2-1 describes the types of weapon system performance errors based on the ballistic phase and the nature of the error. The ballistic phases illustrate that the subjection of firing accuracy to human error during the launch phase where the system components are exposed to human operator in conjunction to, firing condition attribution during the in-flight phase where the system components are manipulated by varying atmospheric conditions (Fann, 2006). This research focuses on the contribution of the ballistic errors as variations in system specification to the performance of the defined weapon system.

For predicted firing, NATO standard (STANAG 4635, 2008) stated main equations where impact accuracy and impact dispersion (consistency) are subjected to these errors, as followed (subscript R,acc and D,acc represent accuracy deviation in range and deflection and R,disp and D,disp represent dispersion deviation in range and deflection, respectively):

$$\sigma_{R,acc}^2 = \sigma_{R,MV}^2 + \sigma_{R,Proj}^2 + \sigma_{R,Fuze}^2 + \sigma_{R,Sub}^2 + \sigma_{R,WL}^2 + \sigma_{R,QE}^2 + \sigma_{R,Met}^2 \quad (1)$$

$$\sigma_{D,acc}^2 = \sigma_{D,Proj}^2 + \sigma_{D,Sub}^2 + \sigma_{D,WL}^2 + \sigma_{D,AZ}^2 + \sigma_{D,Met}^2 \quad (2)$$

$$\sigma_{R,disp}^2 = \sigma_{R,MV}^2 + \sigma_{R,Proj}^2 + \sigma_{R,Fuze}^2 + \sigma_{R,Sub}^2 + \sigma_{R,WL}^2 + \sigma_{R,QE}^2 \quad (3)$$

$$\sigma_{D,disp}^2 = \sigma_{D,Proj}^2 + \sigma_{D,Sub}^2 + \sigma_{D,WL}^2 + \sigma_{D,AZ}^2 \quad (4)$$

Equation (1) and (2) show deviation errors from the standard condition in both range and deflection axes (X and Z) and causing MIP shifted from the aiming point, also called true point of impact (TPI). This shifted value is the quantity of weapon delivery accuracy. From accuracy viewpoint, the range is ballistically function of muzzle velocity magnitude, projectile weight and conditionally a function of metrology (MET) tailwind component. While the deflection is a function of projectile properties and crosswind component. In the other hand, equation (3) and (4) show the errors that cause dispersion from MPI in range and deflection axes. The quantities that affect range and deflection in dispersion are the same in accuracy accept MET conditions which are not considered as contributing to the dispersion error (Driels, 2013). Driels illustrated that “it is assumed the rounds are fired quickly and whatever MET conditions are applicable at that time do not change significantly from one round to another”. The variations for each source of error can be described as follow:

2.2.1.1 Types of delivery performance errors:

I. Muzzle velocity variation (σ_{MV}):

It is the variability appears in plus and minus meter per seconds for a specific weapon system configuration and caused by lots of factors from the manufacturing of system components (charge and projectile) and firing operation (Hunt, 1951). These factors are critically examined in a separate section.

II. Projectile properties variation (σ_{Proj}):

The projectile properties are mainly defined into two parts of errors:

I. Weight and geometry errors which are an independent source of errors caused by tolerances in manufacturing of the projectile mass and shape.
II. Trajectory calculation errors. This error decreases the performance of the projectile during flight and is problematic to measure since it is reliant on the uncertainty of the atmospheric conditions. To correct this kind of error, aero-ballistic coefficients of the trajectory computation can be calibrated with empirical fitting factors from actual firing data (Baranowski, 2013).

The variability of projectile properties (weight) is covered in the next section in more details.

III. Fuze functioning variation (σ_{Fuze}):

Depends on the type of fuzes such as proximity, time fuze and time of flight of the projectile, which actuates the fuze function, differs by correspondent changes in trajectory computation parameters like metrological components variations. For example, the time fuze timing set will be different from the actual time of flight; also, the proximity fuze burst will be different from the desired burst height (Vural, 2012).

IV. Submunition clustering variation (σ_{Sub}):

This type of error relates to a special type of munitions that contain clusters and have the dissemination of destructive effect on the target. The error occurs when there are differences in height and time of the release of the submunition where the footprint of the clusters causes a reduction in terminal effect performance (Gite, Anandaraj, Deodhar, Joshi, & Rajan, 2017).

V. Weapon location variation (σ_{WL}):

The target location is an independent variable to the weapon location in some applications such as moving platform, i.e. self-propelled artillery. This type of errors shifts the assumed location (aimpoint) from the TPI at a particular time. Thus, improving target acquisition will accommodate this type of error by which the measurement noises of the target location reduces (Chernick, 1980).

VI. Quadrant elevation and azimuth estimation variation (σ_{QE}), (σ_{AZ}):

The errors that can take place on the firing elevation are due to several factors including human errors, equipment errors, gun jump errors etc. (STANAG 4635, 2008). If the elevation varies from the nominal value, the projectile will mis-track the correct trajectory, and this is highly potential in low angle firing when the barrel approaches closer to the horizontal axis of the ground. In this situation, the recoil force and muzzle blast will differ and shift the line of departure of the projectile from the line of elevation (Artillery Manual, 1999). These two types of errors generate vector error called aiming error which is computed as TLE (Driels, 2013).

VII. Metrological components variation (σ_{Met}):

The instantaneous atmospheric condition of the projectile while it holds the trajectory is one of the most influential parameters to the accuracy of the weapon. Components like air density, air temperature and wind vector changes cause variations in both range and deflection coordinates. For example, a tailwind can move the MPI backwards or forwards while crosswind can drift the projectile right or left side of the MPI. In addition, air density and temperature changes along the trajectory path can change the drag forces behind the projectile (Artillery Manual, 1999). Error in this relation appears when the metrological massage instrument positioned far from the actual trajectory and/or the time between the instrument and the gunnery operator is delayed (Bellucci, 1961) leading to incorrect computational input parameters.

The relationship among these variations to the overall accuracy and dispersion errors is based on root sum of squares (RSS) where the square operator, in (1), (2), (3) and (4), removes the inverse relationship to the result and only influenced by the magnitude of that specific error source (Willmott & Matsuura, 2005). Furthermore, RSS is a widely used method of measuring average performance in the units of the variable of interest, so, by isolating different portions of error sources, they would be examined separately. This conclusion is true when there is no correlation of the error source to the other error sources (STANAG 4635, 2008).

The partial derivatives can be computed numerically in (5) using a trajectory computation for various values of each source of error in accuracy and dispersion where S_i is the source of error.

$$\sigma_R^2 = \sum_{i=1}^{n} \sigma_{Si}^2 \left(\frac{\partial R}{\partial S_i}\right)^2 \tag{5}$$

where

R: Range [m]

σ_R: Standard deviation of total error in range [m]

S_i: Source of error [-]

Equation (6) associate the change in deflection error to the change in range error where empirical fit coefficients a_0 and a_1 are gathered from real firing data from the field for a specified charge-projectile-gun configuration (Driels, 2013).

$$\sigma_D^2 = \left[\frac{a_0}{1018.59} \times \frac{a_1 \partial D}{(a_1 - QE)}\right]^2 \quad (6)$$

where

σ_D = Standard deviation of total error in deflection [m]

α_0 and α_1 = Empirical coefficients of deflection determining [-]

QE = Quadratic elevation [mil]

2.2.1.2 Delivery performance calculations:

The accuracy of delivery is, as stated before, the distance of MPI to the aiming point. On the other hand, dispersion is defined in the form of standard deviation and can be represented to describe how wide the impact points are scattered around the MPI. The so-called probable error (PE) is the distance from the mean where 50% of the population is expected. As an example, for range, it is expected that 50% of all the shots fired at a target should impact between - PE_R and + PE_R from the mean point of impact. Too, for all practical purposes, it is assumed that 100% of shots fired at a target will impact between -4*PE_R and +4*PE_R. This defines the 100% zone. The weight of PE can be described statistically as in Equation (7).

$$PE_R = 0.6745 \times \sigma_R \quad (7)$$

where

PE_R: Probable error [m]

When the two dimensions (range and deflection) are considered, and the standard deviations for the two dimensions are the same the zone in which 50% of the impacts are expected is described as a circular the so-called circular error probable (CEP). The radius of this circular is often referred to as the CEP and the relation between the CEP, and the standard deviation in any of the two dimensions (being the same) is given by Equation (8) and shown in Figure 2-2.

$$CEP = 1.17741 \times \sigma_R \quad (8)$$

where

CEP: Circular error probable [m]

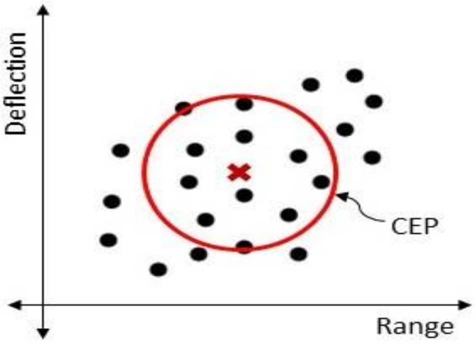


Figure 2-2 Circular error probable

If the standard deviations for the two dimensions are not the same, the 50% zone is described by an ellipse, and the description becomes more complicated to draw the coverage area. It is, however, still possible to define a CEP. The Pitman's equation gives a good approximation for this CEP in terms of equivalent circular error probable (ECEP). There are several equations for ECEP, but the common ones in use within the artillery community are asfollows:

I. For circular distributions, the general Equation (9) can be used and represented in Figure 2-3 (however, if σ_R is more than 10 times the σ_D then Equation (9) is not valid):

$$ECEP = 1.1774\left(\frac{\sqrt{\sigma_R^2 + \sigma_D^2}}{2}\right) \quad (9)$$

Where

$ECEP$: Equivalent circular error probable [m]

II. For elliptical distributions, (where σ_R is significantly different to σ_D there are several equations that can be used:

$$ECEP = (0.587 + .535\alpha + 0.052\alpha^2) \quad (10)$$

where

$\alpha = \frac{\sigma_R}{\sigma_D}$

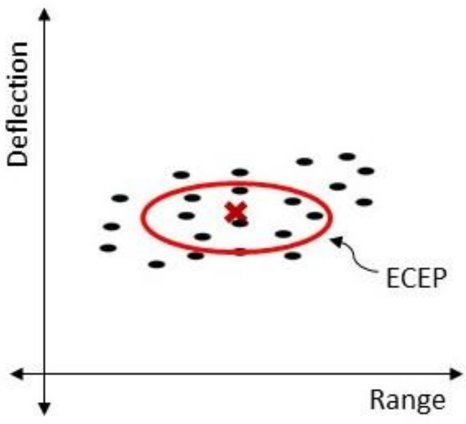


Figure 2-3 Equivalent circular error probable

III. For artillery in general, providing σ_R is no more than five times σ_D the above equations for ECEP will provide a reasonable estimate of the error. If this is not the case, then the value of ECEP may not be representable.

If all the above methods are not applicable to estimate the correct value of accuracy and dispersion, the method of enclosing rectangular is desirable to use (Sherif & Kheir, 1981). The method of enclosing rectangle takes off the connection between the value of range axis and the value of deflection axis where there is no influence of one axis to the another and Equation (6) is not applicable. This method shown in Figure 2-4 counts the scatter points between two perpendicular lines along the range axis and then separately along the deflection axis.

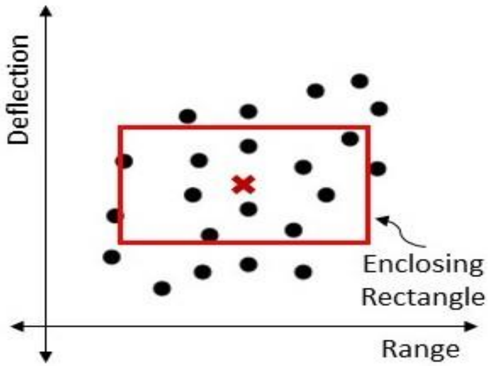


Figure 2-4 Enclosing rectangle

2.2.1.3 Isolation of delivery performance formulation:

After examining different types of errors and their causes, the equations (1), (2), (3) and (4) can be reduced in order to investigate the ballistics influence on the system, as explained in paragraph 1.2, where the MET and firing condition parameters are eliminated, $\sigma_{Met} = \sigma_{QE} = \sigma_{AZ} = \sigma_{WL} = 0$. Furthermore, since predicted firing technique for a unitary round is used for this project, $\sigma_{Fuze} = \sigma_{Sub} = 0$. Hence, the new equations can be described as the following:

$$\sigma_{R,acc}^2 = \sigma_{R,MV}^2 + \sigma_{R,Proj}^2 \quad (11)$$

$$\sigma_{D,acc}^2 = \sigma_{D,Proj}^2 \quad (12)$$

$$\sigma_{R,disp}^2 = \sigma_{R,MV}^2 + \sigma_{R,Proj}^2 \quad (13)$$

$$\sigma_{D,disp}^2 = \sigma_{D,Proj}^2 \quad (14)$$

A study has been held (NATO, 1998) showed the partial contribution of error sources variations to the accuracy of the indirect fire artillery projectile by both ballistics and firing condition errors as follows: 65% of the error due to MET, 23% due to external ballistic variability and 10% muzzle velocity variability (MVV), with 2% due to other effects. An approximation of σ_R and σ_D on this study can conclude that the contribution of σ_R is approximately 3.3 times the σ_D. Another paper has showed, (Matts & ELllis, 1990), that the contribution of projectile and charge dissimilarity to PE_R is 70 m when σ_{MV} is 0.83 m/s. This value of prediction is investigated through the discussion in Chapter 4.

2.2.2 Ballistics parameters variation

For any ammunition (charge and projectile) that is in use of military forces should meet strict safety and operational requirements. However, unmaintainable variations can occur during the manufacturing processes as well as the operational conditions of this ammunition. According to (Hunt, 1951), for charge and projectile, the ballistics properties differ from batch to batch with the progress of time. These changes include, but not limited to, gradual changes due to process quality (i.e., extrusion of propellant grain and projectile weight) and discontinuous changes due to changes in the supply of raw materials and different manufacturing machines not being identical.

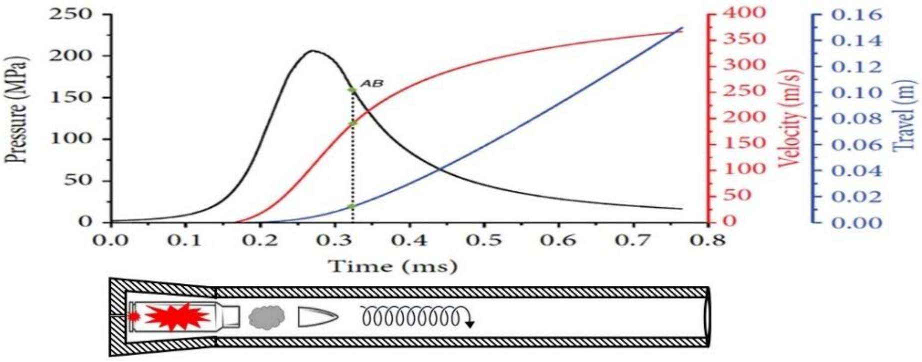


Figure 2-5 Pressure, velocity, travel-time curve (Carlucci & Jacobson, 2007)

The variations of the ballistics parameters cause the all-burnt point to move outside the specifications, which lead to the system to be inaccurate. The aspect of the All-Burnt point, as shown as (AB) in Figure 2-5, is the time since ignition when all the propellant has been burned, i.e. converted to the gas phase. The burn rate of propellants is pressure-dependent, and with a fast-burning propellant, the burnout will occur too early while with a slower burning propellant, it will occur too late. It depends on the burn pattern (progressive, regressive or neutral) that is required to meet the specified mV. Loading condition is the human factor when the charge's parameters are designed to be changed. The department of defence (DoD) of Canada, (Field Artillery, 1992), published approximation variations of these parameters to the maximum pressure and MV for a typical IB sub-system. Table 2-2 shows the causes of loading conditions to the outputs of the IB sub-system (155 mm artillery system).

Table 2-2 Approximation variation due to charge in loading conditions (Field Artillery, 1992)

1% increase	% variation in MV	% variation in maximum pressure
Projectile weight	-0.40	+0.60
Charge weight	+0.60	+1.60
Chamber capacity	-0.25	-1.15
Propellant size	-0.15	-0.85

The DoD of Canada and the US Army Research Laboratories (ARL) have done studies showing the effective parameters causes to the accuracy of the IB system. These two studies explored a variety of different IB parameters and will be reviewed in this section (Field Artillery, 1992), (Schmidt, Nusca, & Horst, 2009). The sensitivity analysis done by ARL has been experimentally performed on 120mm mortar gun (charge 2 and charge 4 only) with multi-dimension modelling code while DoD of Canada handled a variation study described gun-launched IB sub-system.

Correlations of model inputs and outputs can be driven through complicated computational methods or even by statistical techniques to represent the influence of each input or combination of inputs to the model output. A sensitivity analysis has been done to determine the degree of effectiveness of the inputs to the outputs (Schmidt et al., 2009). As seen in Figure 2-6, the most influential ballistics parameter to the peak pressure is the charge weight while the most one to the MV is the burn rate exponent. This exponent is a propellant composition constant that is determined chemically. Whereas, the least influence ballistic parameter to the peak pressure is the force of the combustion reaction inside the gun chamber while the least influence ballistics parameter to the MV is the burn rate coefficient.

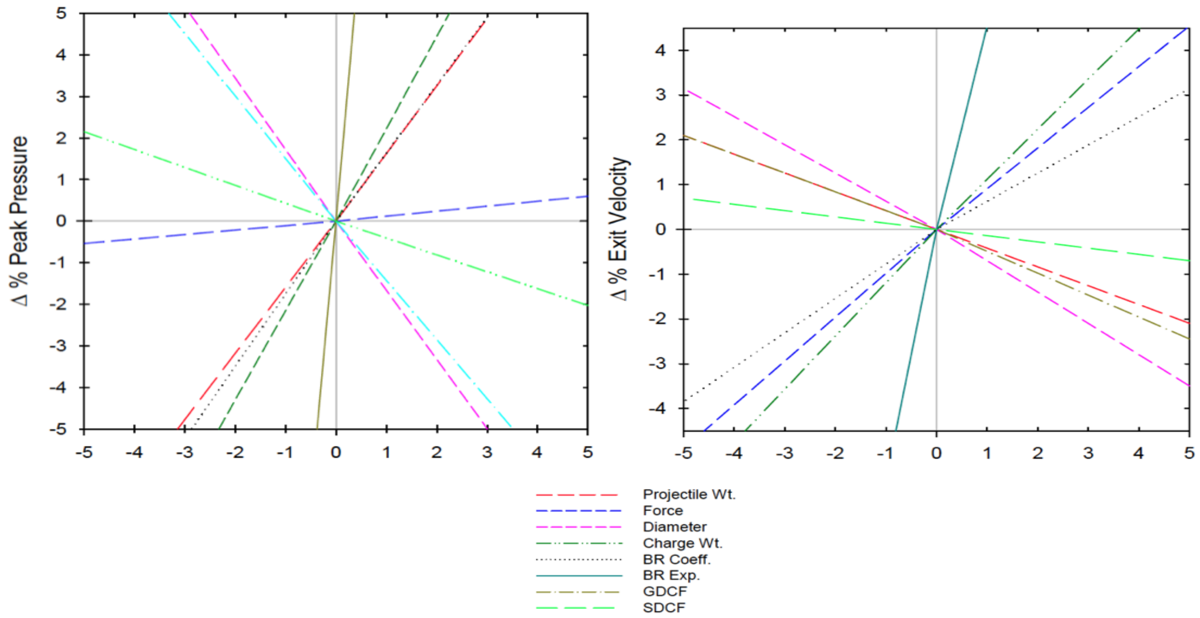


Figure 2-6 Sensitivity correlation to different IB system parameters (Schmidt et al., 2009)

With taking consideration that the MV is dependent output parameter, a unique statistical technique is requested to analyse these correlations. Conclusively, the IB output functions which are represented by the vertical axis are functions of the IB input parameters. The relationship among these parameters can be determined by many methods (e.g. regression coefficients).

2.2.2.1 Charge properties:

The dimension of propellant grains that has the lowest mass and characterised to produce the required MV without reaching the maximum operating pressure of the weapon system utilises the charge design. A propellant composition and configuration that burns too fast (generate the gas at a too rapid rate) creates a destructive pressure spike that usually has a concise duration. Using a propellant that burns too slowly produces poor energy transfer and leaves a lot of unburned propellant slivers, (Acharya, 2009). Slivers are a small section of the propellant that has not burnt out completely, which may cause erosion to the barrel.

According to (Hunt, 1951), and (Field Artillery, 1992), weapon system design begins with the propellant energy required to provide the projectile with the MV needed. Propellant grain geometry and chemistry are then chosen to satisfy this energy requirement. In order to comply with all the requirements of a gun system during the total life cycle, a solid propellant should ideally possess the following properties:

1. Ballistic performance regularity.
2. Absence of smoke, muzzle flash, poisonous fumes and residue.

3. Minimum erosion of the bore and chamber.
4. Ease of ignition.
5. Stability in storage under any conditions, insensitivity to shock and friction.
6. Non-hygroscopic (does not tend to absorb moisture from the air).
7. No tendency to detonate when used in a gun.
8. Rapid, easy and safe to manufacture.
9. Maximum power for minimum bulk.

A frequent objective during charge development for a given weapon system is to optimize the performance parameters within the above system requirement, operational and safety boundaries. To optimize such a system is not a trivial exercise because of the propellant nature, which may traditionally be influenced by any inconsiderable change in its signification. This sensitivity is a result of variations in manufacturing processes of charges, projectiles and different conditions of its operation.

The all-burnt point is the main objective to be achieved in the IB sub-system in order to maintain the desired MV with minimal peak pressure. The solid lines in the below graphs, Figure 2-7, Figure 2-9 and Figure 2-10, represent the P-t curve for the typical IB sub-system while the dotted lines represent the P-t curve after loading condition of each parameter.

I. Charge weight

Naturally, if the charge weight increases, more gases will be released and increase the peak pressure of the combustion. As a result, the all-burnt point may be shifted back, causing the propellant not to burn when the projectile leaves the gun (Field Artillery, 1992). The sensitivity of the changing of the charges' weights to the peak pressure and MV is represented by correlations graphs shown in Figure 2-8, (Schmidt et al., 2009). According to the results of the DoD field artillery document, it is seen that the variations of the charge's weight have the most influence on the other parameters.

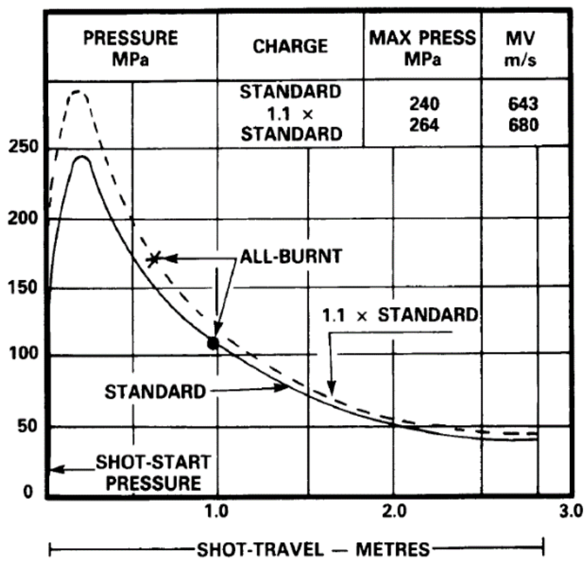


Figure 2-7 Variation in charge weight (Field Artillery, 1992)

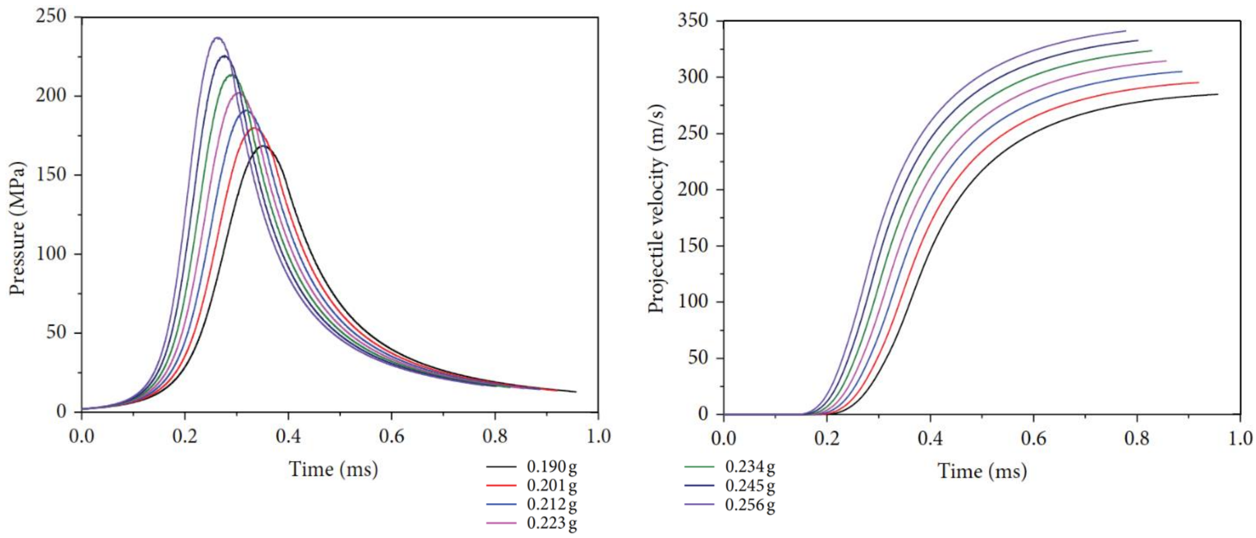


Figure 2-8 Effect of variations of charge weight (Bougamra & Lu, 2014)

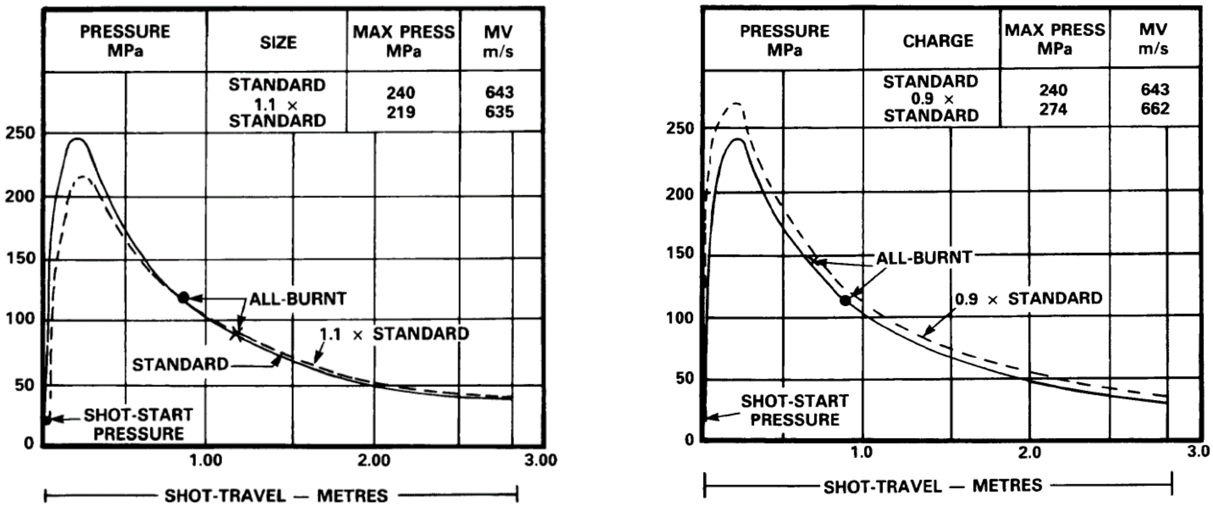
With the tolerance of 1.6 MPa in the peak pressure and 0.6 m/s in MV, the ratio can be manipulated to meet the desired specification. This relationship means the higher the charge weight, the higher the MV with considering that it may reach the pressure limit of the gun. A parametric study has been covered on small arms calibre, 9 mm cartridge, with a 2-D simulation model to analyse the effect of the charge mass to the IB outputs (Bougamra & Lu, 2014). PV-t curves are illustrated to describe variances of masses to the base pressures and the exit velocities in Figure 2-8.

Table 2-3 Effect of weight charge on IB performance (Bougamra & Lu, 2014)

	Solid propellant mass [g]					
	Min. 0.190	**0.201**	**0.212**	**0.223**	**0.234**	**Max. 0.243**
Max pressure [MPa]	169.13	180.52	191.76	203.04	214.53	226.56
MV [m/s]	284.76	295.35	305.09	314.48	323.54	332.72
Shot exit time [ms]	0.957	0.920	0.887	0.857	0.829	0.802

II. Propellant size

An increase in propellant size causes a decrease in the total initial burning surface, a lower peak chamber pressure, the all-burnt point is further forward, and MV could be lower (Field Artillery, 1992). From a ballistic viewpoint, the best propellant grain size is that which, with the smallest charge mass, will impart the required velocity to a projectile without exceeding the maximum pressure of the weapon system.



(a) Grain size increase **(b) Grain size decrease**

Figure 2-9 Variation in grain size (Field Artillery, 1992)

A sensitivity study article has been written on a 155 mm artillery gun to show the influence of the propellant grain size on the IB outputs. Table 2-4 displays the variations in percentage from the reference case values with max pressure of 163.1 MPa and MV of 665.1 m/s. "variations of − 0.9% in the diameter of propellant grain result in variations of +2.8% in the maximum pressure and decrease of − 6.2% in the MV" (Velasco, 2017).

Table 2-4 Effect of grain size on IB performance (Velasco, 2017)

	Size 1		**Size 2**		**Size 3**		**Size 4**	
Length & Diameter [mm]	***L*** **11.46**	***D*** **5.46**	***L*** **10.86**	***D*** **5.50**	***L*** **11.25**	***D*** **5.47**	***L*** **11.60**	***D*** **5.55**
Max pressure [MPa]	2.8		1.2		3.5		4.7	
MV [m/s]	-6.2		-6.6		-5.7		-5.3	

III. Propellant shape

For a single propellant grain, the number and size of the perforations (holes) of the are essential dimensions in determining the gas generation rate and therefore the vivacity of propellant. The vivacity of propellant is the rate of gas generation per time unit. It is vital to have control of the propellant grain dimensions during the propellant manufacturing process to ensure similar gas generation for each one. DoD of Canada released the difference among cord, tubular and multi-perforations grains and how the peak pressure reduced and become flatter.

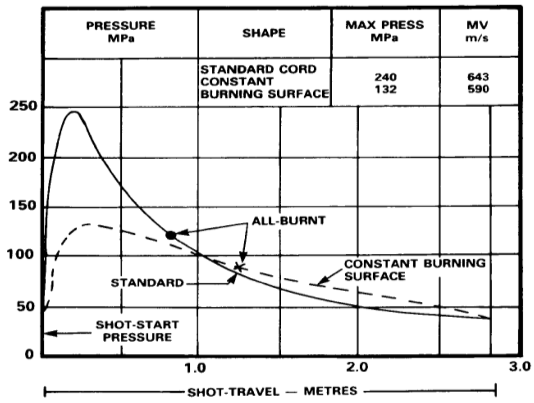


Figure 2-10 Variations in grain shape (Field Artillery, 1992)

Another perspective of a variation of the shape is when the dimensions of different grains vary within the same charge. Usually, any propellant charge uses the same shape but with different perforations dimensions. This variation is due to failures in the manufacturing process of the propellant grains, which cause different holes lengths. A study has been handled on 155 mm artillery gun. It is based on a statistical analysis of varying the grain shape dimensions to observe the tolerances on the IB sub-system outputs. The difference between perfect and non-perfect grains can be shown in Table 2-5.

Table 2-5 Effect of shape variation on IB performance (Pocock, Locking, & Guyott, 2004)

	Perfect grains	**Non-perfect grains**	**Difference**
Max pressure [MPa]	378	368	2.5%
MV [m/s]	875	856	2.0%

2.2.2.2 Projectile properties:

As shown in Figure 2-11, when the projectile weight increases, it requires more pressure to move it forward to the muzzle, which means it needs more pressure. The peak pressure increases, and progressive distribution of the gas spread widely.

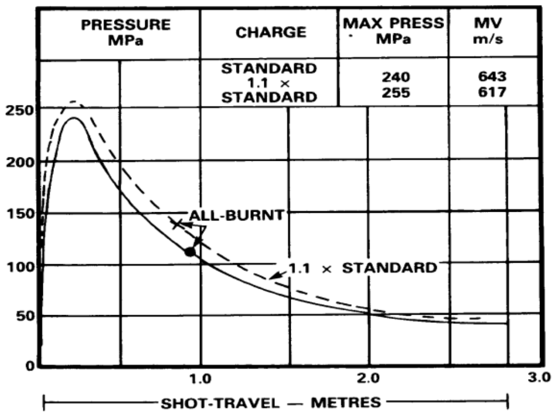


Figure 2-11 Variations in grain shape (Field Artillery, 1992)

2.3 IB sub-system

The process behind designing a robust weapon system is to develop and integrate system components with compatible specifications. Therefore, it is important to perceive that any conventional weapon system consists of main parts which handle the propulsive process from the time the propulsion reaction take place until the projectile leaves the gun. These parts can be shown in Figure 2-12. Besides, there are some auxiliaries which can be fitted to the gun to support the propulsion process and improve the stability of the projectile such as recoil system and muzzle breaks. To represent the IB sub-system schematically, its major components are listed as bellow, (Field Artillery, 1992):

1- Breech: the back of the gun that closes the end of the tube to support the burning reaction to propel the projectile.
2- Primer: the initiation component of the burning of propellant.
3- Charge: the combustion agent that generate rapid gases to propel the projectile.
4- Chamber: the volume that confined the burning reaction until the projectile start to accelerate.
5- Projectile: the shot which carry the terminal effect of the weapon system.
6- Bore: the internal cylindrical path from the end of the chamber throughout the muzzle. The dimension of the bore describes the calibre size of the gun.
7- Muzzle: the place at the end of the weapon in which the projectile comes out from the gun.

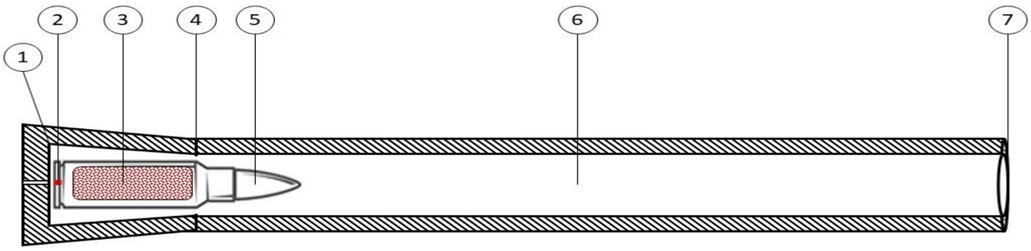


Figure 2-12 IB components

A typical sequence of events, (Field Artillery, 1992), that happens in the tube on firing a gun can be viewed in Figure 2-13 and described as follows:

1- Striker hits the primer to start the ignition. The propellant burns but still slow because of the pressure in the chamber is low, changing combustion energy into hot gases.
2- The gas pressure in the chamber behind the projectile base rises. Specifically, gases from the surface of propellant grains continue to build pressure in the chamber, causing gas progression more rapidly because the burning rate raised.
3- Enough pressure comes to a point to succeed driving band engraving resistance, the structural support of projectile to align to the bore, and the projectile quickly moves down the barrel. After that, the chamber volume behind the projectile rises, decreasing the rate of pressure rise slightly. Maximum pressure is reached when the pressure is matched because of gas evolution by the drops of pressure because of expanding in the chamber volume. Then, pressure starts to decline gradually, while chamber volume is quiet increasing quickly, but gas continues to grow because all the propellant has not been consumed yet. The projectile continuous to move along the bore.
4- The projectile leaves the gun tube with a magnitude of MV.

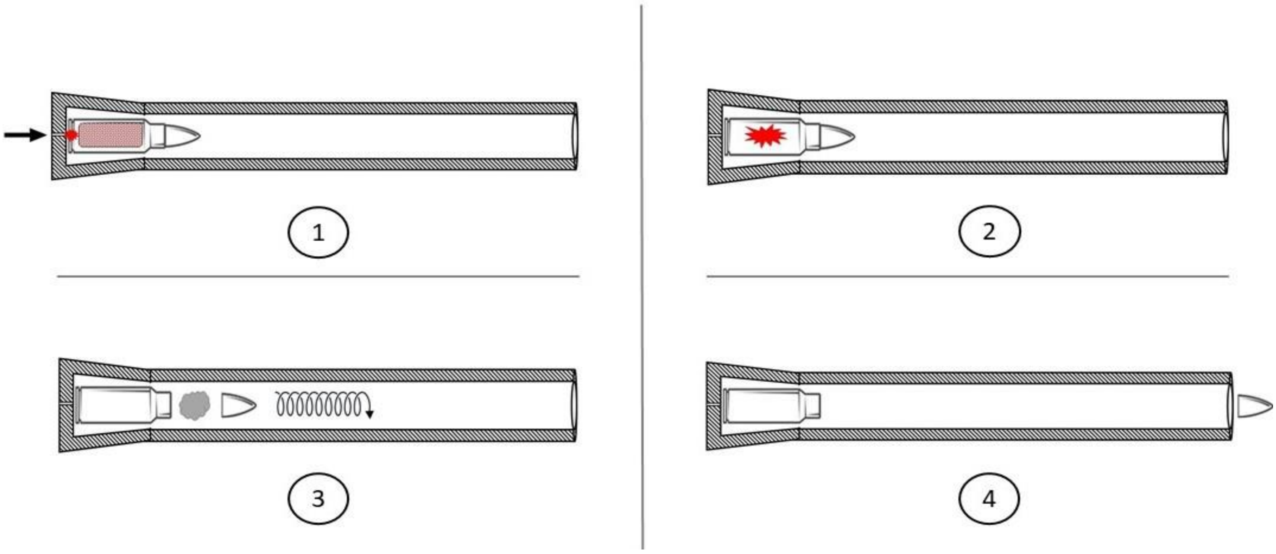


Figure 2-13 IB cycle sequence

2.3.1 IB design considerations

The factors that affect the IB performance (pressure and velocity) differ from gun to gun and depend on the configurations and properties of the charge and the projectile. The capacity of the propellant, which is a function of chamber size and shape, case construction, and bullet seating depth limit the maximum pressure of the propulsion reaction. After that, the relative burning rate and burning characteristics of the propellant used characterise the behaviour of the gas generation. The amount of propellant used and how much it fills the chamber (load density) determine the value of maximum pressure. From the projectile viewpoint, diameter, weight, and the bearing area inside the bore can regulate the movement of the shot and how quick can it exit the gun. For the gun, length and interior dimensions of the barrel govern the limitation of all IB processes. Also, uniformity and speed of ignition of the propellant (primer and loading density related) save the propulsion burning from any scattered behaviour as well as the temperature of the propellant prior to ignition. Last, projectile resistance to travel in the bore is another compelling factor, and that can be maintained by designing a suitable driving band around the back of the shot, (Moss et al., 1995).

By considering the pressure, velocity, travel-time curves in Figure 2-5, a steep increase in chamber pressure can be seen which occur over a very short time as the weapon is fired (milliseconds). Figure 2-14 shows different pressure-time curves for different weapon systems. It can be seen that the large calibres, i.e. howitzers and mortars, have a widespread along time axis compared to the small calibres. The shape of the pressure-time (P-t) curve can be modified by controlling the energy released from the burning of the propellant. This modification is done by characterising the chemical and physical properties of the charge’s propellant. Indeed, the burning rate shows how fast is the propellant burning and the dimensions of the propellant shows how much is it burning (Gonzalez JR., 1978). To understand this more, the manipulation of this curve can be controlled by sensing the distribution of the energy within the IB process.

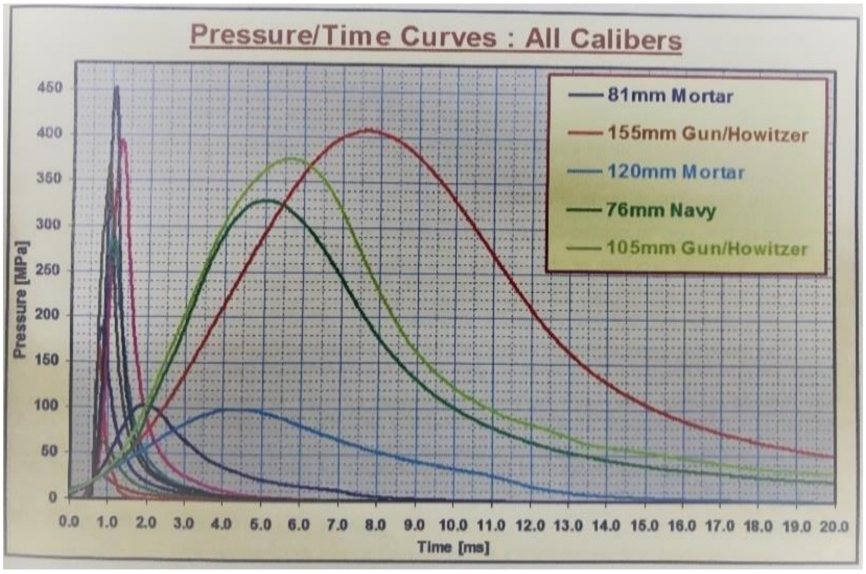


Figure 2-14 Pressure-time curves of different calibre (Moss et al., 1995)

As propellant burns, a considerable amount of hot gases released, causing energy to change its form. Not all the chemical energy in the combustion reaction is effectively utilised to kinetic energy. The bulk of this energy is lost in the form of heat retained by propellant gases. According to (Agrawal, 2010) and (Moss et al., 1995), The energy distribution in conventional weapons is giving as in Table 2-6.

Table 2-6 Energy distribution in typical weapon system

Energy	Loss
Total work done on projectile	34.1%
1. Kinetic energy of the projectile	32%
2. Rotation of the projectile	0.1%
3. Frictional losses	2%
Energy in the recoiling parts	0.1%
Translation of the propelling gases	3%
Heat loss to barrel and projectile	20%
Sensible and latent heat losses in gases	42%
Total	99.2%

Hence, most of the energy is unusable to give an efficient propulsion system. Around 42% is lost in the form of hot gases, and this is since the projectile is moving and leaving more chamber volume behind. In other words, the generation of hot gases cannot be fully utilised to pressure because of the movement of the projectile. Moreover, it is unavoidable energy loss based on the laws of thermodynamics: “the pressure in the gun barrel can be expended only by the cooling of the combustion gas to the atmospheric temperature”, (Agrawal, 2010). For rough estimations of ballistic systems, a ballistic efficiency (ε_B) is of interest. It is the amount of the kinetic energy extracted from the total heat energy of the propellant for a specific weapon system. Another preliminary indication and method to determine the expected performance of the IB sub-system is based on the concept of the average pressure to maximum pressure ratio, called the pressure ratio or piezometric efficiency (ε_P) and defined by the following equation (Moss et al., 1995):

$$\varepsilon_B = \frac{Muzzle\ energy\ of\ projectile}{Total\ heat\ of\ propellant} \times 100 \tag{15}$$

$$\varepsilon_P = \frac{Average\ pressure}{Maximum\ pressure} \times 100 \tag{16}$$

Where

ε_B: Ballistic efficiency [-]

ε_P: Piezometric efficiency [-]

For maximum energy transfer to the projectile with the resulting maximum MV, the charges should burn out just before the projectile leaves the barrel. Overpressure that cannot be handled by the gun is reached if all-burnt point occurs early, and if it occurs too fast, it will not ensure the desired MV. “Therefore, the ideal position for the all-burnt is at a point of one-third of the way up the bore for 155 mm artillery system” (Field Artillery, 1992).

The previous comprehensive scheme of an IB system shows the importance of charge design and how it patterns all different weapon system components such as the operator, the gun, and the projectile. It all starts when army forces procure a new weapon system to fill their strategical capability gap by choosing a particular gun depends on thread type then match the propellant charge to deliver the projectile to its destination. In other words, the considerations of charge design are essential roots to meet other system components requirements. For instance, from army point of view, propellant shall be smokeless, flash-less and maintained in storage in different environmental conditions while from the gun point of view, propellant shall not cause any erosion to the barrel and ensure that it does not detonate in all operational conditions. Modern propellants maintain different projectile types and deliver different velocities for the same weapon system.

2.3.2 Propellant definition

Propellants must be distinguished from high explosives. In fact, it is considered as low-explosive energetic material of which the rate of combustion is low enough and its other properties suitable to permit its use as a propelling charge. By its character, the propellant linearly burns to start at the available surfaces and continue burning layer-by-layer until it is completely consumed, (Piobert, 1839). Indeed, burning of a propellant advance into the unreacted material at a velocity slower than the sonic velocity of the propellant, (Kubota, 2018).

The ballistic properties of a propellant charge depend on the rate at which gases are generated as the propellant burns. For the common purpose, it is sufficient to note that the ballistic properties are primarily controlled by the energy content and energy release of the propellant. The energy content is mainly a function of the composition of the propellant, which can be broadly coupled to the type of propellant, i.e. single, double or base. The energy release, however, is controlled by the burning rate of the propellant.

The burn rate which is a parameter that used to quantify the performance of the propellant in terms of burning characteristics, and includes propellant chemical composition, propellant burn rate and propellant grain geometry, can be expressed by a pressure exponent law, the so-called Vieille’s law in the following equation, (Kubota, 2018).

$$r = \beta P^n \tag{17}$$

Where

r: Burn rate [m/s]

P: Pressure [MPa]

β: Burn coefficient (or pressure index) [mm/s/MPa]

n: Burn rate exponent [-]

The coefficient of the burning depends on the initial temperature of the propellant while the burn exponent is a function of propellant formulation, (Agrawal, 2010). This chemical makeup will ultimately determine the amount of protentional energy available to produce propellant gas to propel the projectile.

The higher energy released by the propellant must be maintained since it produces a higher flame temperature. As a consequence, it results in barrel erosion and hotter gases leave the barrel at the muzzle. This outgrowth results in a fuel-air mixture above an ignition temperature, that gives muzzle blast and flashes and defined as losses to the system, (Moss et al., 1995).

2.3.2.1 Propellant grain geometry

The rate at which gas is released during the IB cycle is predominantly controlled by the morphological characteristics of the propellant grain, i.e. dimension, shape and size. Perforations in propellant grains are used for controlling the rate of gas generation, as well as the burning time of the propellant grains. Figure 8 and Figure 9 illustrate, for several shapes of propellant grains, the ratio of exposed burning area to initial grain area as a function of the grain consumed. Propellant grains burning with the slope of the curve below 1 are regarded as degressive, where the slope of the curve is 1 is regarded as neutral and where the slope is above 1 it is regarded as progressive burning curve, (Pocock et al., 2004).

The uniformity of the ballistic effect must also be taken into account in this connection. Depending on the initial shape, the surface area can increase, decrease or stay the same during the burning. This burning behavior allows for the design of the required surface burn area.

The propellant configuration, see Figure 2-15 and Figure 2-16, can basically lead to three types of burning progression namely, (Moss et al., 1995):

I. Progressive: if the burning surface increases as the grain burns, i.e. multi-hole grains.
II. Regressive: if the burning surface decreases as the grain burns, i.e. solid cord.
III. Neutral: if the burning surface stays constant as the grain burns, i.e. single-hole grains.

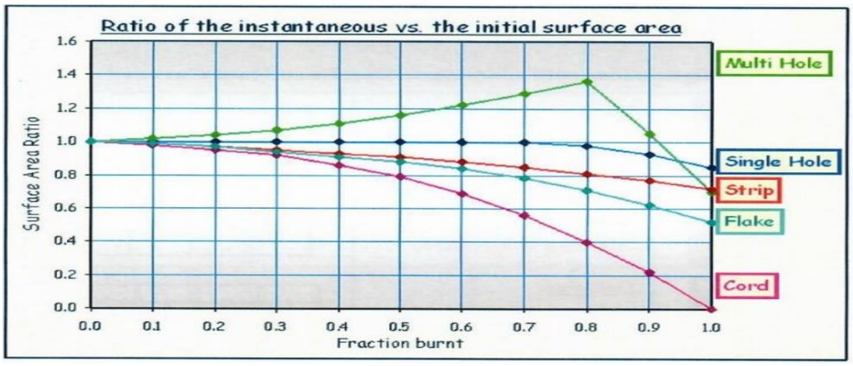


Figure 2-15 Instantaneous vs initial surface area of different propellant grains (Moss et al., 1995)

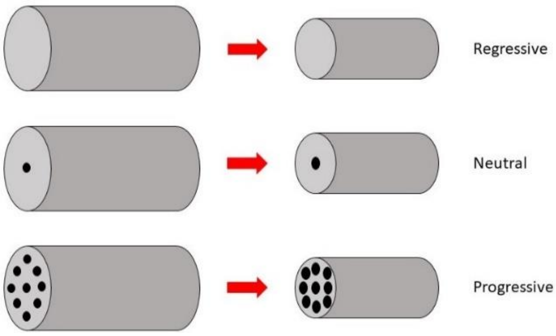


Figure 2-16 Burn behaviour of different propellant grains

The graph above, Figure 2-15, shows the amount of propellant burnt by comparing different shapes of propellant grain. By comparing cord grain with a multi-hole grain shape, it shows that the multi-hole propellant is consumed at a slower rate than the cord shape. Thus, for a given weight of a certain propellant, the initial burning surface will depend on the form and dimension of the grains. As burning continues, the rate of combustion will depend on the composition, how the burning surface changes (increase or decrease) and subsequently on the chamber pressure.

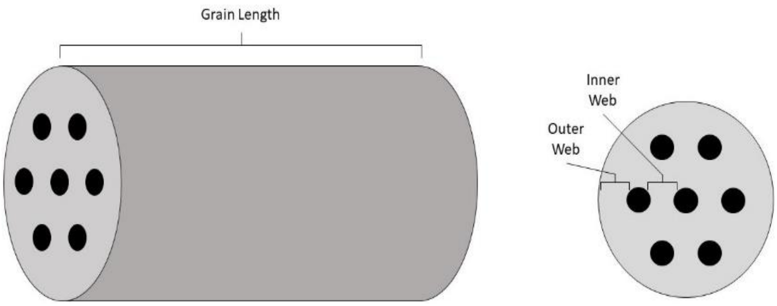


Figure 2-17 Propellant grain dimension

The most significant dimension is called web size. The web size (also called ballistic size) is usually the shortest distance between any two opposing surfaces from perforation. The burning characteristics of propellants can be influenced by way of changing the tolerance on the shape of the grains caused by grain inconsistence extrusion process.

2.3.3 Survey on IB models

The simultaneous study of pressure, temperature, velocity curves which are responsible for projecting the projectile out from the barrel, is a typical representative approach to the analysis of the effect of models' inputs. In the past, the conventional models were based on the chemical combustion reaction equilibriums inside the chamber. The outcomes of such models are entirely insufficient to represent sophisticated MACS, and only give an overall performance of the gun. For MACS, the realisation of the IB cycle requires a more accurate representation of the pressure wave. This is because of the dimension and shape of the charge modules where the grains are parted by the combustible cases and lead to propellant burning discontinuity as well as non-simultaneous ignition of the charge (Ma & Zhang, 2013).

Miner R said (Miner, 2008) "Closed-form solutions are convenient because they give you a basis of what parameters are important and how they can affect the overall performance of the launcher." A thesis has been written to compare a wide range of conventional and thermodynamic models. Figure 2-18 illustrates the error percentage of experimented and simulated results between the conventional and thermodynamic models (Miner, 2008).

2.3.3.1 Representation of different modern IB models

The new IB models are divided into two different categories, depending on the model approach of each one, lumped parameter and computational fluid dynamics (CFD) models. Figure 2-18 shows comparisons among different equilibrium and thermodynamic IB models. It can be seen that the equilibrium-based IB models result in errors higher than the thermodynamic-based models. Also, the lumped parameter model has the lowest total average percentage error among all IB models.

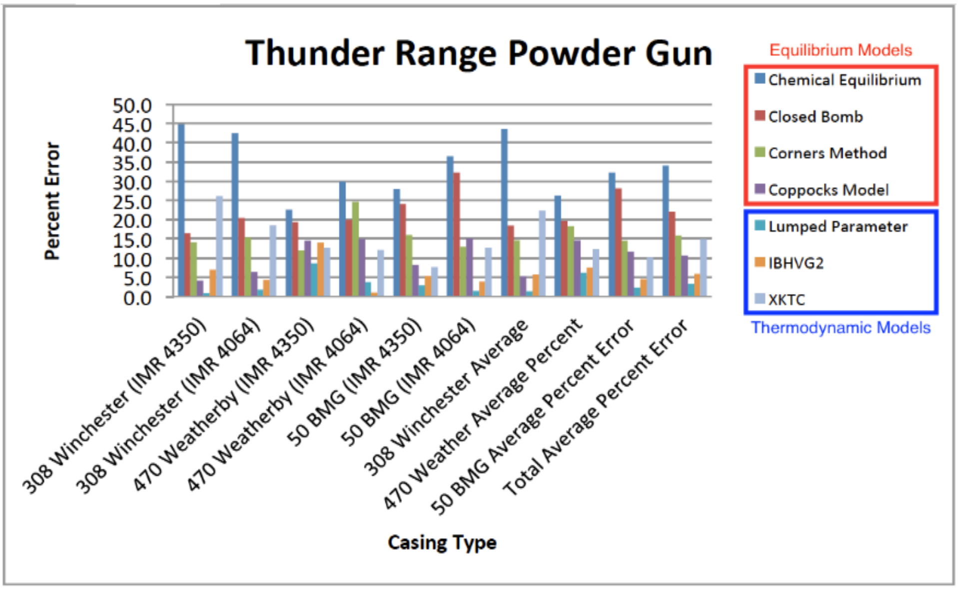
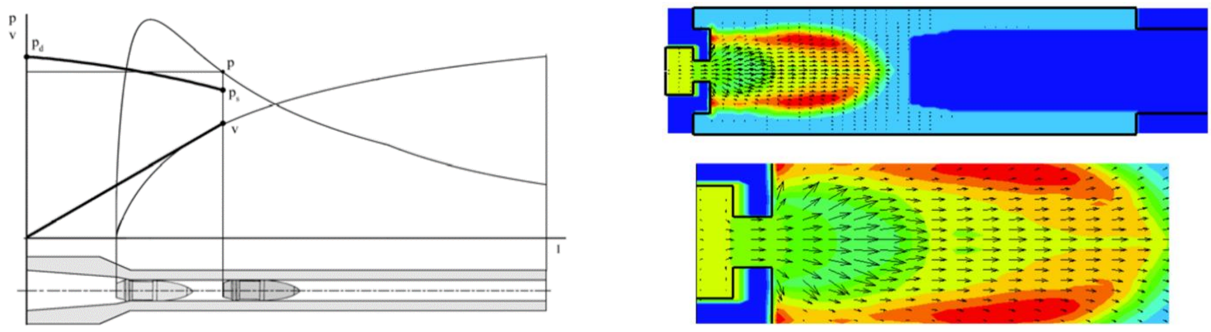


Figure 2-18 Percentage error of equilibrium and thermodynamic models (Miner, 2008)

The principle of lumped parameter models is based on the thermodynamic behaviour of the gases behind the projectile. Theoretically, it is the zero-dimensional (0-D) representation which analyses the pressure distribution between the gun breech and the projectile base under one control volume. Figure 2-19 (a) explains the difference between breech pressure p_d and base pressure p_s. On the other hand, the models of CFD, (b), have a different concept of representing the IB behaviour, more clearly; they have the capability of multi-dimensional (multi-D) representation when different ignition and loading processes are applied, by taking the consideration of the axial and radial changes inside the gun. CFD type is divided into two methods (Gollan, Johnston, Flaherty, & Jacobs, 2007):

- Separated flow theory that forms averaging technique over two separated flow of gases.
- Continuum mixture theory which treats the gas flow as one continuum flow of mixtures.



(a) Lumped parameter type **(b) CFD type**

Figure 2-19 Concept of modern IB models; (a) (Jedlicka, Beer, & Videnka, n.d.), (b) (Nusca, 2011)

Presently, numerous models have been validated through the various defence departments and military agencies in Europe and US. Configurationally, 0-D lumped parameter such as SNL, IBHVG2, and IBRGA; one-dimensional (1-D) axial change such as NGEN2 and XKTC; multi-D axial and radial change such as NGEN3 (Bougamra & Lu, 2014) consider different representations of the propellant charges that ensure the sufficient MV for each zone. The representation of different charges configurations is displayed in Figure 2-20.

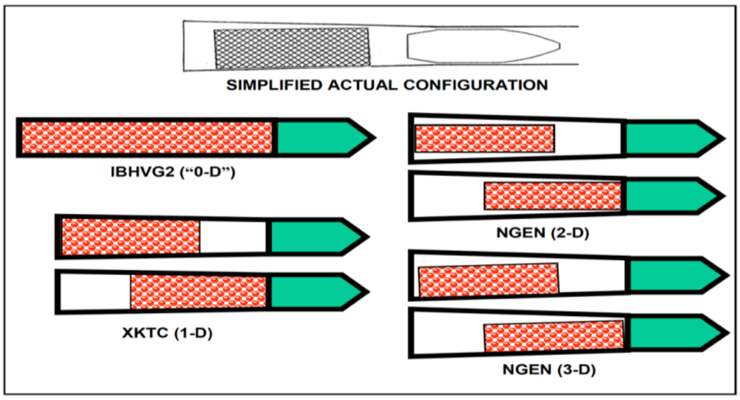


Figure 2-20 Representations of different IB models (Horst & Nusca, 2006)

2.3.3.2 IB models as diagnostic tools

"The number of dimensions is not the only factor that determines the applicability of a model" (Toit, 2001). The capability of each type lies on its mathematical formulation and the proportionality of model inputs to the outputs.

First, the general uses of 0-D IB models are to predict the global parameters such as maximum pressure and MV; implying that, the performance of IB sub-system can be determined by implementing this type of models. These predictions are due to the reliability of the model outcomes to the inputs. For example, the burn rate of propellant grains is indirectly proportional to the determination of the pressure inside the combustion chamber. 0-D models are the least accurate ones among the IB models, but they are enough for sensitivity applications.

Second, 1-D models have the prediction capability as well as the ability to analyse the gases conductance within the gun chamber to identify potential overpressures. The results are more accurate, but the complexity of the models is higher, which may lead to adding correction factors to the model. For instance, when the propellant grains get larger or smaller, variations may occur and result in inaccurate predictions. This phenomenon is called interphase drag and can be reduced by manipulating charge configuration and adding correction factors (Woodley, 2001). Lastly, as the models become more sophisticated, multi-D are more accurate as a result of representing both axial and radial movements within the chamber. The method is to use CFD theory, dividing the IB cycle into a number of meshes, and apply microscopic representation of different considerations.

To summarise, multi-D models can bring the most accurate results but, categorically stating, to build this model is very complicated. Likewise, 1-D models can bring sights to analyse the behaviour of some charge components such as ignitors and combustible cases. However, this study contributes only to investigate the performance of the IB sub-system. The previous examination shows conclusively that the 0-D models, such as the lumped parameters are the best model to be used providing fast, indicative results to determine the performance of the IB sub-system.

2.4 System engineering methods for MACS

The need for formalising a model-based system engineering (MBSE) methodology to the MACS is to comprehensively structure this system by different layers (system phases) in order to enable the realisation through these split phases that allow prediction of the system overall performance. Different phases of a typical system engineering practice can be seen in Figure 2-21, namely, system definition, system implementation, system integration and system verification phases. Firstly, the **system definition phase** is through a top-bottom approach to translate the stakeholder expectation into specifications to establish characteristics of the system by which the performance is imprinted as a representative parameter. The stakeholder expectation, as an input to the system, is a more general description of the needs of artillery effectiveness outcomes. These outcomes are typical milestones of the MACS delivery, namely effective range and hit probabilities values, (US Army, 1986). By allocating the best technical requirements for each level of the system, subsequently, the system will easily architecture its characterisation in shape of specification and design baseline, and the stand-alone components are then successively designed employing the **system implementation phase**.

After constructing the top-bottom system definition process and configuration items (CIs) are designed per sub-system breakdown, the **system integration phase** is prepared based on the system configuration of the sub-system level which consolidates different CIs to restrict their design performance. CIs are the cannon, the projectile and the charge after they are configured to the MACS. Finally, the **system verification phase** is prepared based on the requirement specification of each level which reflects the systematic demonstration of the system right at the beginning of the development lifecycle against the requirements to ensure ultimate conformance to the specifications, (Kapurch, 2007), (Hitchins, 2007).

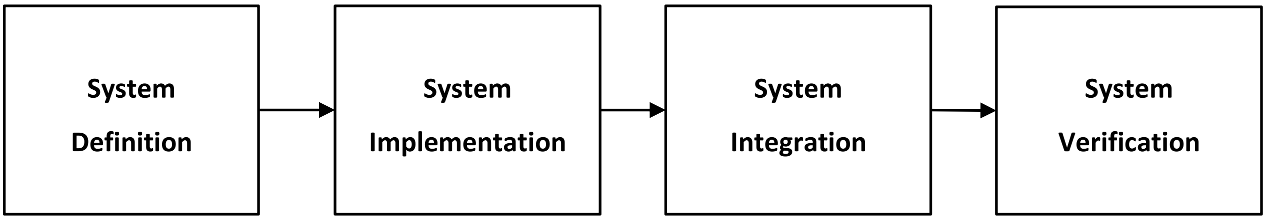


Figure 2-21 System engineering phases

The process of implementation for this research will go through the definitions of different CIs specifications in order to integrate them and through which MACS system verification processes verify them

Usually, and for interchangeability purpose of different countries from NATO, standardised cannon and projectile properties assign the constraints of the system while the charge properties are set to maintain the IB specification. In other words, and recall from chapter 1, TB objectives, and range requirements of the MACS are set then projectile weight and MV fulfil these system requirements (US Army, 1990). Therefore; in the next chapter, the research framework constructs the MACS in the way of setting fixed specifications of the cannon and projectile aerodynamics and applying varied specifications of the projectile weight and charge characteristics. Another variation which is considered is the operating variation of setting the charges inside the chamber done by the gunner which cause differences in the chamber volume leading to MV variations, (Moss et al., 1995).

2.4.1 System definition process

The first level output is system requirement specification (SRS) to translate operational requirement specification (ORS) into unambiguous functional and physical performance characteristics, which describes the development objectives to the industry in more scientific and technical terms, (Kapurch, 2007).

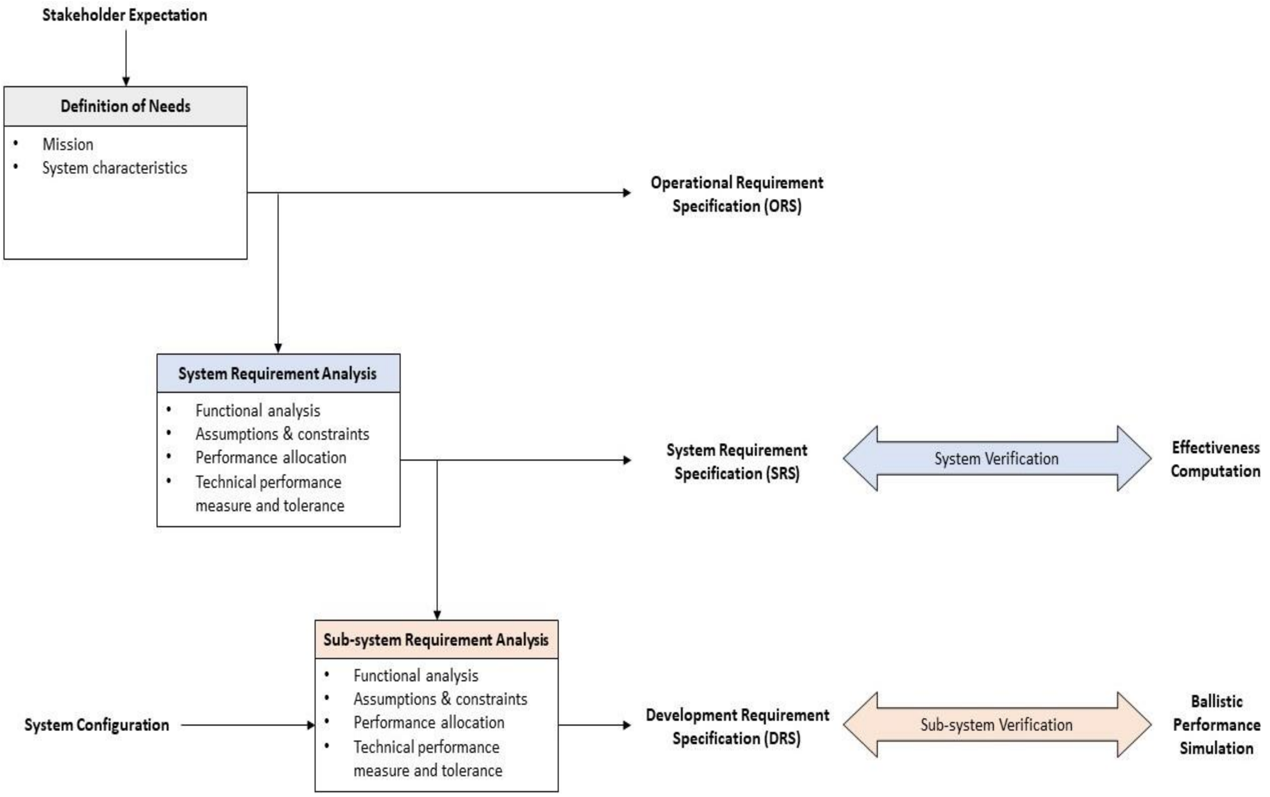


Figure 2-22 Model-based system engineering for MACS

The more precise definition of the system requirements decomposition can be described from (Kapurch, 2007) as the followed steps:

I. **Definition of needs:** The stakeholder expectation is translated to so-called operational requirements, as can be seen in Figure 2-22, which are substantial to derive the specifications of the MACS and are characterised for this research as only IB design parameters. The concerns in this stage of development are to fulfil the operational capability gap with a practical and feasible mission that is formalised as a systematic solution and characterised by its system effectiveness.

II. **Requirements analysis:** The operational requirements from the definition of needs assign translated technical requirements in format of functional and performance requirements of the MACS in which the combination of projectile, charge and cannon is defined. Accordingly, each sub-system requires to determine its technical requirements and constraints as well as its technical performance measures (TPM).

III. **MBSE verification plan:** The output of the requirement analysis in the sub-system level is defined as development requirement specification (DRS) which is a description of the CIs design properties and verified through ballistic performance simulation. The agreement of the sub-systems properties will generate SRS and then shape the performance of the MACS by effectiveness computation. These two methods of verification can be seen on the right-hand side of the model in Figure 2-22.

2.4.1.1 Operational requirement specification

The ORS includes the primary role of MACS which can be described as providing indirect fire support to the defence forces. The indirect firing is a defence capability and is represented as a mission demand in the MBSE. MACS afterwards will be characterized by its functionality and performance. This step is a consideration of army forces other than defence industries.

2.4.1.2 System requirement specification

The typical functions of MACS are; wisely **planning** the assets of artillery forces to maintain the operation, correctly **sensing** the target to locate the position of delivery, effectively **controlling** the operation to perform firing tasks, and accurately **engage** the target to deliver the system. While planning, sensing and controlling functions of MACS are maintained by operations development, the engaging function is fulfilled by the applicable design of its components, (US Army, 1986). Therefore, design for engagement is to establish an effective MACS that ensure the function of engaging the target by utilizing cannon, projectile and charge. The system performance defines the function of engagement by terms of effective range and hit probability.

Table 2-7 MACS requirements and specifications architecture

Level		Functional Requirements	Performance Requirements	Technical Performance Measure	Weight/Tolerance
[System Level]	Modular Artillery Charge System	F.0.1. Engage target.	P.0.1. Range coverage. P.0.2. Hit probability.	M.0.1. Effective range. M.0.2. Probable error.	W.0.1. Impact accuracy. W.0.2. Impact dispersion.
[Sub-system Level]	1. Cannon.	F.1.2. Hold propulsion. F.1.1. Aim projectile. F.1.3. Spin projectile.	P.1.2. Heat conduction. P.1.1. Barrel emplacement. P.1.3. Rifling twist.	M.1.2. Wall temperature. M.1.1. N/A. M.1.3. Projectile rotation.	W.1.1. N/A. W.1.2. N/A. W.1.3. N/A.
[Sub-system Level]	2. Projectile.	F.2.1. Restrain propulsion. F.2.2. Deliver terminal effect. F.2.3. Confirm angle of attack.	P.2.1. Engraving printing. P.2.2. Trajectory hold. P.2.3. Flight stability.	M.2.1. Resistance pressure. M.2.2. Projectile weight. M.2.3. Aerodynamic coefficients.	W.2.1. Projectile efficiency. W.2.2. Projectile efficiency. W.2.3. Projectile efficiency.
[Sub-system Level]	3. Modular Charge.	F.3.1. Employ propulsion.	P.3.1. Pressure profile.	M.3.1. Top-charge muzzle velocity. M.3.2. Top-charge maximum pressure.	W.3.1. Charge efficiency.

Table 2-7 describes the processes handled to generate MACS specifications in both system and sub-system levels. For system level, the function of MACS is to engage the target and translates to performance in the form of range coverage and hit probability. The TPMs of the system level is the maximum range and probable error. Next, the weight of the system TPMs assign firing accuracy and dispersion and thus verify the MACS delivery performance.

2.4.1.3 Development requirement specification

As mentioned before in section 2.4.1, the definition of CIs for MACS is sequential as followed and shown in Table 2-7:

I. Define cannon

The main functions of the cannon are to contain the propulsion process, aim the projectile through its trajectory and spin the projectile to increase its stability. The first function is constrained by the heat conduction of the barrel wall capacity and measured as TPM by the wall temperature. Elevation angles of the weapon limit the second function. The last function is determined by the rifling twist of the grooves inside the bore and measured by TPM as projectile rotation unit. Since the cannon is already defined for this study, therefore, the tolerances of the previous TPMs are not applicable.

II. Define projectile to fixed cannon

The projectile functional requirements for MACS are restraining the propulsion process, delivering the terminal effect to the target and confirming the angle of the attack. To maintain these functions, first, resistance pressure is measured as TPM through the engraving printing along the bore. Second, as the projectile has a directly proportional relationship to the maximum range, it ensures the delivery of the load to the target. Third, the aerodynamic characterisation of the projectile shape and weight determines the angle of attack and better kill area. The sum of the three TPMs defines the projectile efficiency in the firing.

III. Define charge to fixed projectile fixed cannon

The only function of the modular charges is to employ the propulsion process, which is characterised by the shape of the pressure profile inside the gun. The values of the top-charge MV and maximum pressure define top-charge efficiency. It is crucial to notice that the other charges configuration will have lower efficiency since the chamber volume increases. The verification of ballistic specifications will investigate these reductions in charges efficiencies.

The remaining phases of the MBSE go through full system construction in the next chapters in order to calculate the performances of the sub-systems and MACS overall performance.

2.5 Conclusion

MACS was introduced by application and definition of its characteristics. The performance of the system, as mentioned in this chapter, is measured by accuracy and dispersion of the firing. As explained before, the standard deviation of sources of error cause changes in values of the system performance and by isolating them, it is likely to determine their contribution to the system performance.

The quality of the components of MACS is subjected to the manufacturing capability that causes variation to the IB outputs and subsequently leads to changes in MACS performance. Projectile mass, charge mass, propellant size and dimension, as well as the chamber volume of the gun system have different portions of effect to the system performance. After a successive assessment of different IB models, lumped parameter model shows the applicability of simulating the performance of the IB system as its inputs are subjected to predefined variations.

For the next chapters, a framework will be constructed to handle a set of variations in the input and maintain the changes through the MBSE practice, phase by phase, to finds out the changes to the overall output of the MACS.

CHAPTER 3 : MBSE METHODOLGY

3.1 Introduction

The previous chapter covered the first step of the MBSE methodology where the MACS went through definition process of setting the system requirements. In this chapter, the remaining processes of system implementation, system integration and system verification will be constructed by building the framework to ultimately connect the manufacturing capability of the charge and projectile to the MACS performance outputs.

3.2 MACS configuration

The CIs configuration is a set of DRSs of the cannon, the projectile and the charge which will determine the SRS of MACS. From the gun system side, the bore length and the chamber length are reciprocated as the ramming of the gunner tolerates the length of both leading to variation in chamber volume. When applying the tolerances, the chamber volume will vary from 23480 cm^3 to 23580 cm^3. From the projectile side, the variations of 500 g for the total mass represent the manufacturing capability. From the charge side, the mass of igniter is minimal, and its tolerance is insignificant while tolerance in the propellant grains mass is not defined at this stage because the range sensitivity to the MV is significant. The correct propellant grains mass will be determined and fixed in the modularisation stage in the proposed framework, as shown in Figure 3-4. The parasites masses (combustible case, end cap, igniter cube and flash reducer) have small tolerances compared to propellant grains. Thus, they will be considered only in the first stage of the framework.

Table 3-1 DRSs for MACS CIs

CI	Configuration Parameter	Value	Tolerance	Unit
Cannon	Bore length	6940	± 2	mm
	Chamber length	1120	± 2	mm
	Chamber volume	23530	calculated	cm^3
	Rifling twist	22	n/a	calibres/turn
Projectile	Total mass	45550	± 500	g
Charge	Igniter mass	20	n/a	g
	Propellant grains mass	13710	n/a	g
	Combustible case mass	220	± 15	g
	End cap mass	35	± 2	g
	Igniter cube mass	33	± 3	g
	Flash reducer mass	83	± 15	g

3.3 MACS specification

The DRS described in 3.2 will generate IB and EB specifications that set as references for the system verification processes.

Table 3-2 IB specification

	MV	Maximum Pressure
Charge 6	923.00 m/s	330.00 MPa
Charge 5	800.00 m/s	228.00 MPa
Charge 4	672.00 m/s	146.00 MPa
Charge 3	541.00 m/s	91.00 MPa

The values of MV and maximum pressure in Table 3-2 are verification values for the predefined MACS and should be used to calibrate the IB model for each configuration as resulting from the nominal input values. They will provide a simulated reference point for each configuration after which the various input parameters is stochastically varied yielding in variation outputs in both IB and EB parameters.

Table 3-3 EB specification

	Minimum Range	Maximum Range
Zone 6 [m]	16980	32011
Zone 5 [m]	13940	25435
Zone 4 [m]	10850	20143
Zone 3 [m]	7838	15359

During verification of the system, the results of MACS ranges should be in accordance with the values in Table 3-3 to demonstrate compliance with the SRS. The firing simulation will be limited to the minimum elevation of 200 mils subjected to the barrel minimum emplacement of the cannon. The minimum elevation is a safety operational standard for the artillery.

3.4 Ballistic modelling

As for recommendations from chapter 2, the lumped parameter model is used for the IB model (IBM), and the modified point of mass (MPMM) is used for the EB model (EBM). The aim with MPMM is to calculate the trajectory, that is projectile position and velocity, as a function of time. The CIs specifications feed the two models then treat as stand-alone blocks in order to be encompassed by stochastic modelling.

The values of CIs technical specifications in Table 3-4 are the outcomes of the TPM to meet the performance requirements of the system, as indicated previously in Table 2-7. The values in tolerance and sigma columns in Table 3-4 are gathered from actual quality data of the projectile and the charge manufacturing processes which, in fact, representations of the manufacturing capability and limits to produce them.

Table 3-4 Technical specifications for MACS CIs

CI	Technical Parameter	Value	Tolerance	Sigma	Unit
Cannon	Initial air temperature	293	n/a	n/a	K
	Initial chamber temperature	300	n/a	n/a	K
	Heat conductivity	35	n/a	n/a	W/m-K
	Specific heat capacity	460280	n/a	n/a	J/cm^3-K
	Heat transfer coefficient	11350	n/a	n/a	W/cm^2-K
	Wall thickness uniformity	2	n/a	n/a	µm
Projectile	Total mass	45550	± 500	83	g
	Drag coefficient	$\frac{27}{100}$ at Mach 1	-	-	-
	Driving band stiffness	Calibrated by bore friction fitting factor	-	-	-
Charge	Full charge mass	13710	-	-	g
	Propellant shape	7 perforation (round)	-	-	-
	Grain perforation number	7	n/a	n/a	-
	Grain length	20460	± 726	121	µm
	Inner web diameter	2300	± 174	29	µm
	Outer web diameter	2300	± 174	29	µm

3.4.1 IBM model initialisation

The process of initialising the IBM model prepares all the necessary inputs to calculate the IB cycle and the pressure profile throughout the lumped equations. The equations constitute the IB mathematical model, a set of non-linear differential and algebraic equations, which simulate the one-dimensional motion of a conventional, spin stabilized artillery projectile inside the gun tube. The IBM in Figure 3-1 is accomplished by (a) including the most essential energies as described in Table 2-6, (b) approximating the burning of solid propellants, and (c) applying bore friction fitting factor to match the simulated MV and maximum pressure results to the IB specification in Table 3-2. Friction losses of the IB cycle are accounted only through empirical experiments.

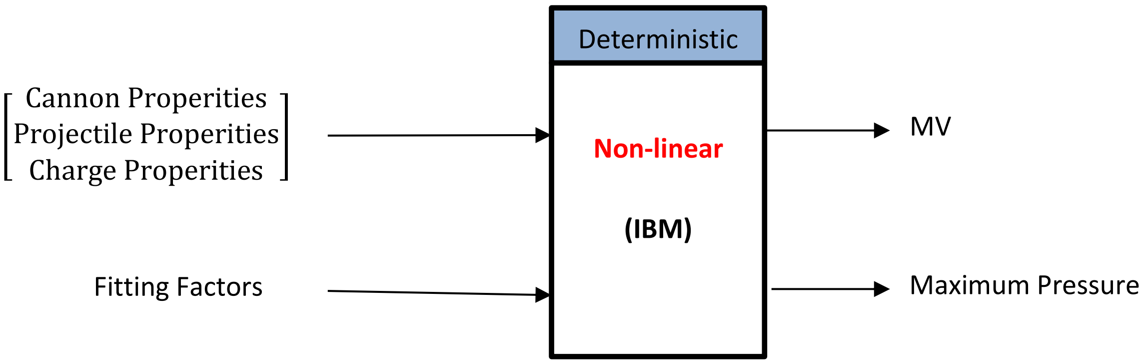


Figure 3-1 IB model initialisation

3.4.2 IBM model built-in data

The IBM stores input data requirements by defining all technical properties of all the necessary CIs specifications from Table 3-4 to calculate the outputs of the IB cycle.

3.4.3 IBM model calibration

The bore friction fitting factor applied to correct the values of MV and maximum pressure with respect to Table 3-2. Table 3-6 shows the values of calibrated bore friction factors to verify to the model with the IB specification. Due to the complexity of a realistic friction model for the IBM, the bore friction resistance values employed are simplified and encapsulated by a simple model as illustrated in Figure 3-2.

Table 3-5 IB calibration results

	MV	Maximum Pressure	ε_B	ε_P
Charge 6	922.98 m/s	329.87 MPa	31.00	55.46
Charge 5	800.31 m/s	228.37 MPa	27.98	60.55
Charge 4	672.34 m/s	146.97 MPa	24.68	66.82
Charge 3	541.95 m/s	91.25 MPa	21.20	70.53

Table 3-6 Bore friction fitting factor values

X	X (1)	X (2)	X (3)	X (4)
Bore Distance [mm]	0.0	21.8	43.5	6898.0
Pressure	**P (1)**	**P (2)**	**P (3)**	**P (4)**
Charge 6 [MPa]	16.0	31.8	10.6	10.6
Charge 5 [MPa]	16.0	34.9	11.9	11.9
Charge 4 [MPa]	16.0	21.2	10.6	10.6
Charge 3 [MPa]	16.0	12.7	9.5	9.5

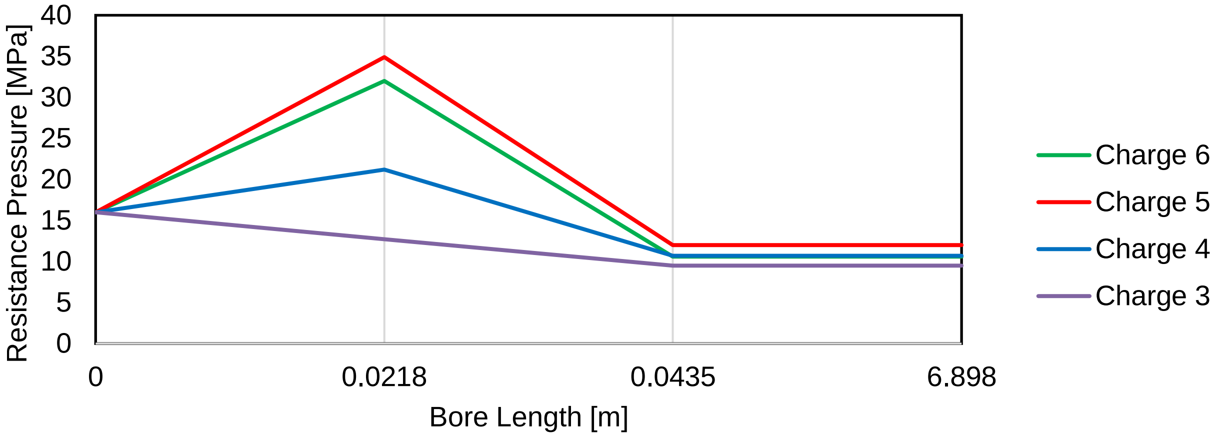


Figure 3-2 Resistance pressure vs bore length for different charges

3.4.4 EBM model initialisation

The EBM is used to calculate the trajectory, that is projectile position and velocity in flight, as a function of time. The desired outputs for this framework are the range and deflection coordinates for each zone.

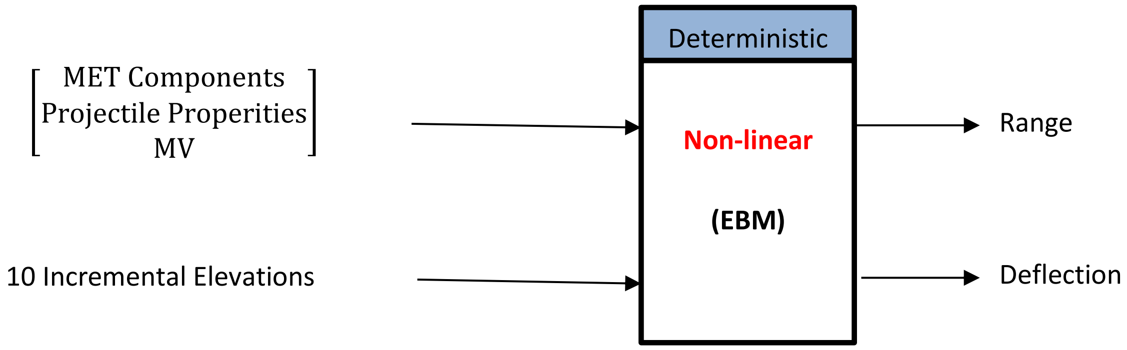


Figure 3-3 EB model initialisation

3.4.5 EBM model built-in data

The EBM stores input data requirements by defining all the projectile and MV values from Table 3-4, the standard atmospheric conditions of MET component from Table 3-7 and the elevation angle of firing from Table 3-8. The variations of EBM input parameters are taken from Table 3-4 for projectile total mass. Another input is the MV variations from the IBM output. To generate a full band of the zones ten incremental elevation angles inserted as input to the model bounded by the minimum and maximum operational elevations. Table 3-8 shows the min and max elevations that generate EB specification in Table 3-3. The maximum elevations in the higher zones are high to overcome the air resistance when the projectile is in flight.

Table 3-7 MET Component inputs

MET Component	Value	Tolerance	Sigma	Unit
Air density	1.23	n/a	n/a	kg/m^3
Air Temperature	288.20	n/a	n/a	K
Wind vector	0.00	n/a	n/a	knot

3.4.6 EBM elevation adjustment

Table 3-8 EB calibration results

	Minimum Elevation	Minimum Range	Maximum Elevation	Maximum Range
Zone 6	200 mils	16907 m	800 mils	32051 m
Zone 5	200 mils	13891 m	820 mils	25479 m
Zone 4	200 mils	10802 m	860 mils	20210 m
Zone 3	200 mils	7803 m	910 mils	15416 m

3.5 System implementation process

The process of system implementation in Figure 3-4 is to examine the charge performance through the manufacturing limits where the dimensions of the propellant grain have variations, as typically found during the manufacturing process, to generate different grain length and web sizes at a time. The method of investigation is to randomly generate different values of the grain dimension and observe the impact in the output of the IBM. The random number generator (RNG) generates probability distribution function that has mean value and standard deviation values of the technical specifications from Table 3-4.

3.6 System integration process

The model receives a range of outputs that represent the charge performance, but the values of achieved MV are not constrained by the maximum operating pressure of the cannon. The process of system integration is to ensure the charge-gun compatibility by maintaining the exact propellant grain mass, also it is called charge mass determination (CMD), for the maximum charge (CM_6).

The charge modularisation frame as shown in Figure 3-4 is to linearly decrement the maximum charge by splitting the mass into smaller modules. In other words, the maximum charge is subtracted by one sixth of CM_6 that is called charge mass subtraction (CMS) and as followed:

$$CM_5 = CM_6 - \left(\frac{CM_6}{6}\right) \quad (18)$$

Where

CM_5: Charge 5 mass [g]

$$CM_4 = CM_6 - \left(\frac{CM_6}{3}\right) \quad (19)$$

Where

CM_4 Charge 4 mass [g]

$$CM_3 = CM_6 - \left(\frac{CM_6}{2}\right) \quad (20)$$

Where

CM_3: Charge 3 mass [g]

3.7 Sub-system and system verification processes

After the CIs are integrated into the system, it is ready for verification that all the integrated CIs can satisfy the system performance. Figure 3-4 shows the two stages of system verification, where the sub-system verification is to test the performance of the IB and EB within the MACS system. IB performance frame tests the changes of system configuration by generating variations in projectile weight, ram depth and MV values. Next, the output of the frame (changes in MV) is recorded and inserted to the EB performance frame. It investigates the variations in MV by simulating trajectory where ten sets of elevation angels are taken to cover the whole band of each zone. Last, the outputs of the EB performance come as range and deflection to assign delivery performance of MACS.

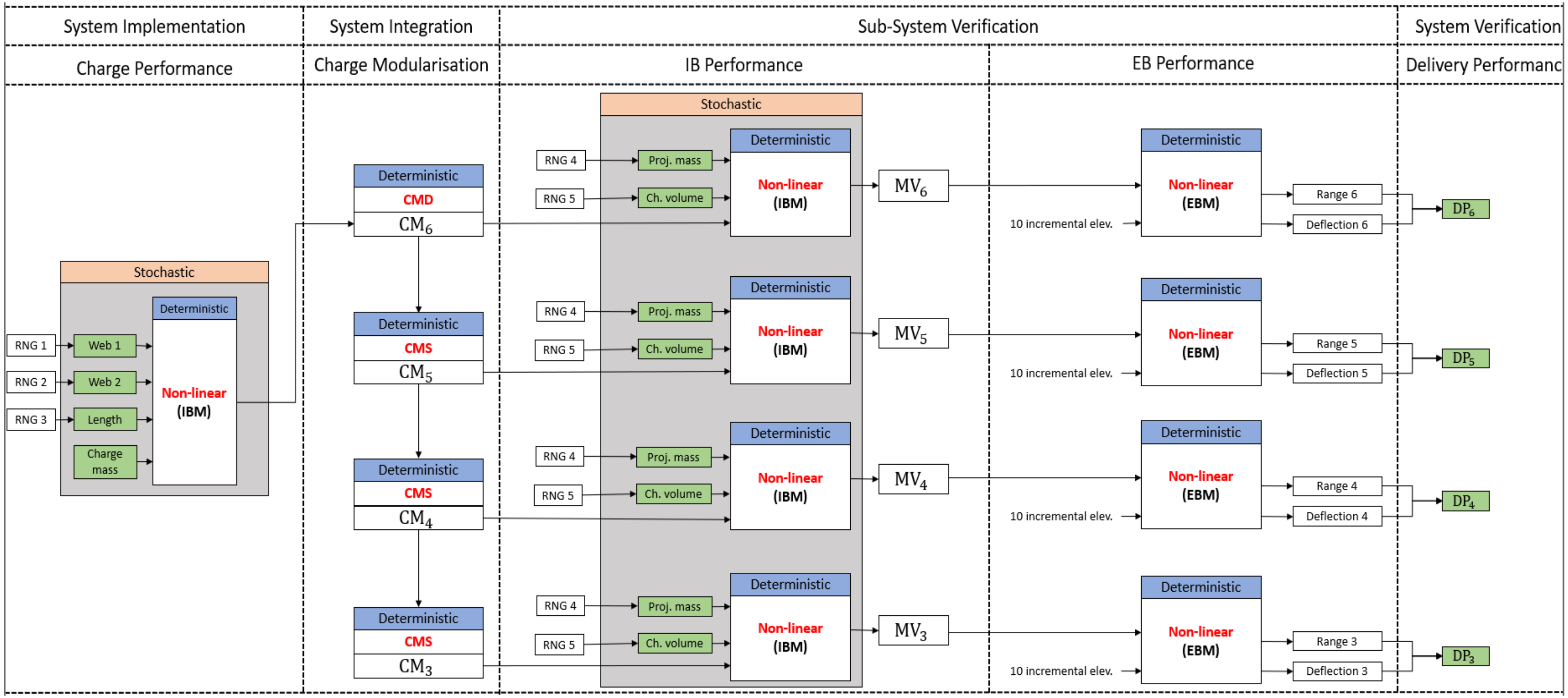


Figure 3-4 MBSE framework

Where

RNG: Random number generator

Web 1: Propellant grain inner web

Web 2: Propellant grain outer web

Length: Propellant grain length

Ch. volume: Chamber volume

Proj. mass: Projectile mass

CM_6: Charge 6 mass

CM_5: Charge 5 mass

CM_4: Charge 4 mass

CM_3: Charge 3 mass

MV_6: Charge 6 MV

MV_5: Charge 5 MV

MV_4: Charge 4 MV

DP_6: Zone 6 delivery performance

DP_5: Zone 5 delivery performance

DP_4: Zone 4 delivery performance

DP_3: Zone 3 delivery performance

3.8 Conclusion

All the models that are used in the MBSE framework were calibrated and set to the initial conditions in order to execute the whole framework. As a result, the output values of the IB and EB sub-systems were determined as reference values. Thus, when the input variations are inserted to the framework, the deviations per sub-system are calculated and defined.

CHAPTER 4 : MBSE RESULTS AND RECOMMENDATIONS

4.1 Introduction

The construction and description of the research framework were stated in chapter 3, where it is divided into three combined models to simulate the system implementation, system integration and system verification. Afterwards, all the constructed simulation models were set to the initial conditions and calibrated accordingly. In this chapter, each system phase will be executed to generate the output to the next system phase, as seen in Figure 3-4, along to generate the MACS overall performance.

4.2 System implementation results

The charge manufacturing performance indicates how much MV varies by the variations in the propellant characteristics. The performance drivers for this study are as mentioned before the dimensions of the propellant grains. The output MV as in Figure 4-1 shows the sensitivity of the charge to the variations in the inputs. The process of execution generates 50 trials (manufacturing batches) with different values of the technical parameters, propellant grain inner web (web 1), outer web (web 2) and total length. The charge mass is a configuration parameter and will remain to the same value at this phase.

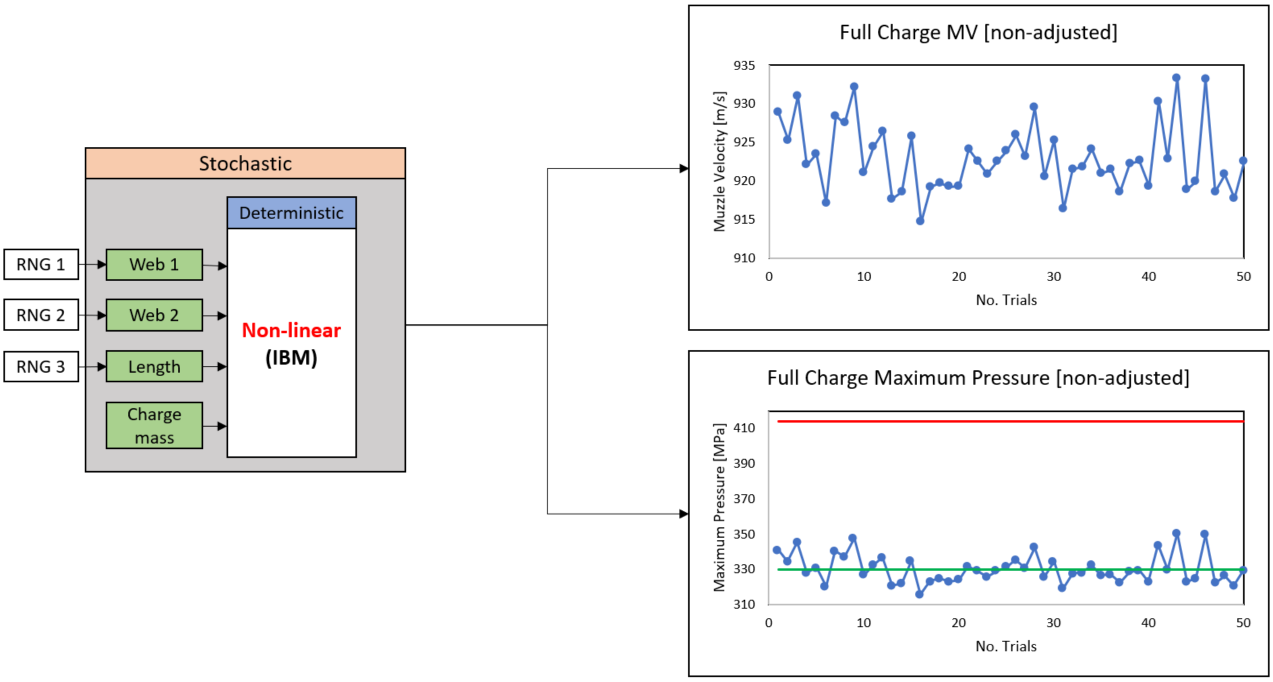


Figure 4-1 System implementation phase

It can be seen in Table 4-1 that the mean values of the MV and maximum pressure are the same as the IB system specifications in Table 3-2. The tolerance of in MV ± 13 m/s is undesirably high because each value represents on manufacturing batch that needs to meet the specification output of 923 ± 0 m/s. The tolerance in maximum pressure is ± 24.55 MPa may describe the system limitation where the IB output is subjected to the maximum operating pressure of 414 MPa as drawn by the red line in Figure 4-1.

Table 4-1 Charge manufacturing performance results

Input	RNG		Output	Statistic Coefficients	
	Mean	Sigma		Mean	Tolerance
Web 1	2300 µm	29 µm	**MV**	923 m/s	± 13 m/s
Web 2	2300 µm	29 µm			
Length	20460 µm	121 µm	**Maximum Pressure**	330 MPa	± 25 MPa
Charge mass	13710 g	0 g			

4.3 System integration results

After receiving the values of the full charge MV from the system implementation phase, it will comply with the MV specification of 923 m/s by CMD process. After determining the mass of charge 6 (CM_6) the charge mass is subtracted to generate three more different charge configurations. Table 4-2 defines the charge mass for each system configuration through the CMS process by recalling equations (17), (18) and (19) from 3.6.

Table 4-2 Charge modularisation

Charge Configuration	Charge Mass	Statistic Coefficients	
		Sigma	Tolerance
$\mathbf{CM_6}$ **[g]**	13710	93	± 279
$\mathbf{CM_5}$ **[g]**	11425	77	± 231
$\mathbf{CM_4}$ **[g]**	9140	62	± 186
$\mathbf{CM_3}$ **[g]**	6855	46	± 138

When variations apply to the input, the charge mass will be reduced if the values of MV are above 923 m/s, and it will be added if the values of MV are below 923 m/s. By applying this charge control process, the charge can now be integrated into the system, and the new values match the specification. Figure 4-2 shows the process of CMD where the variation in MV from the input (non-adjusted) is settled into the output (adjusted). It can be noticed that the standard deviation of the lower charges decreases because of the subtraction from the mean for each value of CM_6.

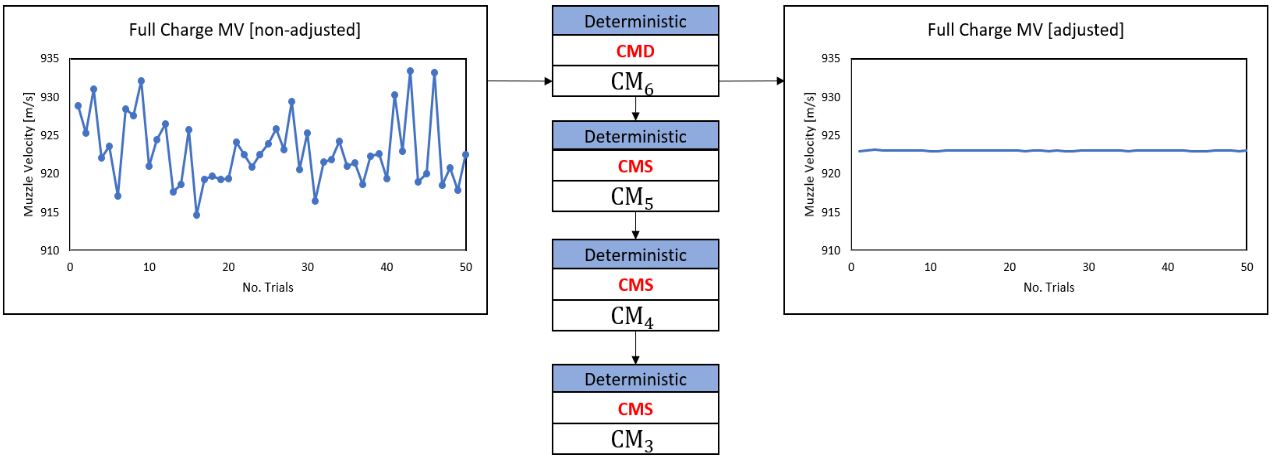


Figure 4-2 System integration phase

4.4 Sub-system and system verification results

The verification method, as mentioned in chapter 3, is divided into two phases, sub-system verification phase and system verification phase.

4.4.1 IB sub-system verification results

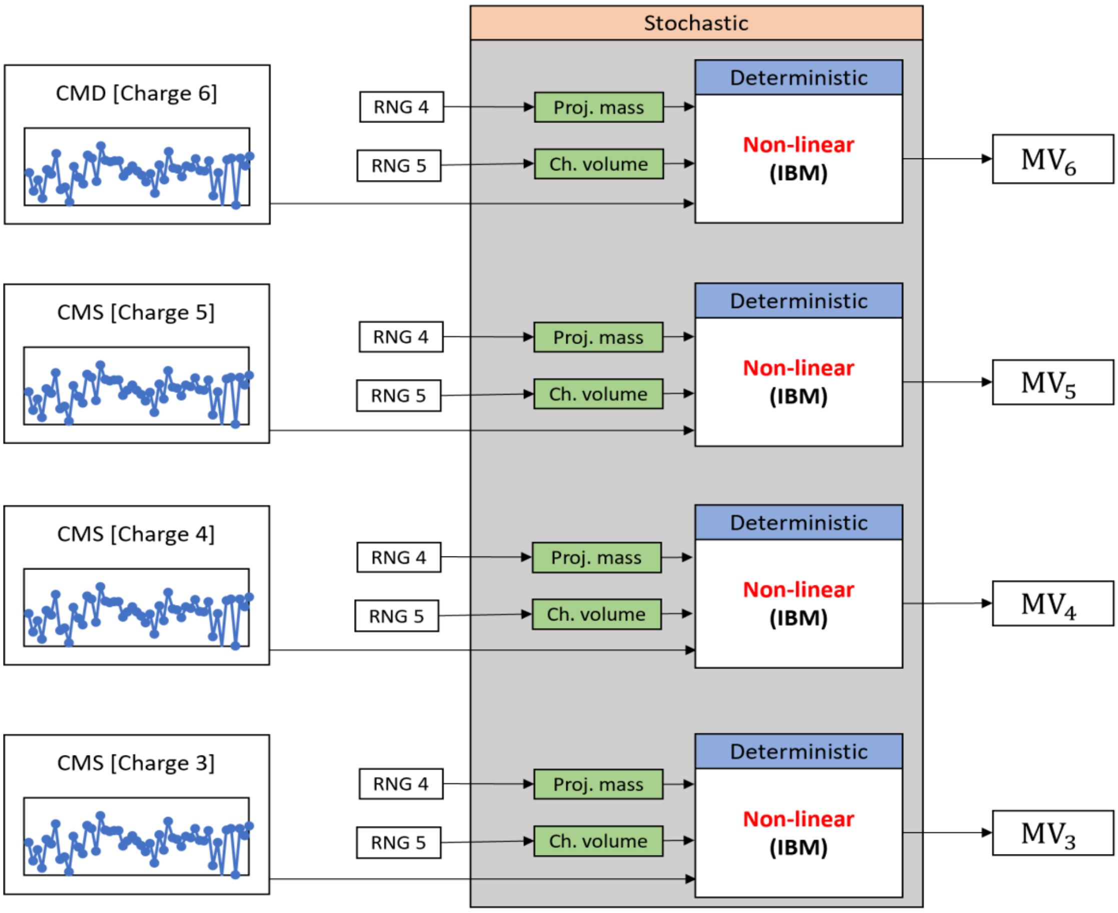


Figure 4-3 IB sub-system verification

Now, all the parameters are ready to represent complete IB performance that simulates actual IB cycles with different values in the CIs. For charge mass, the values of 50 different charge masses that gathered out from the charge modularisation model are inserted as input to the IB sub-system verification model. For projectile mass and chamber volume, 10 random numbers will be generated for each charge mass representing one manufacturing batch and with accordance to Table 3-1 and Figure 4-4 shows the performance of all charges, where the tolerances increase in the lower charges. Charge 4 and 3 have skewness tendency to lie in the region above the mean. This skewness is a result of the CMS process where each charge mass set is multiplied by a percentage of reduction to generate the lower charge modules.

Table 4-3. This randomisation will generate 10 times 50 different values at the output of the IB model. The mean values of MVs in Figure 4-4 shows the performance of all charges, where the tolerances increase in the lower charges. Charge 4 and 3 have skewness tendency to lie in the region above the mean. This skewness is a result of the CMS process where each charge mass set is multiplied by a percentage of reduction to generate the lower charge modules.

Table 4-3 meet the specification values, but the tolerances increase in the lower charges. These high tolerances will cause higher dispersion in the lower zones when the system executes the EB sub-system verification model. In other words, these changes of MV values in tolerances will lead the system being out of specification in the lower zones.

Figure 4-4 shows the performance of all charges, where the tolerances increase in the lower charges. Charge 4 and 3 have skewness tendency to lie in the region above the mean. This skewness is a result of the CMS process where each charge mass set is multiplied by a percentage of reduction to generate the lower charge modules.

Table 4-3 Charge modules performance results

CI	Input	RNG Mean	RNG Sigma	Output	Statistic Coefficients Mean	Statistic Coefficients Tolerance
Charge 6	**Proj. mass**	45550 g	167.54 g	**MV_6**	923 m/s	± 2.66 m/s
	Chamber volume	23530 cm^3	15.53 cm^3			
	Charge mass	13710 g	92.64 g			
Charge 5	**Proj. mass**	45550 g	167.54 g	**MV_5**	800 m/s	± 2.59 m/s
	Chamber volume	23530 cm^3	15.53 cm^3			
	Charge mass	11425 g	77.20 g			
Charge 4	**Proj. mass**	45550 g	167.54 g	**MV_4**	672 m/s	± 3.6 m/s
	Chamber volume	23530 cm^3	15.53 cm^3			
	Charge mass	9140 g	61.75 g			
Charge 3	**Proj. mass**	45550 g	167.54 g	**MV_3**	541 m/s	± 4.98 m/s
	Chamber volume	23530 cm^3	15.53 cm^3			
	Charge mass	6855 g	46.32 g			

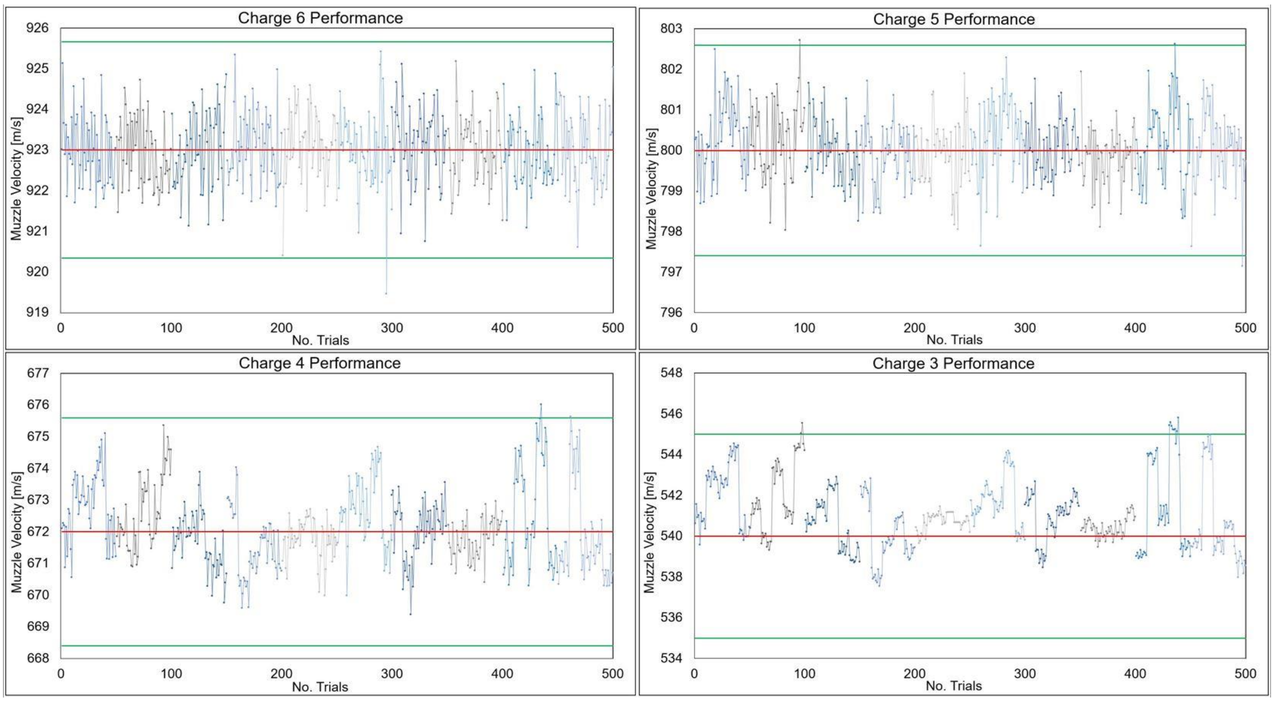


Figure 4-4 Charges performance

4.4.2 EB sub-system verification results

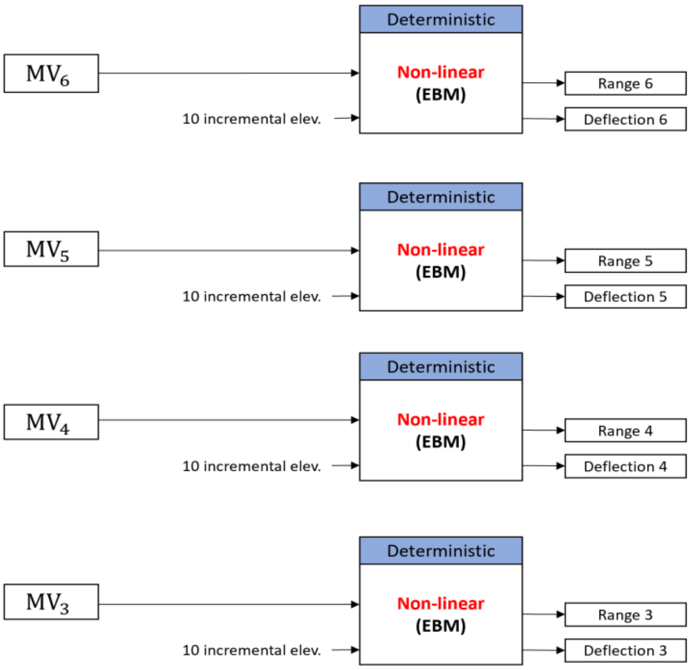


Figure 4-5 EB sub-system verification

The process of EB performance is to simulate actual firings that take the MV value per charge and execute the EBM with 10 elevations to cover the band for each zone. This process is repeated to generate 10 times 500 firing points per zone. Table 4-4 defines the elevation angels for each zone to cover the zone band. The MPIs for each group of firing per zone is calculated by taking the mean of the range and deflection coordinates and are defined in Table 4-5.

Figure 4-6, Figure 4-7, Figure 4-8 and Figure 4-9 show zones coverage and the EB performance as the groups of MPI are coordinated by range and deflection. It can be seen in EB performance graphs that the dispersion form MPIs increases in the lower zones (decrease in consistency).

Table 4-4 Elevation inputs per zone

Firing Group	Zone 6 Band	Zone 5 Band	Zone 4 Band	Zone 3 Band
Elev. 10 [mils]	910	860	820	800
Elev. 9 [mils]	831	787	751	733
Elev. 8 [mils]	752	713	682	667
Elev. 7 [mils]	673	640	613	600
Elev. 6 [mils]	594	567	544	533
Elev. 5 [mils]	516	493	476	467
Elev. 4 [mils]	437	420	407	400
Elev. 3 [mils]	358	347	338	333
Elev. 2 [mils]	279	273	269	267
Elev. 1 [mils]	200	200	200	200

Table 4-5 Zones performance

Zone 6			Zone 5			Zone 4			Zone 3		
MPI	**Range**	**Deflection**	**MPI**	**Range**	**Deflection**	**MPI**	**Range**	**Deflection**	**MPI**	**Range**	**Deflection**
MPI_{6-10}	32052 m	1165 m	**MPI_{5-10}**	25480 m	674 m	**MPI_{4-10}**	20219 m	439 m	**MPI_{3-10}**	15422 m	293 m
MPI_{6-9}	31787 m	1022 m	**MPI_{5-9}**	25289 m	597 m	**MPI_{4-9}**	20072 m	386 m	**MPI_{3-9}**	15313 m	255 m
MPI_{6-8}	31079 m	860 m	**MPI_{5-8}**	24800 m	523 m	**MPI_{4-8}**	19660 m	338 m	**MPI_{3-8}**	15000 m	220 m
MPI_{6-7}	29968 m	706 m	**MPI_{5-7}**	24036 m	450 m	**MPI_{4-7}**	19007 m	294 m	**MPI_{3-7}**	14495 m	188 m
MPI_{6-6}	28537 m	568 m	**MPI_{5-6}**	23022 m	380 m	**MPI_{4-6}**	18159 m	251 m	**MPI_{3-6}**	13811 m	158 m
MPI_{6-5}	26852 m	446 m	**MPI_{5-5}**	21769 m	313 m	**MPI_{4-5}**	17133 m	211 m	**MPI_{3-5}**	12957 m	131 m
MPI_{6-4}	24900 m	342 m	**MPI_{5-4}**	20278 m	250 m	**MPI_{4-4}**	15924 m	172 m	**MPI_{3-4}**	11942 m	106 m
MPI_{6-3}	22678 m	254 m	**MPI_{5-3}**	18531 m	192 m	**MPI_{4-3}**	14510 m	134 m	**MPI_{3-3}**	10767 m	83 m
MPI_{6-2}	20099 m	176 m	**MPI_{5-2}**	16460 m	137 m	**MPI_{4-2}**	12845 m	98 m	**MPI_{3-2}**	9409 m	61 m
MPI_{6-1}	16924 m	105 m	**MPI_{5-1}**	13894 m	85 m	**MPI_{4-1}**	10817 m	64 m	**MPI_{3-1}**	7814 m	40 m

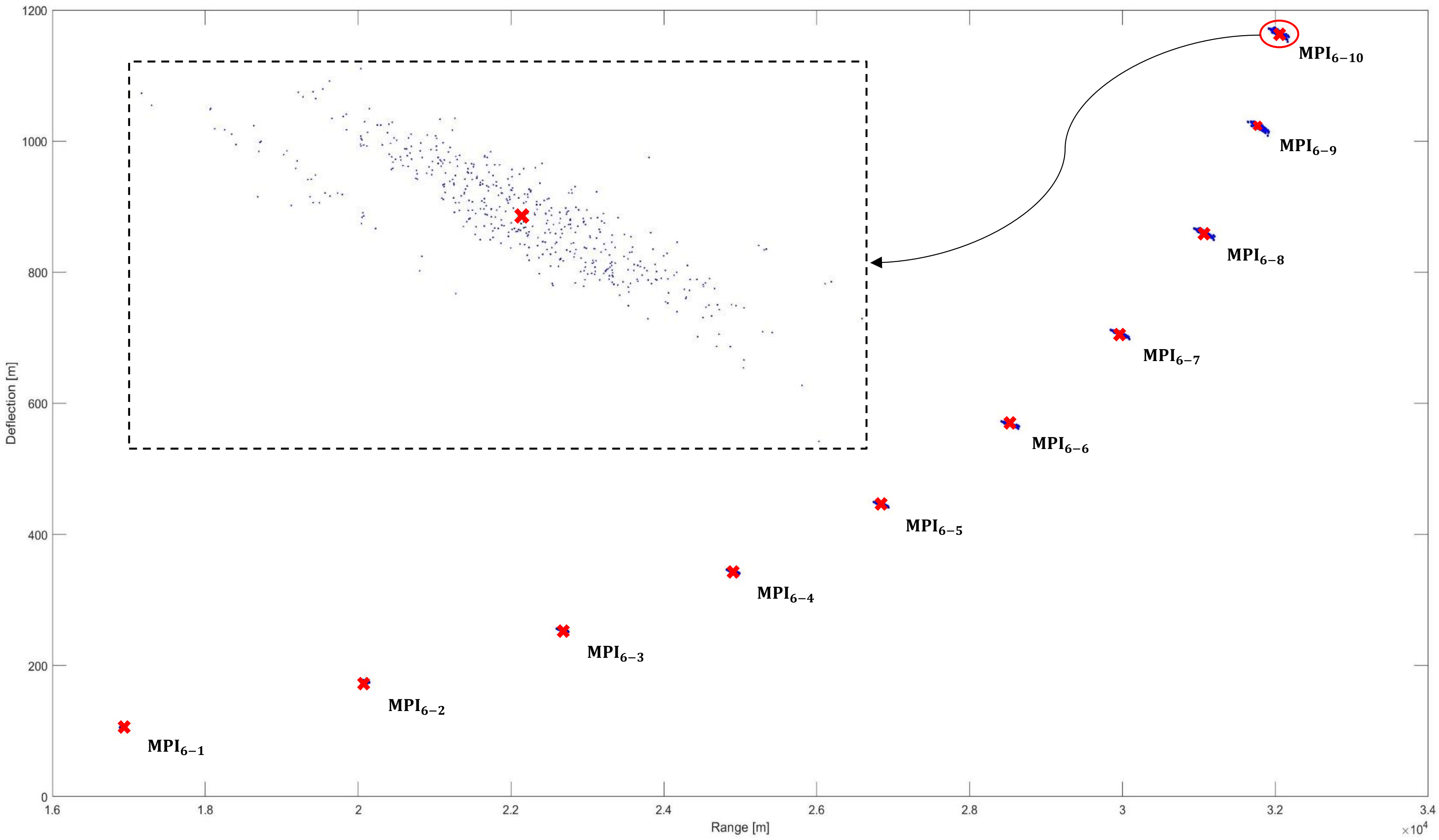


Figure 4-6 Zone 6 performance

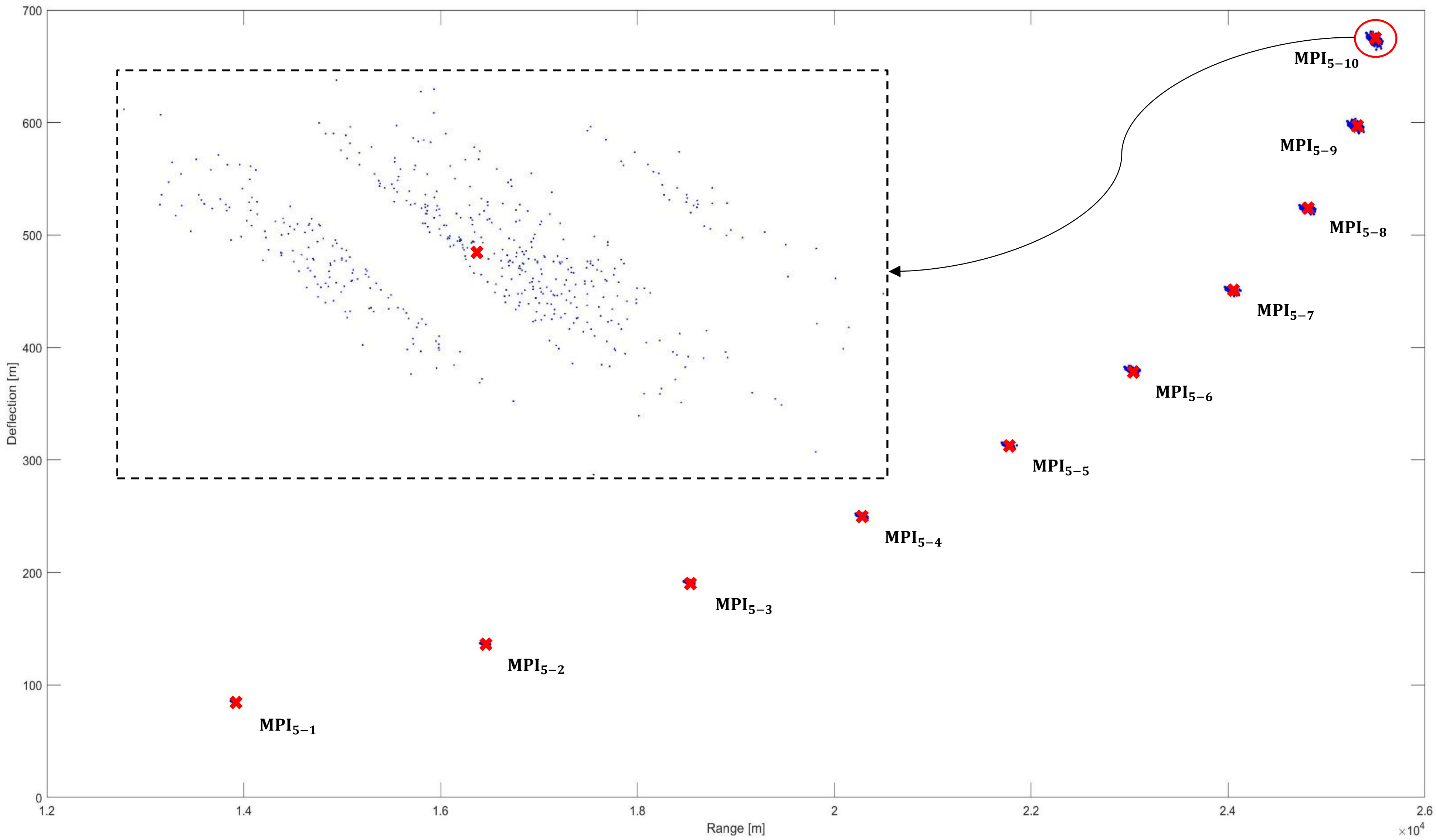


Figure 4-7 Zone 5 performance

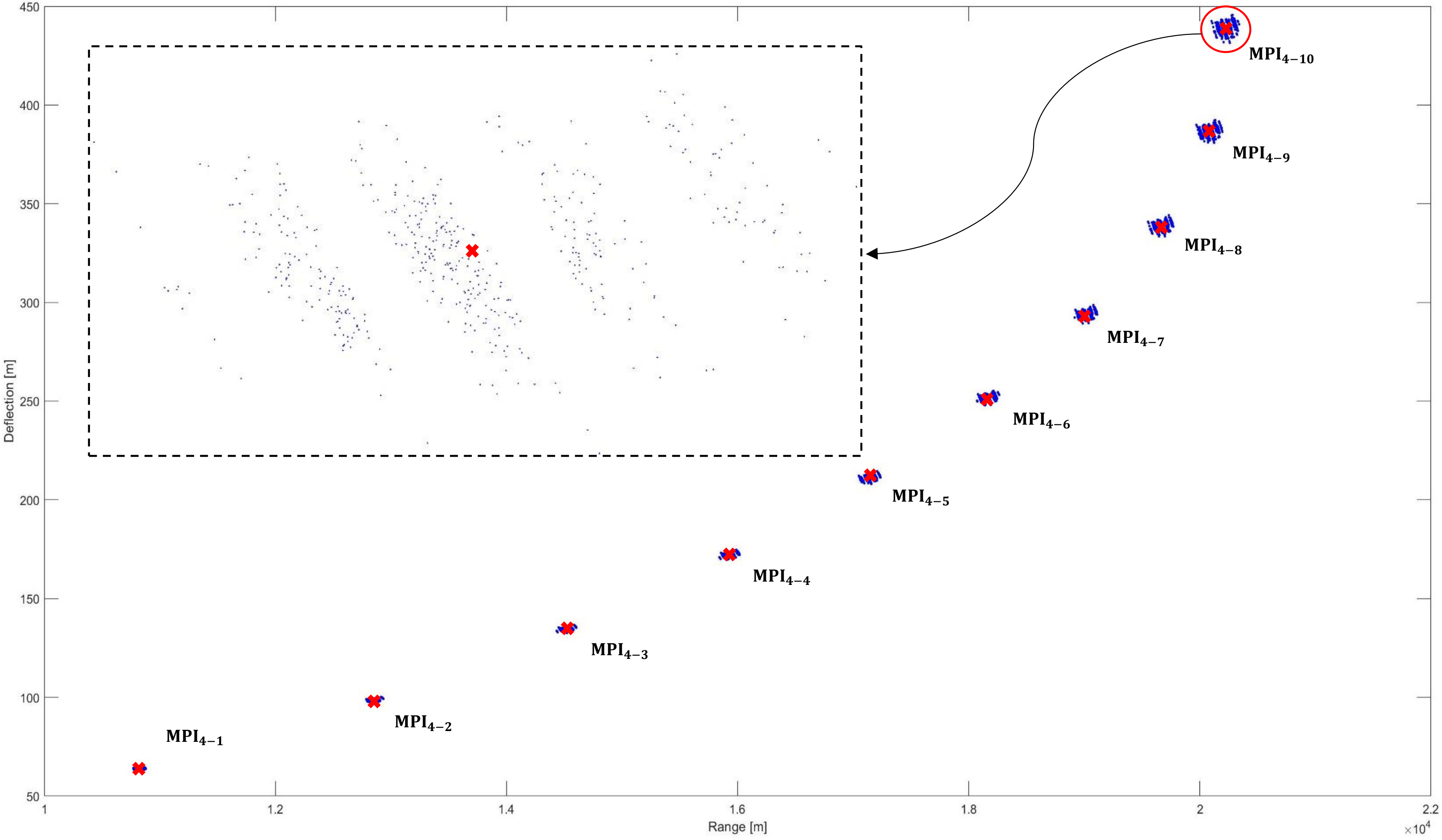


Figure 4-8 Zone 4 performance

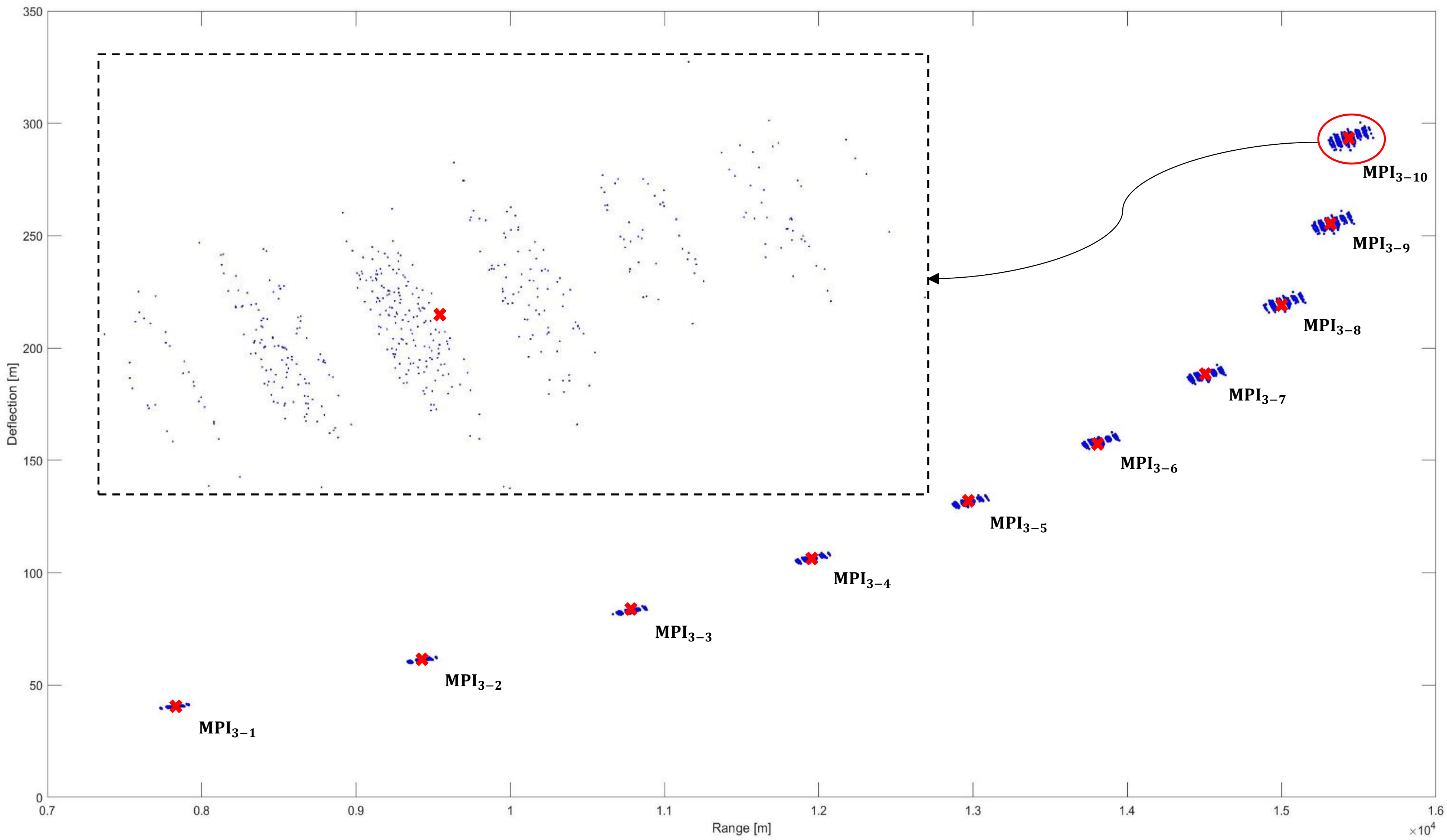


Figure 4-9 Zone 3 performance

4.4.3 System verification results

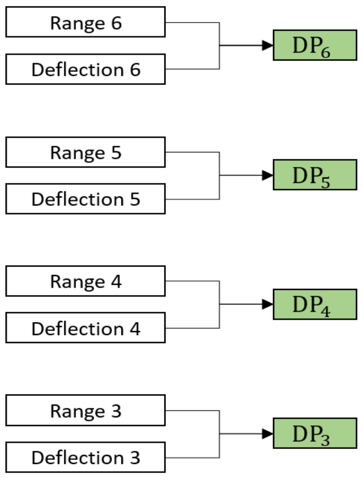


Figure 4-10 MACS verification

Once receiving all coordinates for range and deflection, the delivery performance for each zone can be calculated. Appendix B shows the scatter plots for zone firing simulated by 10 different elevation angles to create 10 firing groups. It can be obviously seen that all the 40 firing groups are in elliptical scatter because of that the sensitivity in range is much higher than the sensitivity in deflection. This disparity in sensitivity is due that the inputs variations that cause sensitivity in deflection were neglected, namely, azimuth estimation variation (σ_{AZ}) and weapon location variation (σ_{WL}).

First, to choose the best method of delivery performance calculation, the shape and scatter distribution are analysed. By taking 6 standard deviations in both range and deflection axes as shown in Figure 4-11 the results of tolerance bands are 104 m in range and 8 m in deflection.

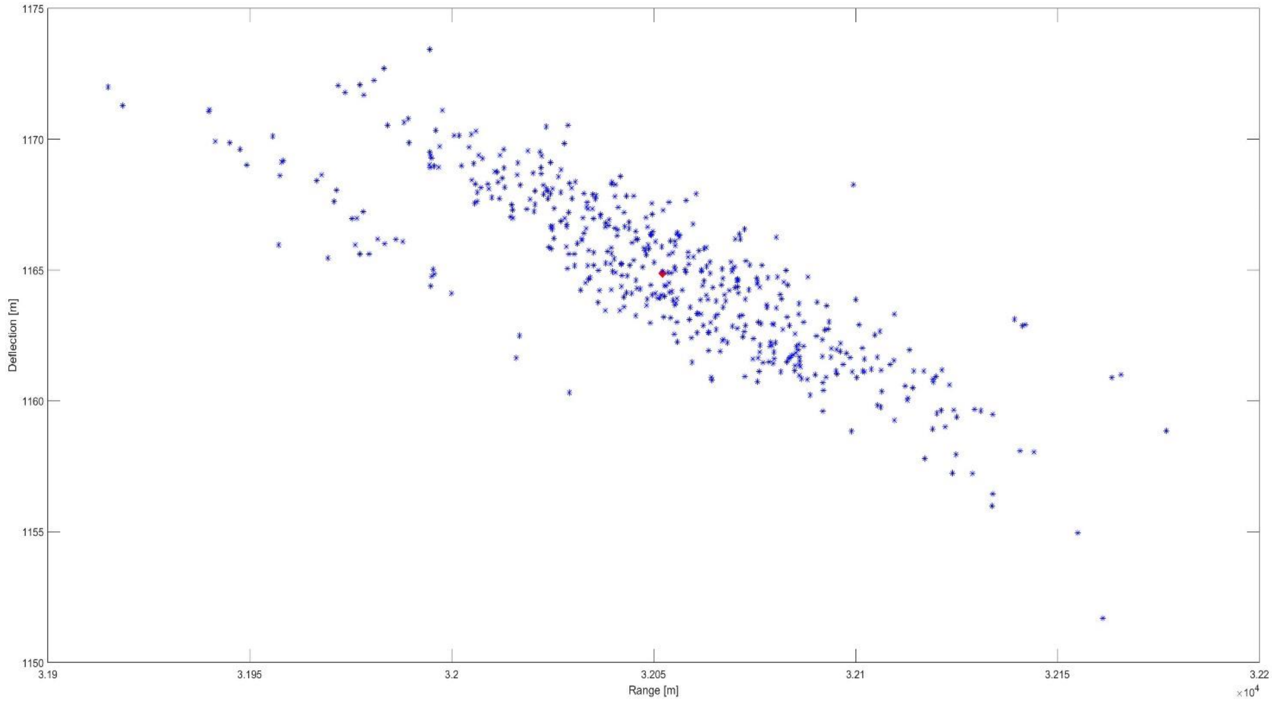


Figure 4-11 Scatter plot for firing group Zone 6 - Elev.10

Second, the tolerance bands of 104 m and 8 m are examined to whether choose CEP, ECEP or enclosing rectangle method of calculation. For CEP, it can be seen in all plots in Appendix B that the shape of the group scatters is not circle thus, CEP method is not applicable to calculate the dispersion. For ECEP, it is stated in chapter 2 that if σ_R is less the 10 times σ_D the method of ECEP is appropriate for dispersion calculation. Therefore, if the tolerance bands for range and deflection are 104 m and 8 m then σ_R = 17.33 m and σ_D = 1.33 m respectively. As a result, ECEP is not the best method of dispersion calculation because σ_R is more than 13.3 m. Consequently, because of that the previous two method are not appropriate, the enclosing rectangle is the best way to calculate the system dispersion.

For each of firing group of zone 6, PE_R and PE_D is determined and the shape of the rectangle is drawn. Then, the total of PEs is calculated to generate the hit probability of zone 6. When the total value of PE_R and PE_D is calculated, RSS is used to sum them because they are standard deviation values. As stated in section 2.2.1.3 of a previous study that if σ_{MV} is 0.83 m/s the value of PE_R will be 70 m. By compering this value of PE_R to the result in Table 4-6, the result of PE_R of the framework shows approximately the same (69 m) when σ_{MV} is 0.87 m/s.

Table 4-6 MACS performance

	Enclosing Rectangle		**Results**			
Firing Group	**PE_D**	**PE_R**	**Zone 6**	**Zone 5**	**Zone 4**	**Zone 3**
Elev. 10	26 m	2 m	250 shots	288 shots	210 shots	201 shots
Elev. 9	27 m	2 m	250 shots	325 shots	244 shots	196 shots
Elev. 8	26 m	2 m	250 shots	308 shots	235 shots	214 shots
Elev. 7	28 m	2 m	250 shots	302 shots	251 shots	214 shots
Elev. 6	22 m	1 m	250 shots	326 shots	227 shots	155 shots
Elev. 5	15 m	1 m	250 shots	192 shots	214 shots	132 shots
Elev. 4	16 m	1 m	250 shots	177 shots	104 shots	74 shots
Elev. 3	24 m	1 m	250 shots	425 shots	227 shots	263 shots
Elev. 2	12 m	1 m	250 shots	289 shots	52 shots	222 shots
Elev. 1	12 m	1 m	250 shots	363 shots	54 shots	78 shots
Total (RSS)	**69 m**	**5 m**	2500 shots	2995 shots	1818 shots	1749 shots
Consistency	-	-	**50%**	**60%**	**36%**	**35%**
Accuracy	-	-	**21 m**	**16 m**	**36 m**	**22 m**

Next, each rectangle per firing group will be drawn over the same firing group of the other zones. The rectangle of all firing groups per zones can be seen in Appendix B. Now, firing shots inside each triangle are counted to produce the consistency for each zone, 50% for zone 6, 60% for zone 5, 36% for zone 4 and 35% for zone 3. Last, the remaining performance measure is the accuracy of MACS which is the difference between MPI and TPI. It is also maintained by RSS of each firing group. The results of MACS consistency and accuracy are seen in Table 4-6. The outcome values of zone 5 show higher performance in both consistency and accuracy results while the zone 4 and 3 have lower performance.

4.5 MACS performance discussion

Output from the models for CMD (CM_6), CMS (CM_5), CMS (CM_4) and CMS (CM_3) in Figure 4-2 showed that repeated reduction in scale by subtracting one-sixth of the full-charge mass and a reduction in mean and standard deviation, indicating less variation and a more normalised distribution of values, see Table 4-2. This behaviour is expected as a reduction in scale would result in lower mean and standard deviation.

Results from stochastic models in Figure 4-3 using input from simulated points based on the data obtained above showed an expected repeated reduction in mean values for CM_4 and CM_3. However, there was an increase in variation as clearly indicated by the skewed distribution for MV_4 and MV_3, see Figure 4-12. This distribution may be due to the differences in efficiency in MV_6, MV_5, MV_4 and MV_3, which is likely to be related to the sizable increase in chamber volume.

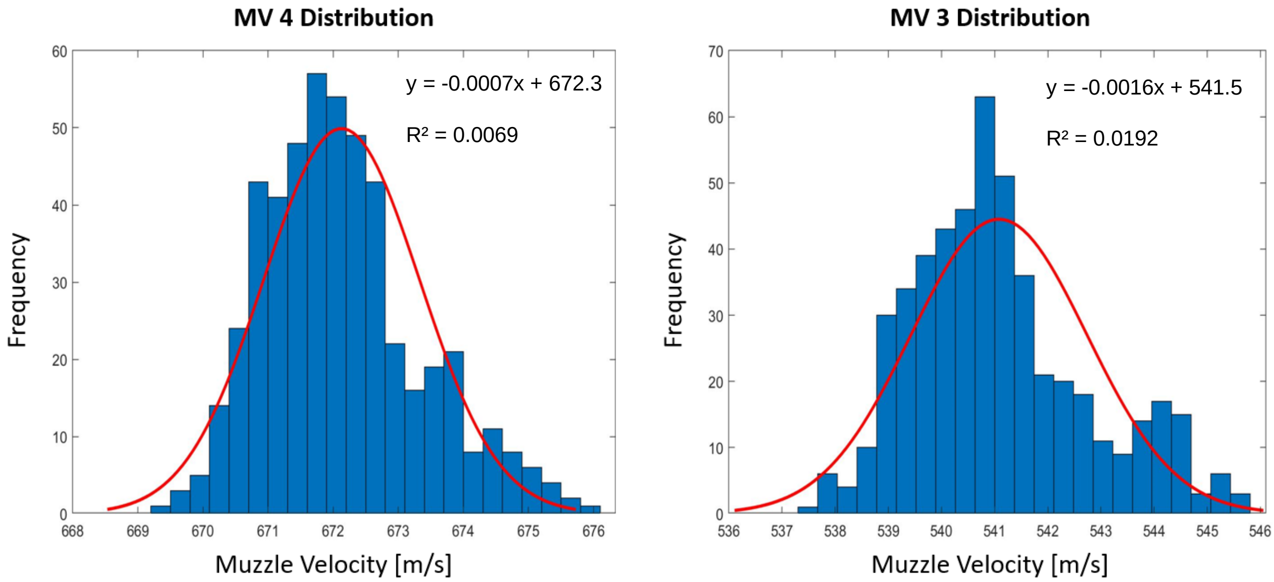


Figure 4-12 MV distribution for charge 4 and 3

MACS is designed to meet the requirement of maximum range by characterising the charge 6 to generate the desired MV. When the integration process of MACS (modularisation) takes place, the system is composed of a reduction in its performance. This reduction is 28% in zone 4 and 30% in zone 3 due to the variations in MV values in charge 4 and charge 3.

Figure 4-13 and Figure 4-14 show the range of variations in horizontal green band representing the manufacturing limits which is 6 times sigma of MV_4 and MV_3, respectively. The range of designed-to in red band straiten the acceptable operation limits and defined as the above and below 3 sigma zone of MV_6. The area that is backgrounded in diagonal orange strips represents the zones that exceed the design zone leading to MACS moving outside specification. These figures show a broad demonstration of limitation to charge and projectile manufacturing variations. The design and system engineers, as mentioned before with lake of prediction, have now the ability to observe the effect of charge and projectile design parameters to the overall system specifications.

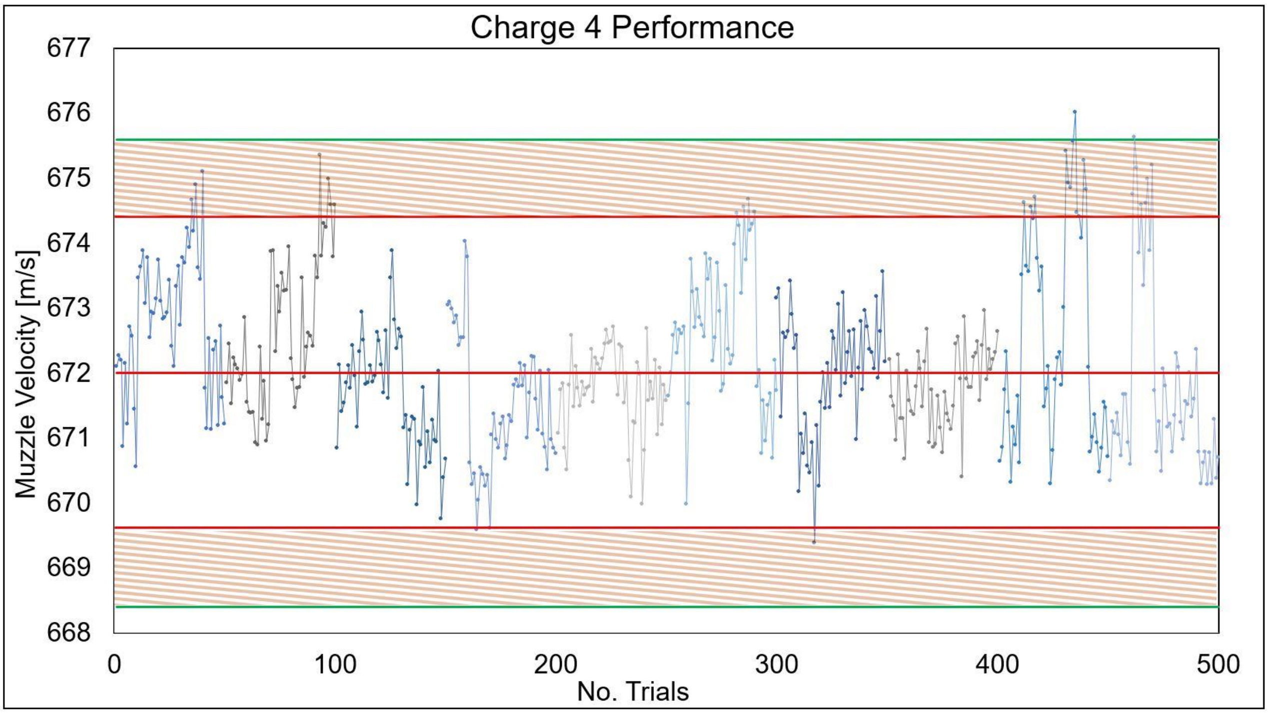


Figure 4-13 Charge 4 performance

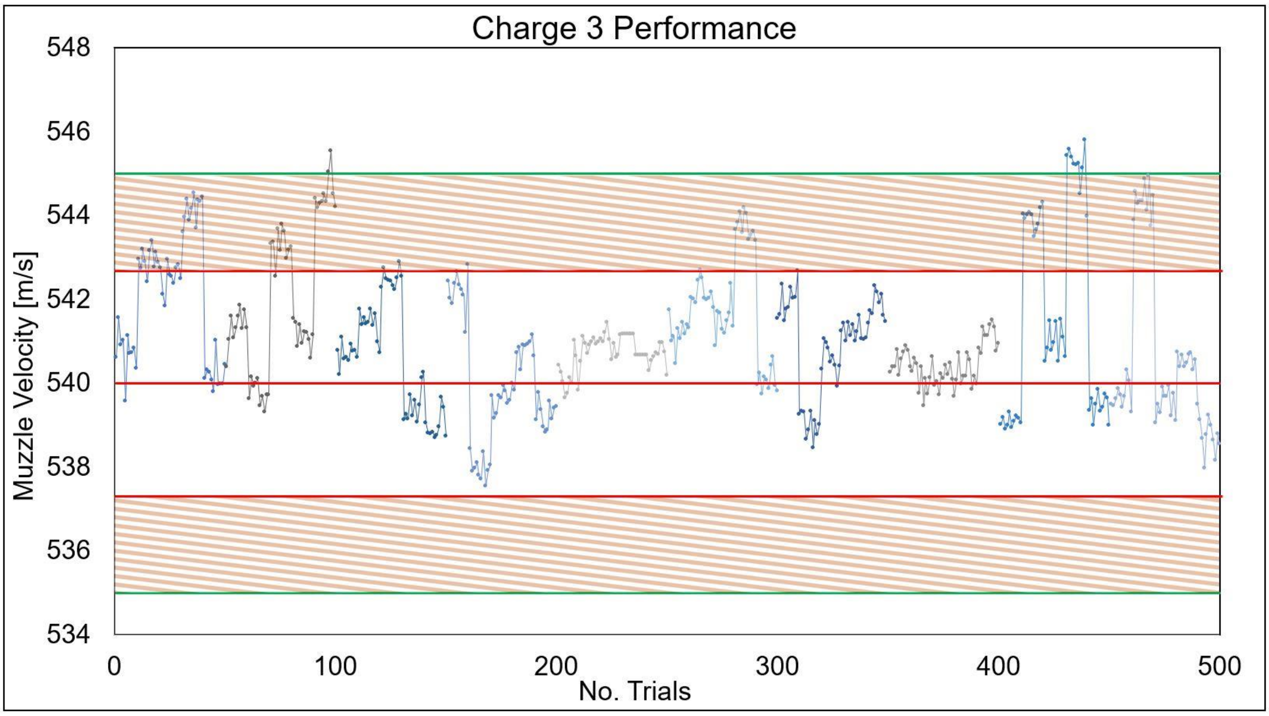


Figure 4-14 Charge 3 performance

4.6 Conclusion

The practice of developing MACS has remarkable shortages in terms of consistency of the overall performance to all its operational conditions. It is observed that the performance reduction in different MACS modules is resulted throughout divergent errors starting from the dissimilarities in the propellant grains, projectile and gun dimensions expanding to the differences in the system efficiency. The fulfilment of MACS requirement regarding the mobility of the system restricts the designer to modulate the charges to the same mass segments. This design restriction limits the designer to enhance the system or increase the sufficiency of its performance.

The study results showed how variabilities in the manufacturing of MACS's charge and projectile can constitute the performance of the system. Small manufacturing tolerance, for example in projectile mass, leads to shifts in consistency and accuracy values of the system. As the problem mentioned early in chapter 1, predicting these shifts and their causes can help the design engineers to consolidate development efforts, hence, improve design decision making.

4.7 Recommendations

To improve the system performance is to increase the quality control in the manufacturing side to reduce the variations in the dimensions and masses of the CIs. This quality control will decrease the variation in MV outputs of the IB sub-system and ensure adequate consistency and accuracy of the system. Thus, the multiplication of the errors throughout the development phases can be maintained. Also, this research recommends studying the efficiency of the different MACS charge modules and investigates how the differences among them are generated as they decrease in the lower charge modules.

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Appendix A: Muzzle Velocity Variability (MVV)

A.1 Charge 6 performance

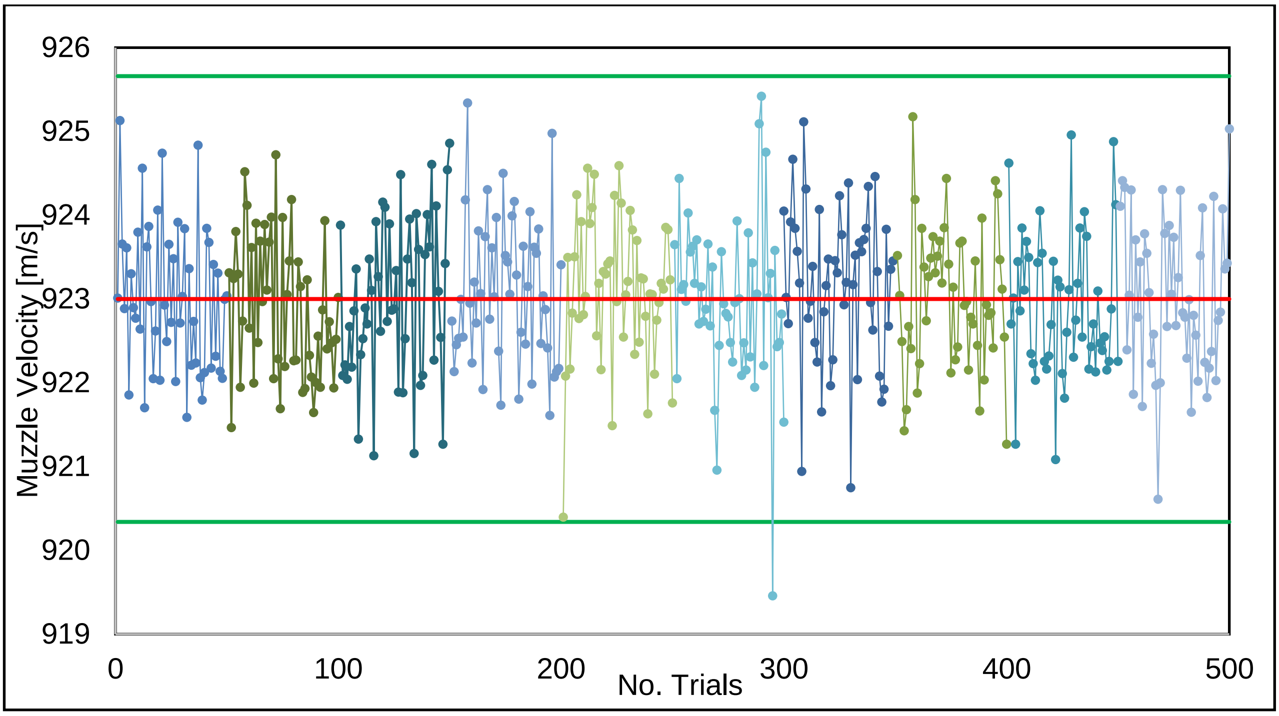

Figure A-1 Charge 6 performance

A.2 Charge 5 performance

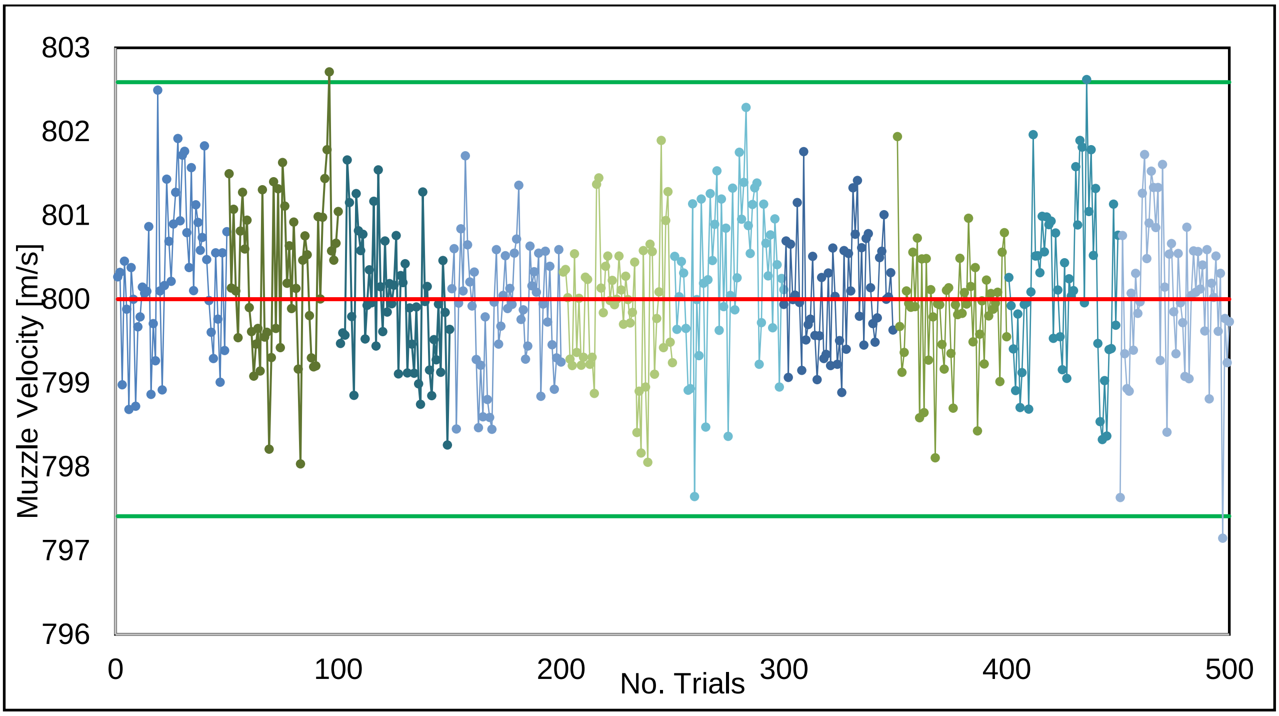

Figure A-2 Charge 5 performance

A.3 Charge 4 performance

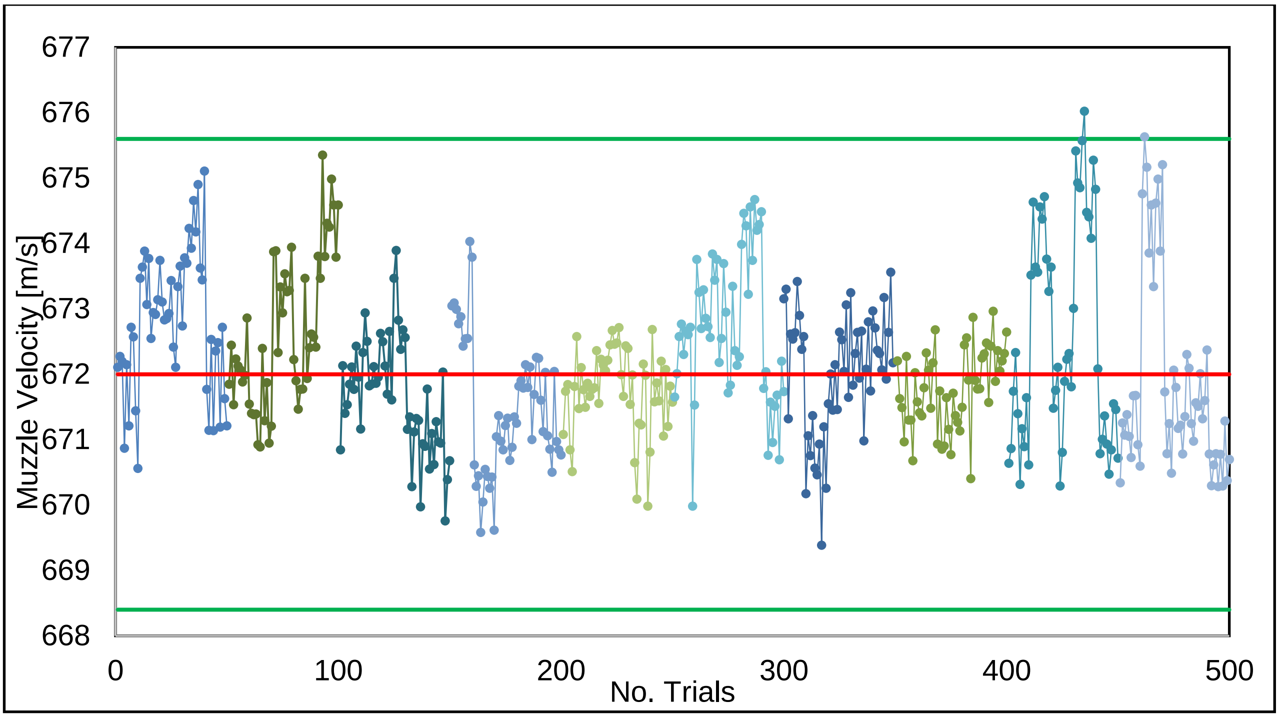

Figure A-3 Charge 4 performance

A.4 Charge 3 performance

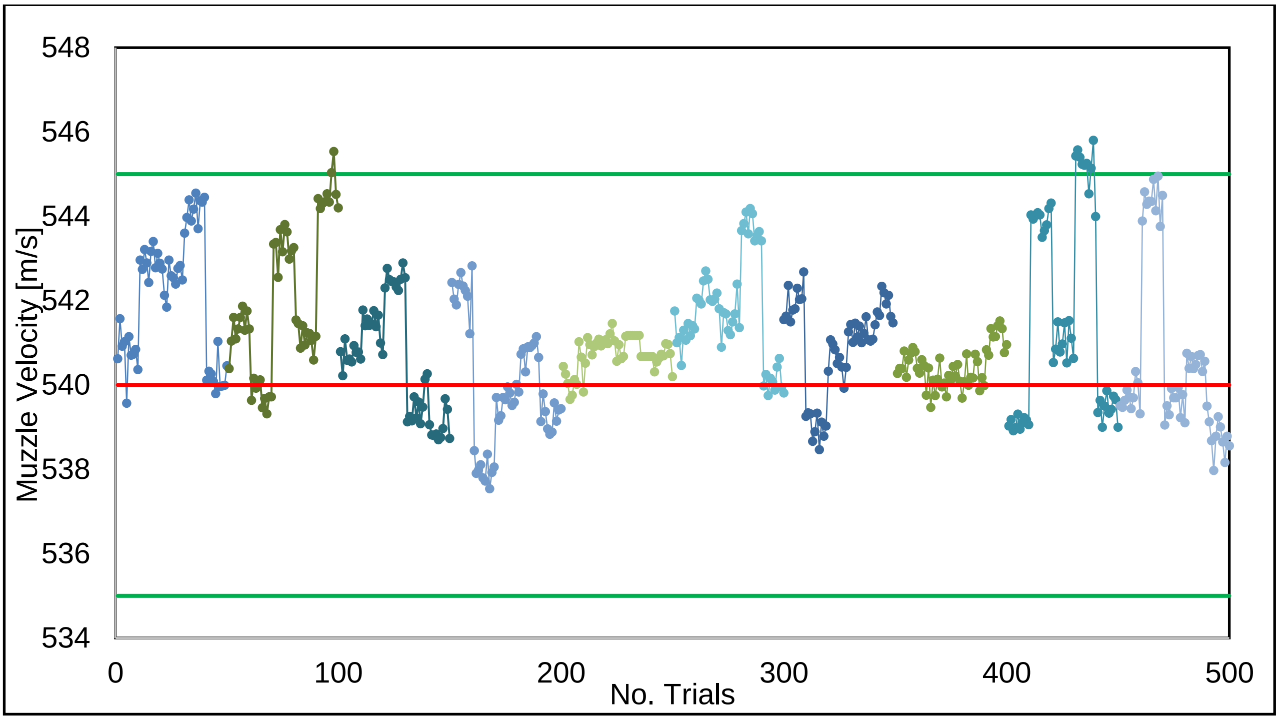

Figure A-4 Charge 3 performance

Appendix B: Firing groups plotting

B.1 Probable error plotting for zone 6.

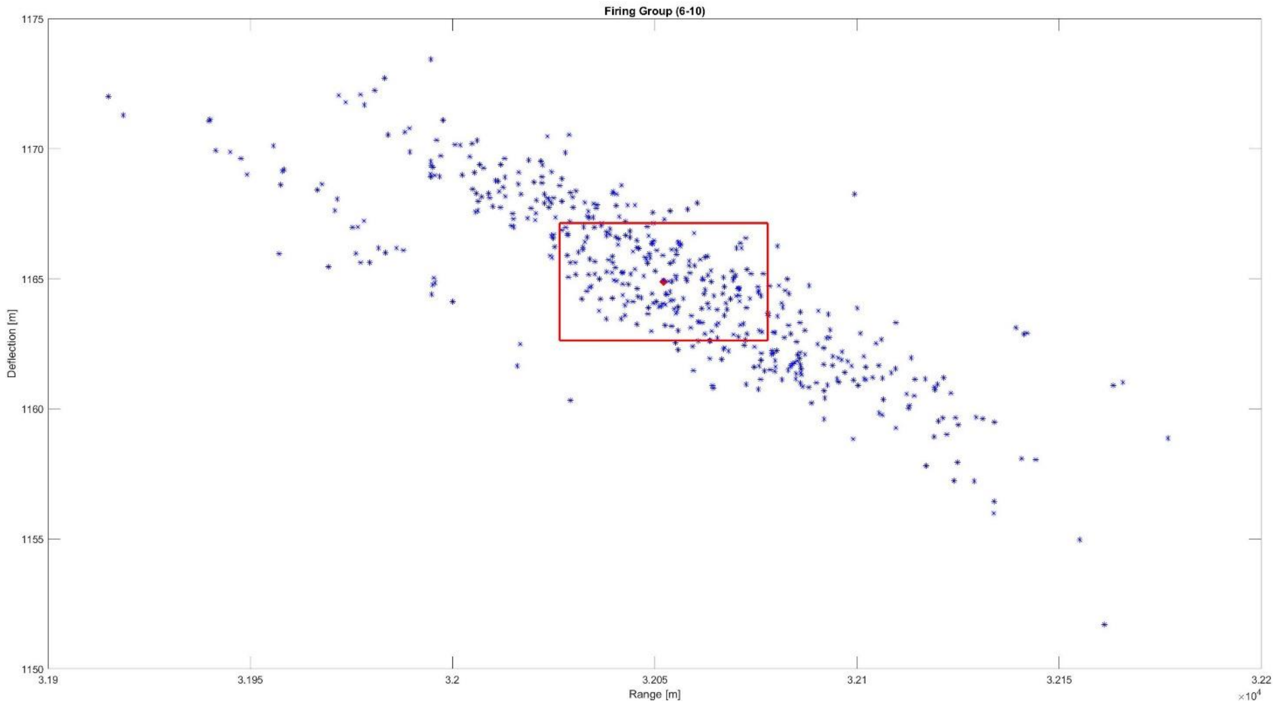

Figure B-1 Firing group zone 6 – elev. 10

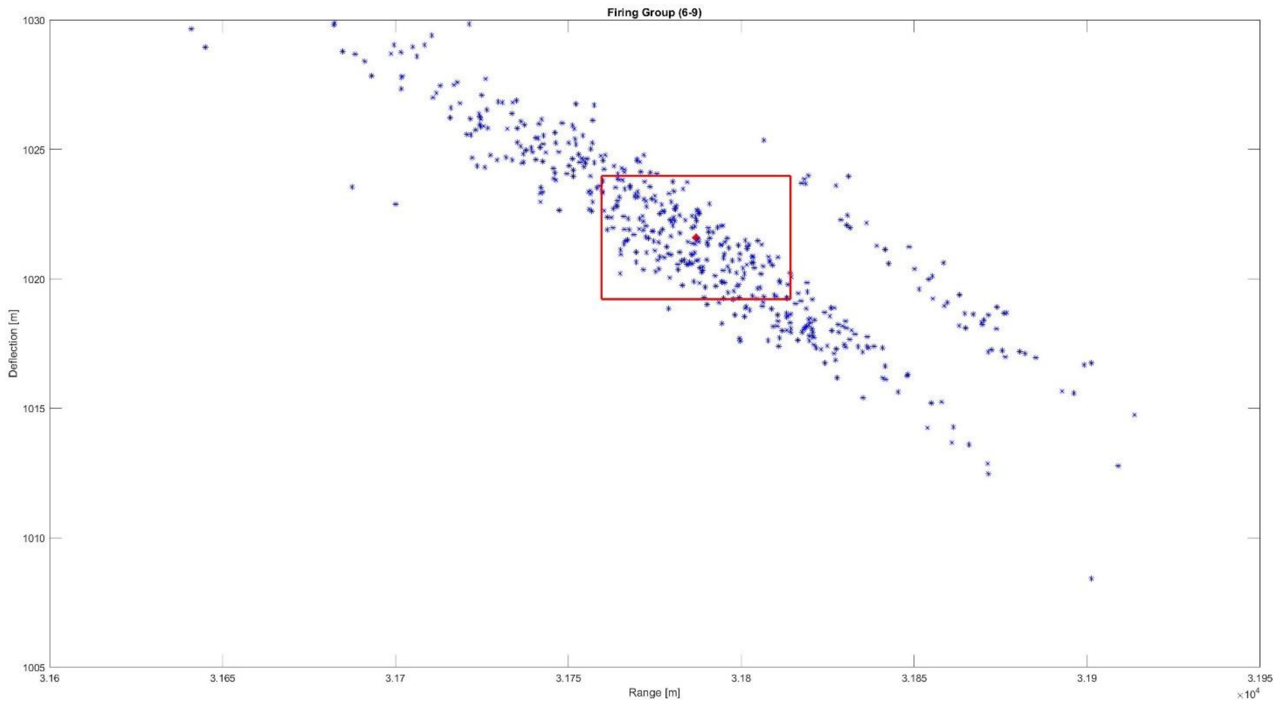

Figure B-2 Firing group zone 6 – elev. 9

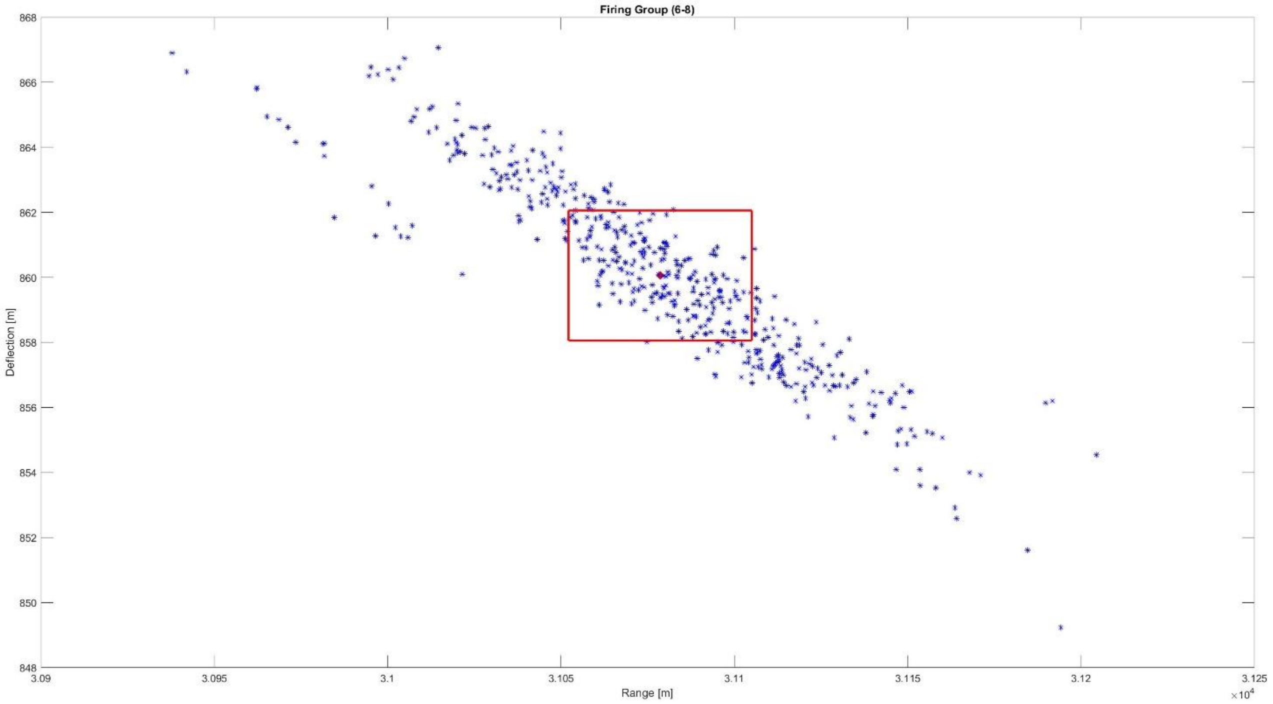

Figure B-3 Firing group zone 6 – elev. 8

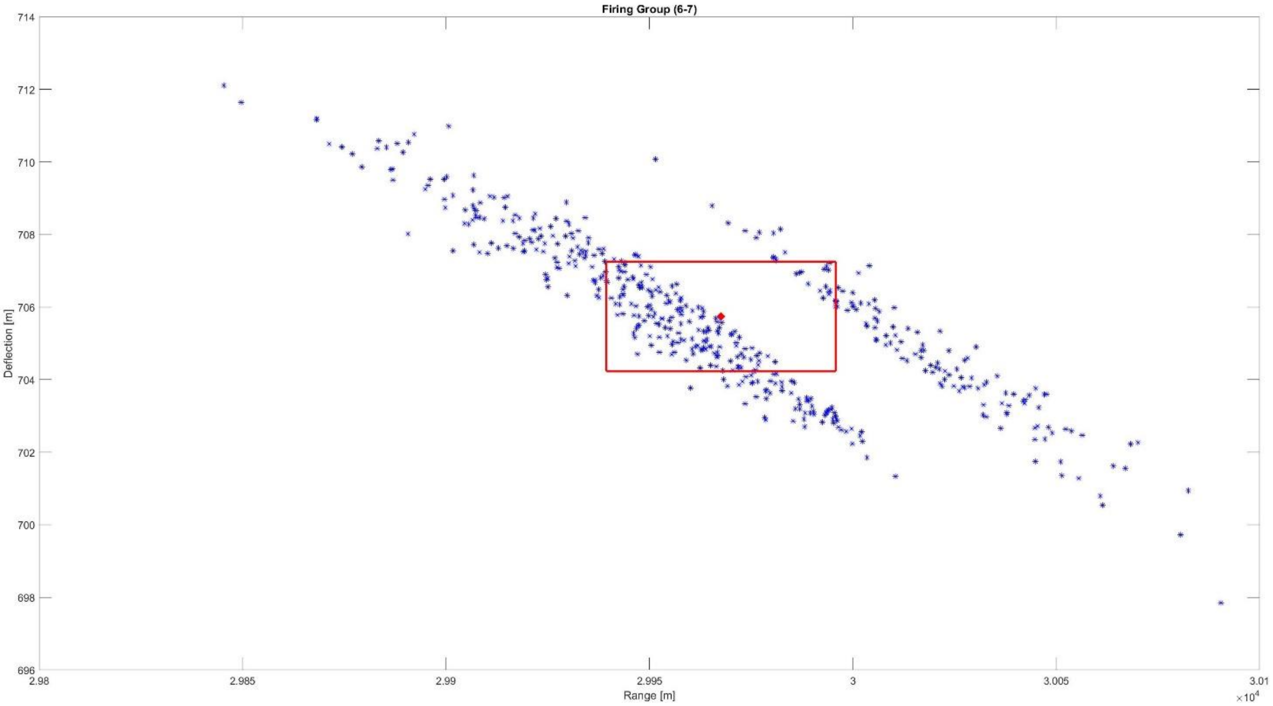

Figure B-4 Firing group zone 6 – elev. 7

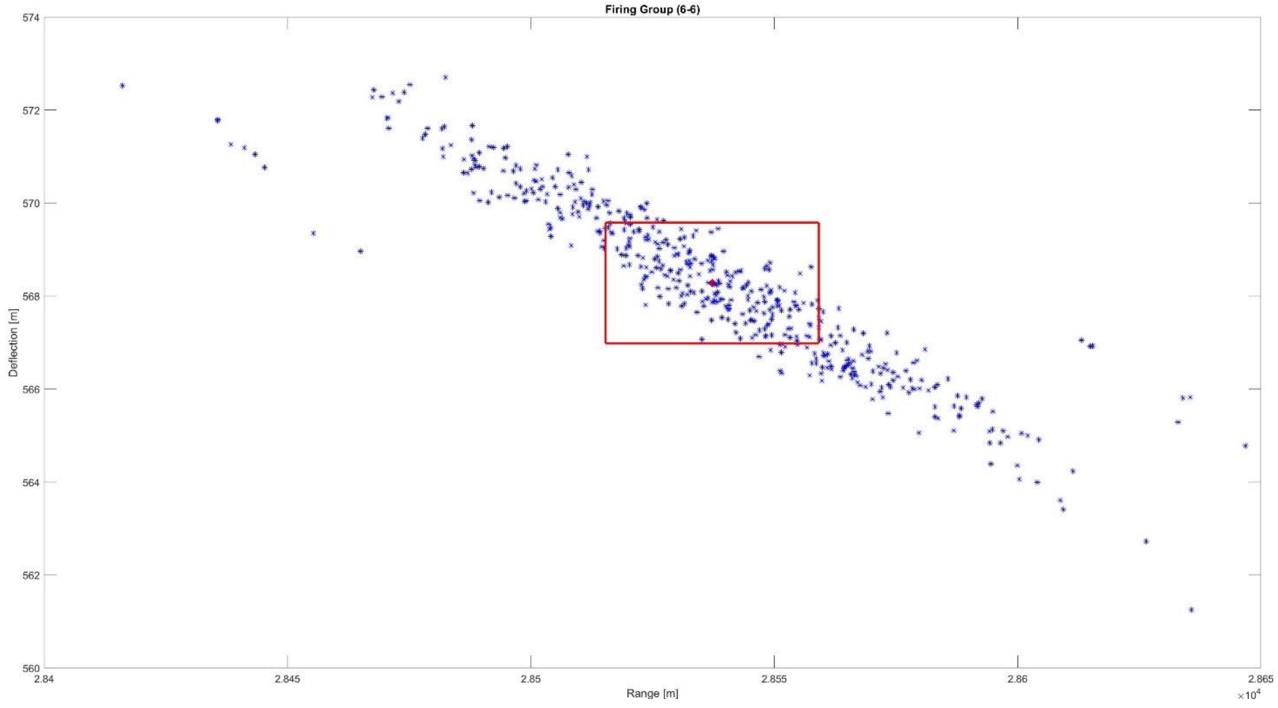

Figure B-5 Firing group zone 6 – elev. 6

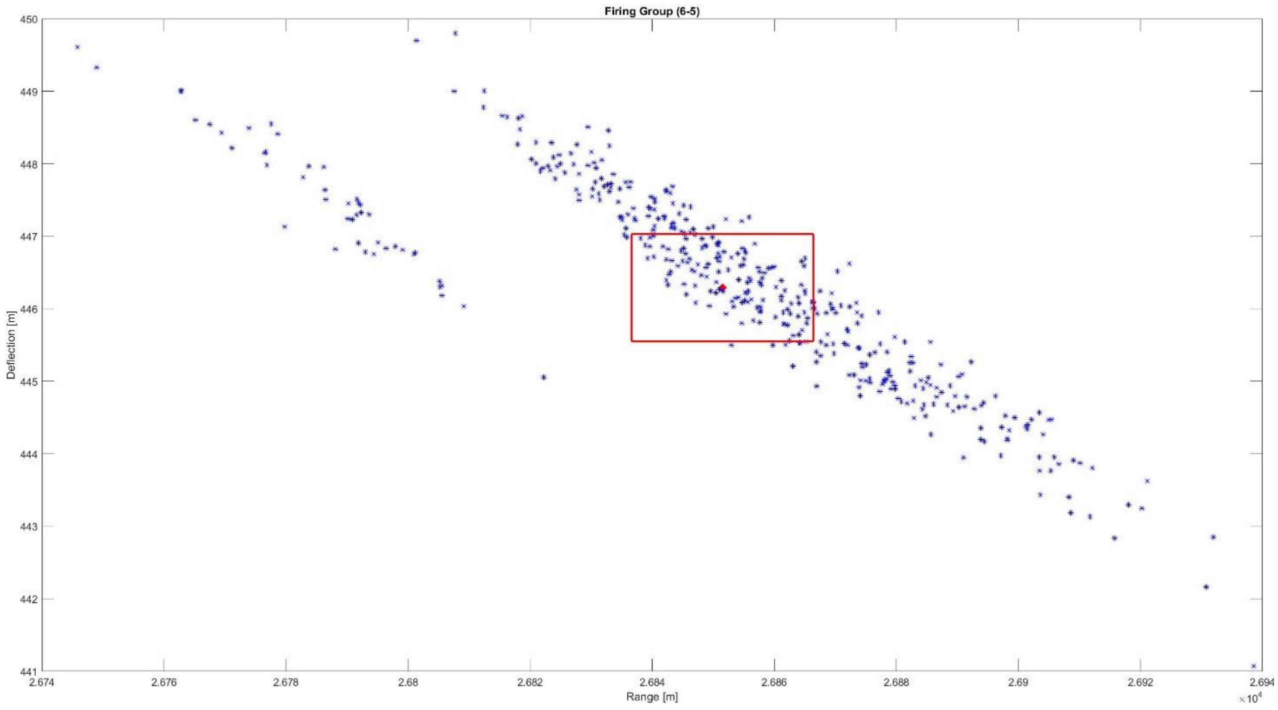

Figure B-6 Firing group zone 6 – elev. 5

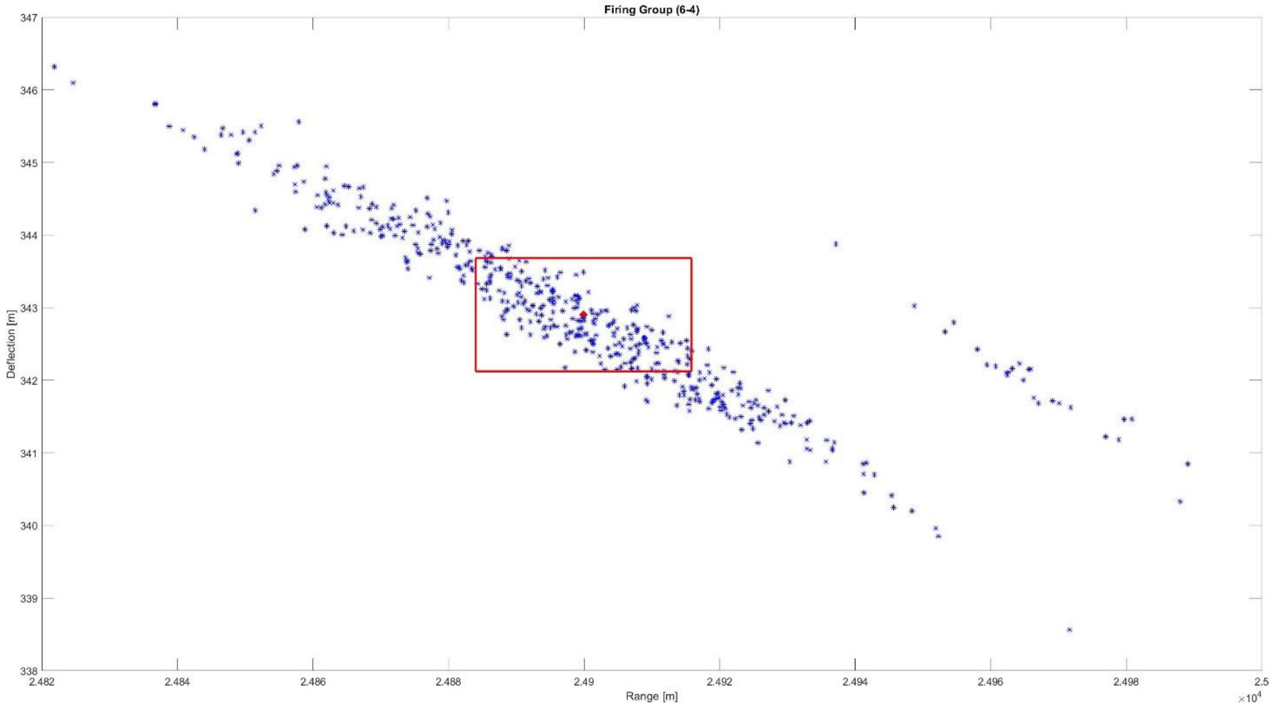

Figure B-7 Firing group zone 6 – elev. 4

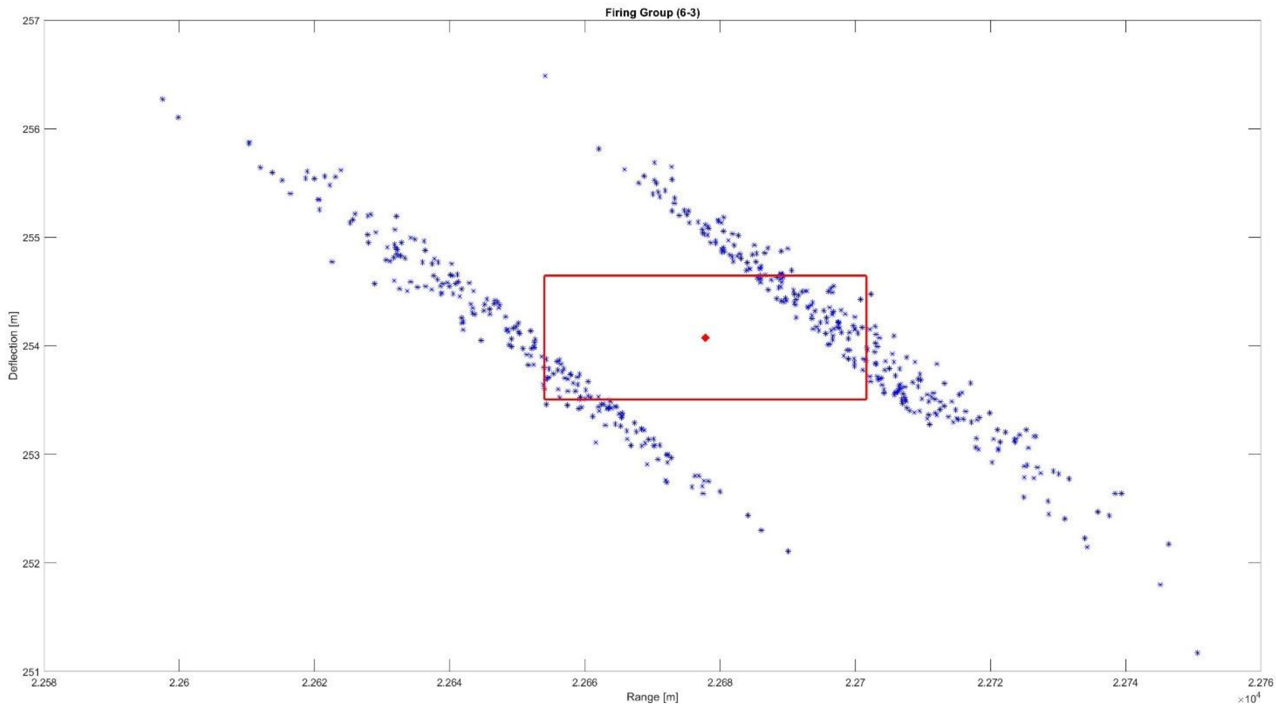

Figure B-8 Firing group zone 6 – elev. 3

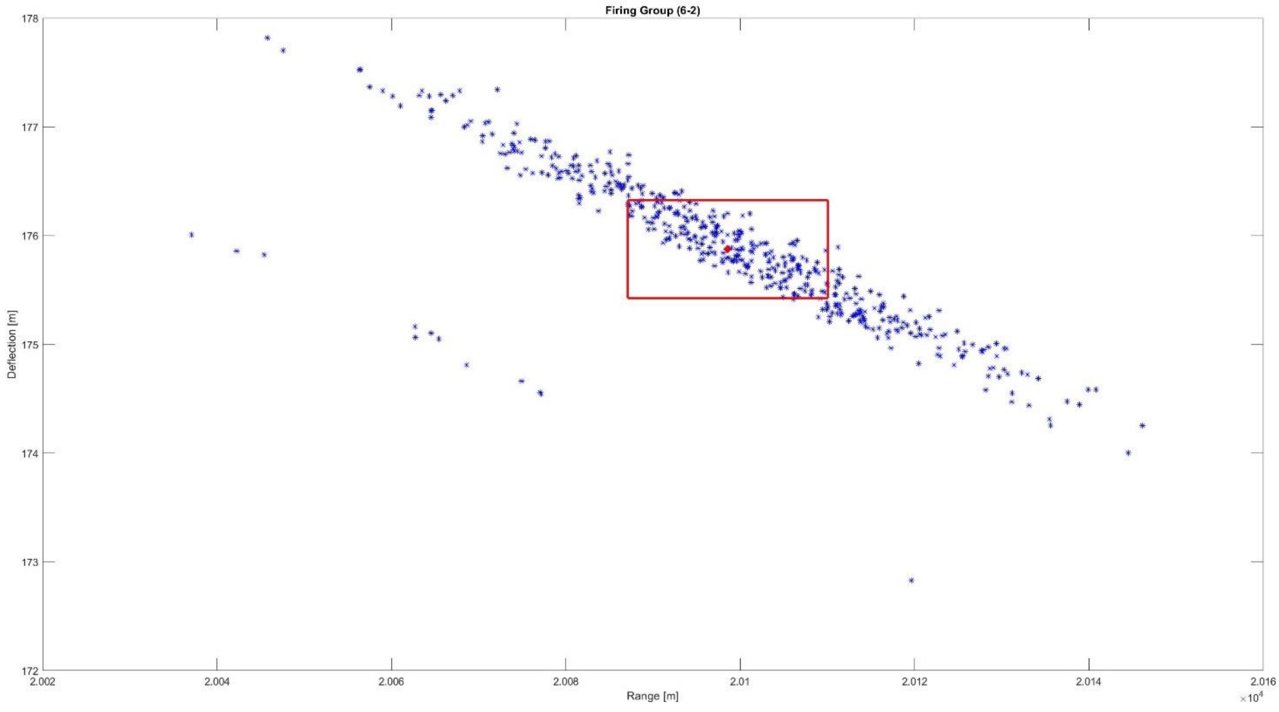

Figure B-9 Firing group zone 6 – elev. 2

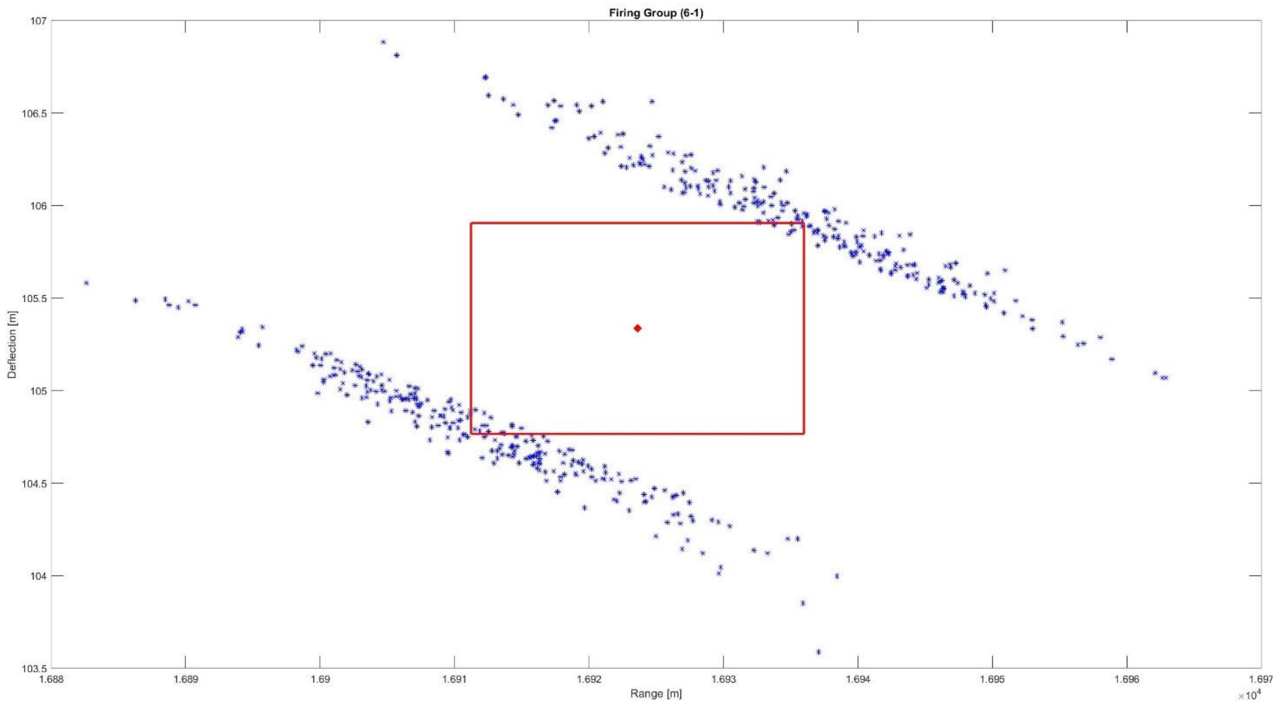

Figure B-10 Firing group zone 6 – elev. 1

B.2 Probable error plotting for zone 5.

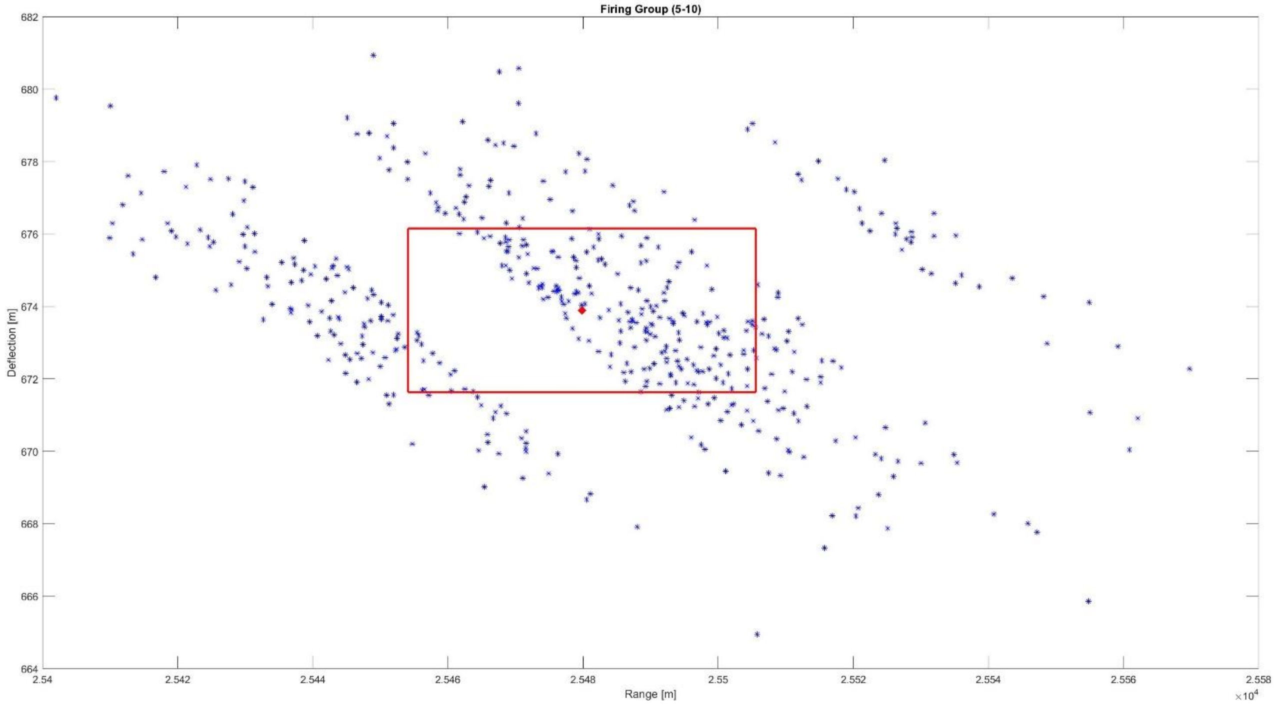

Figure B-11 Firing group zone 5 – elev. 10

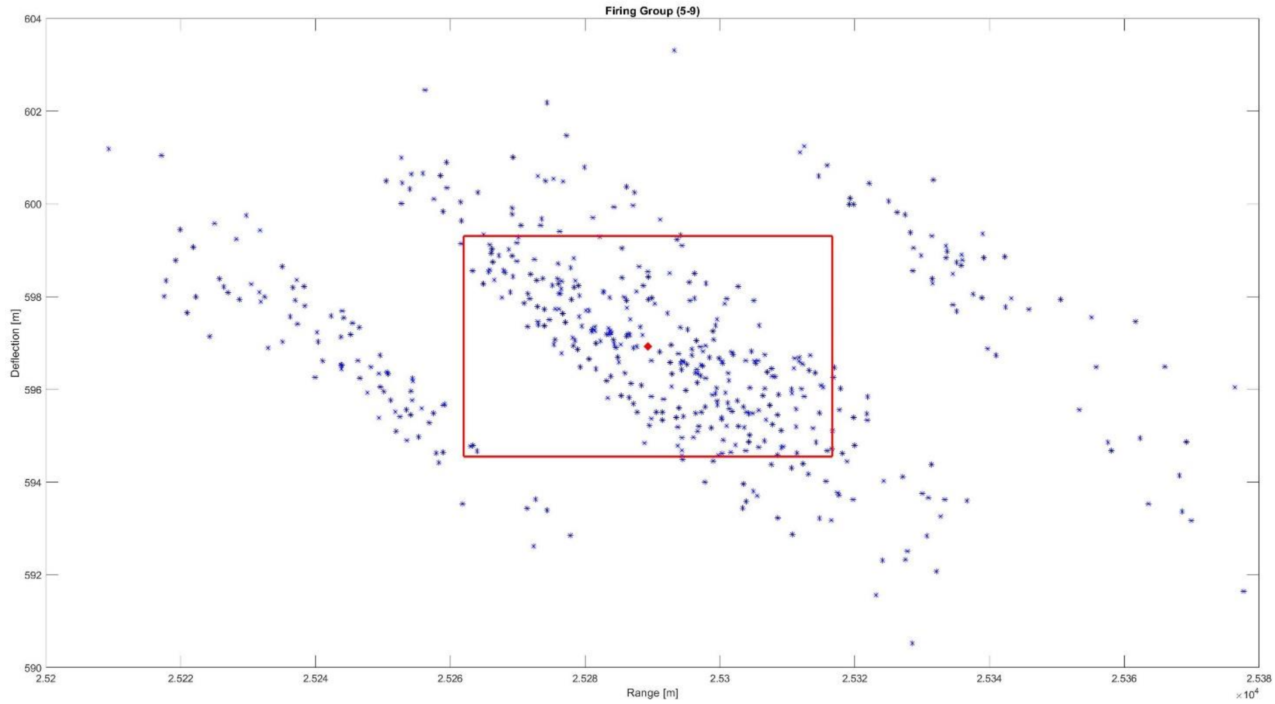

Figure B-12 Firing group zone 5 – elev. 9

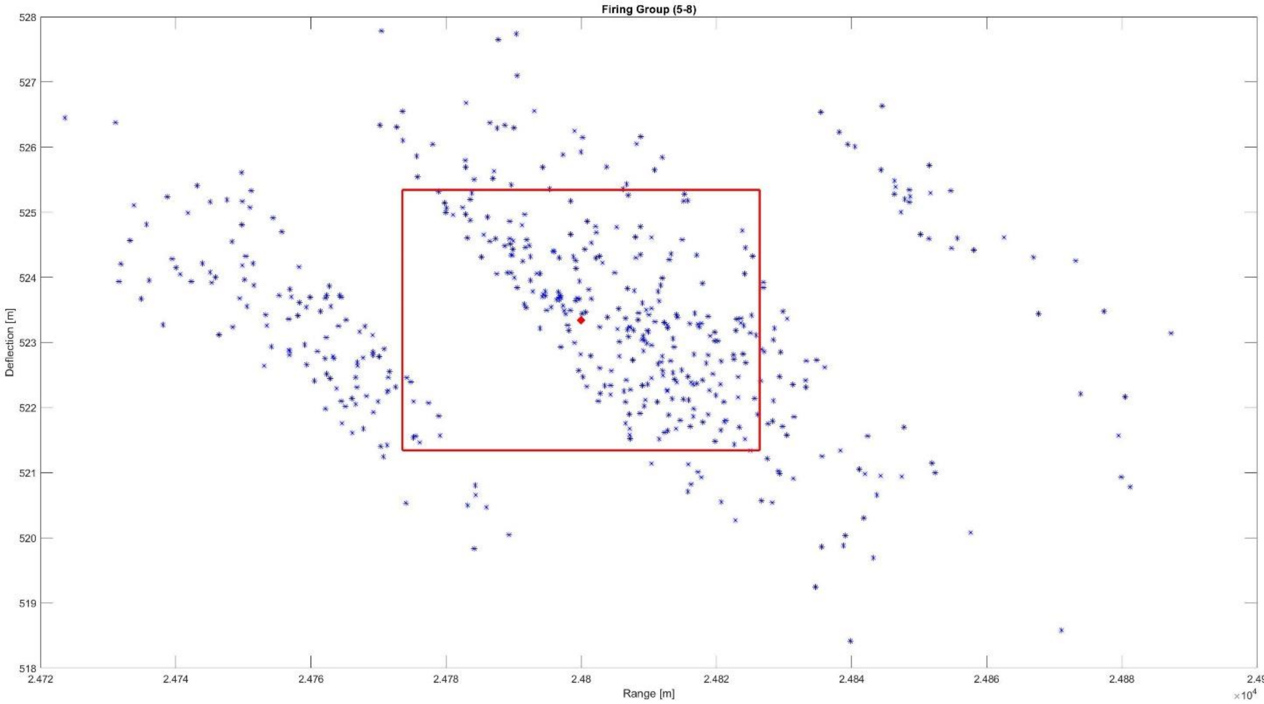

Figure B-13 Firing group zone 5 – elev. 8

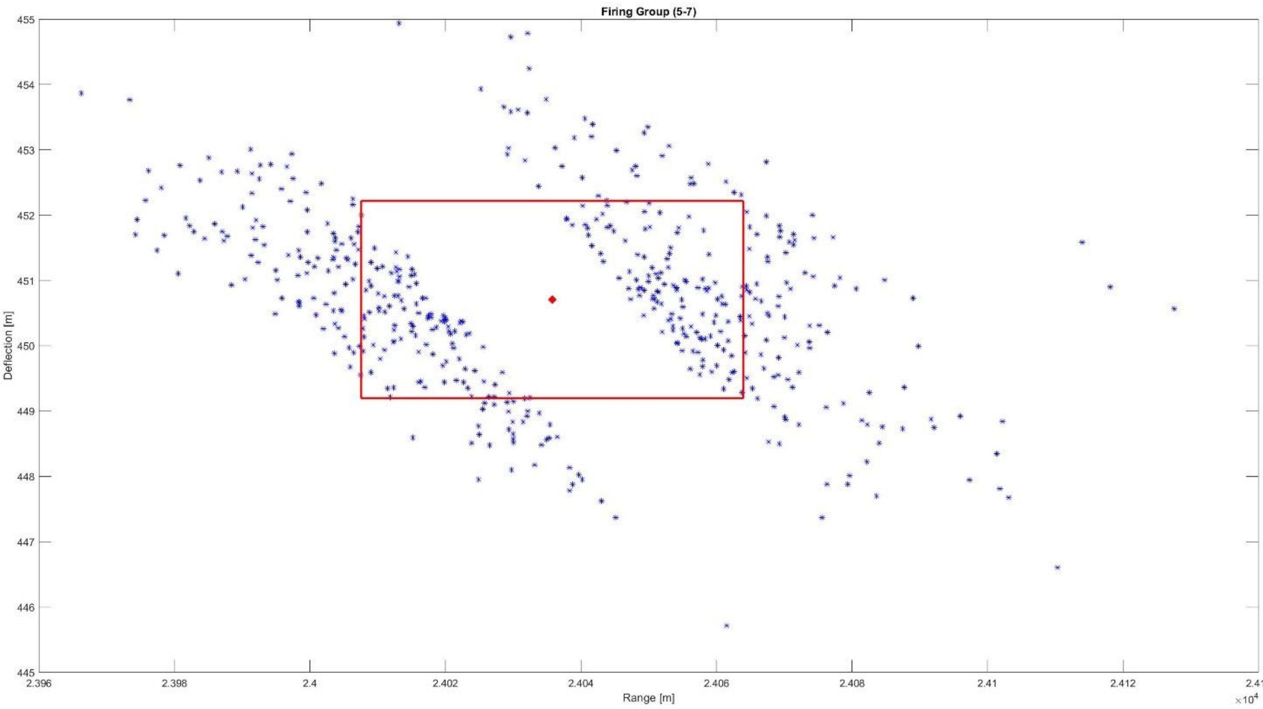

Figure B-14 Firing group zone 5 – elev. 7

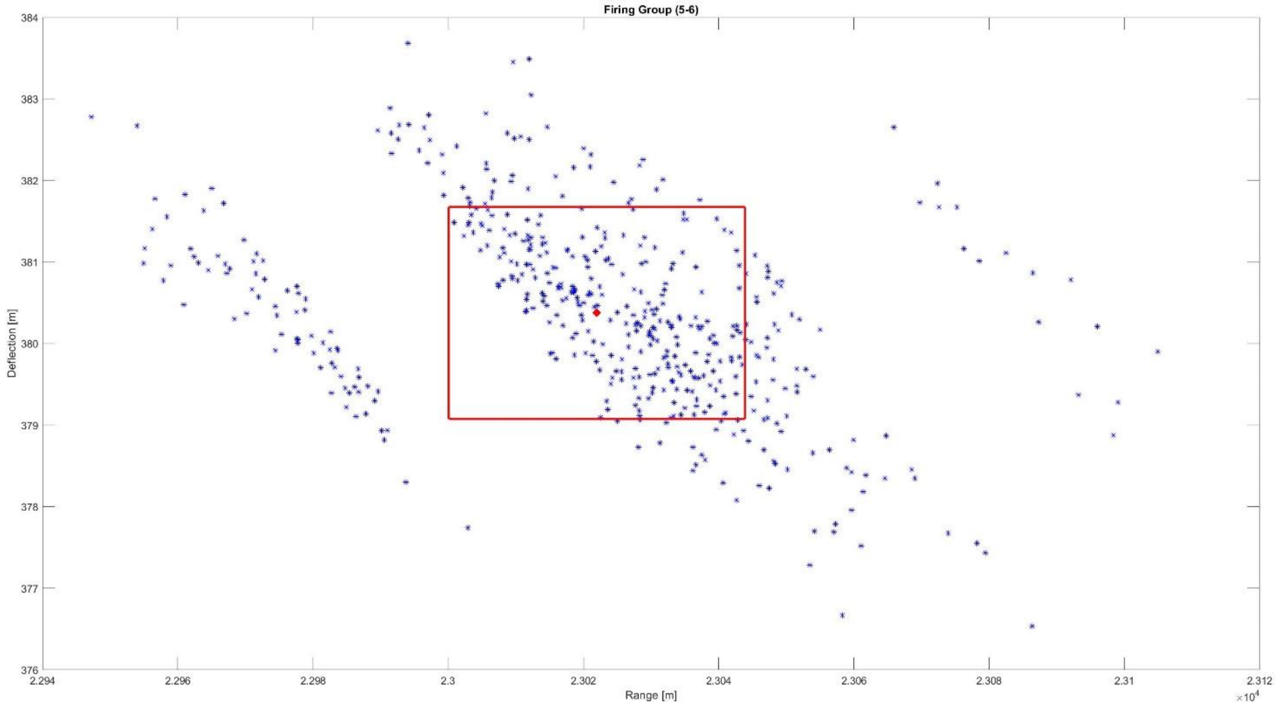

Figure B-15 Firing group zone 5 – elev. 6

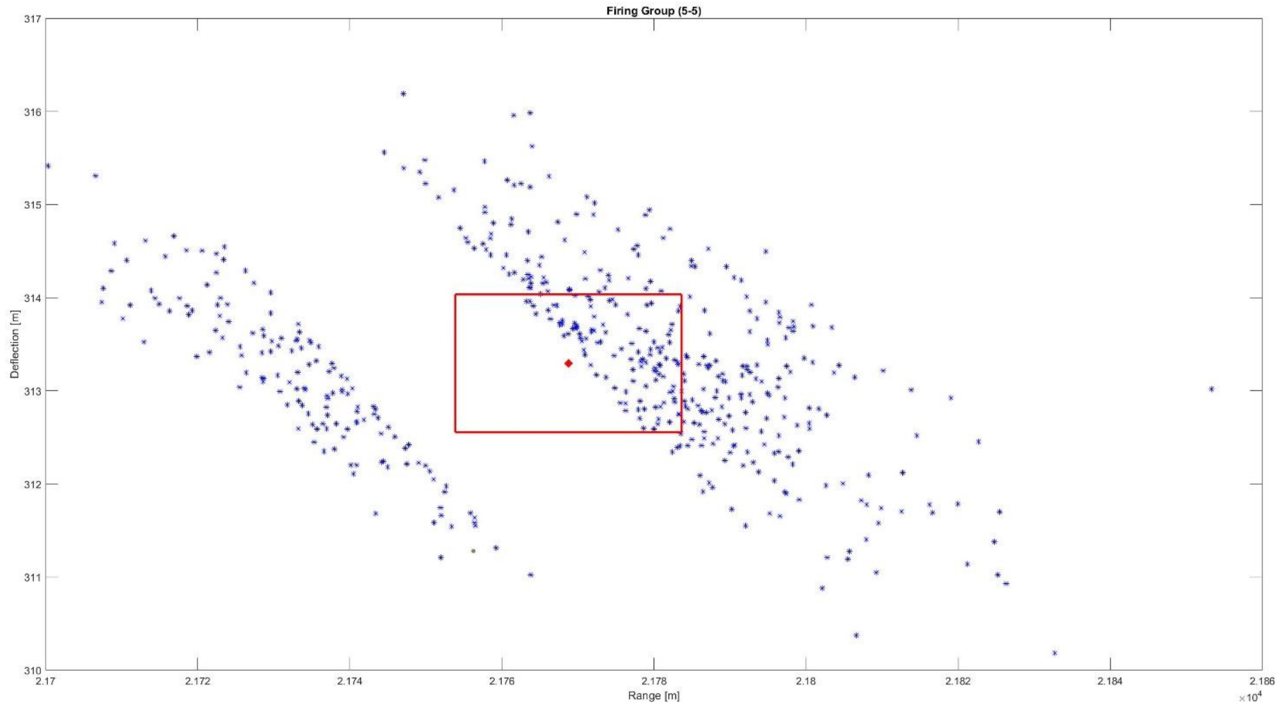

Figure B-16 Firing group zone 5 – elev. 5

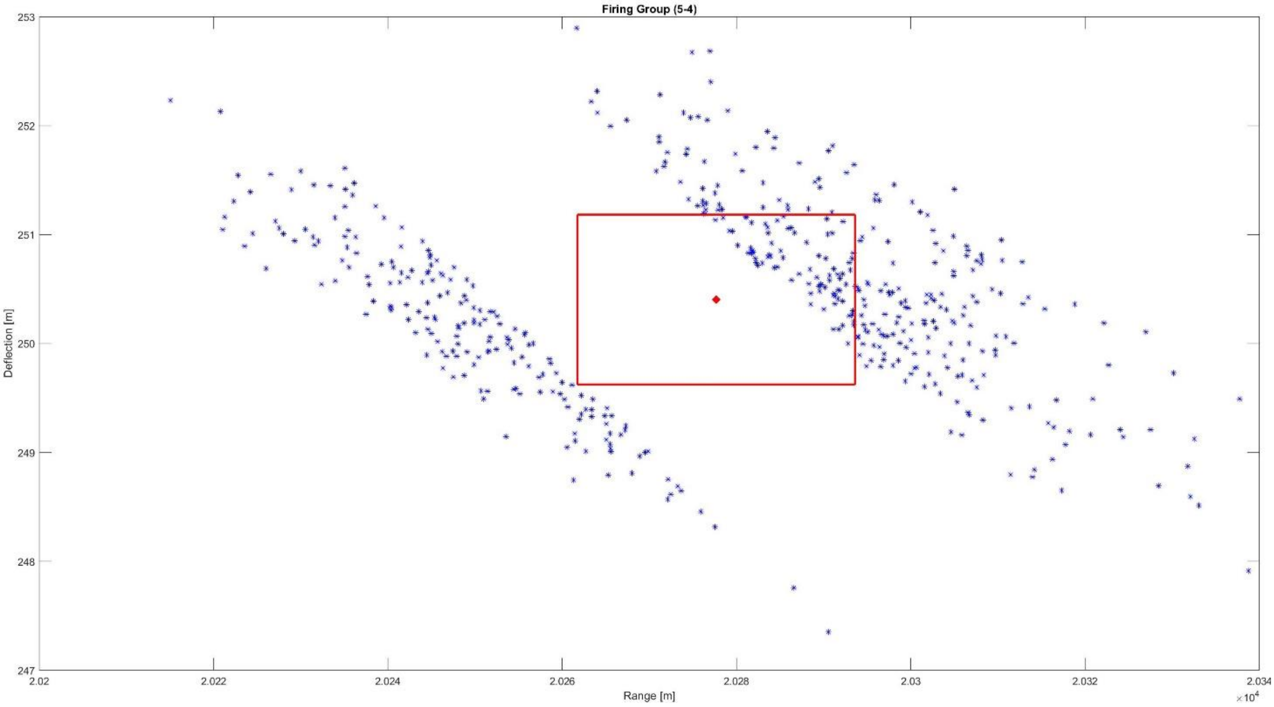

Figure B-17 Firing group zone 5 – elev. 4

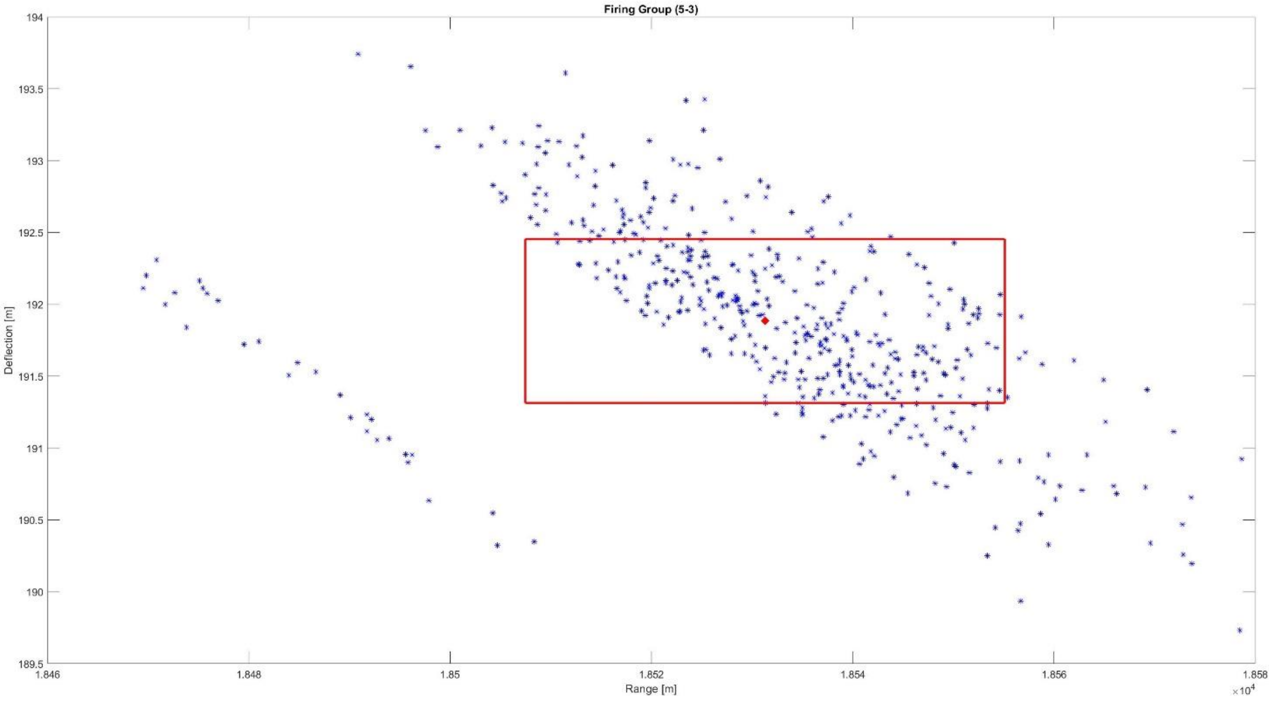

Figure B-18 Firing group zone 5 – elev. 3

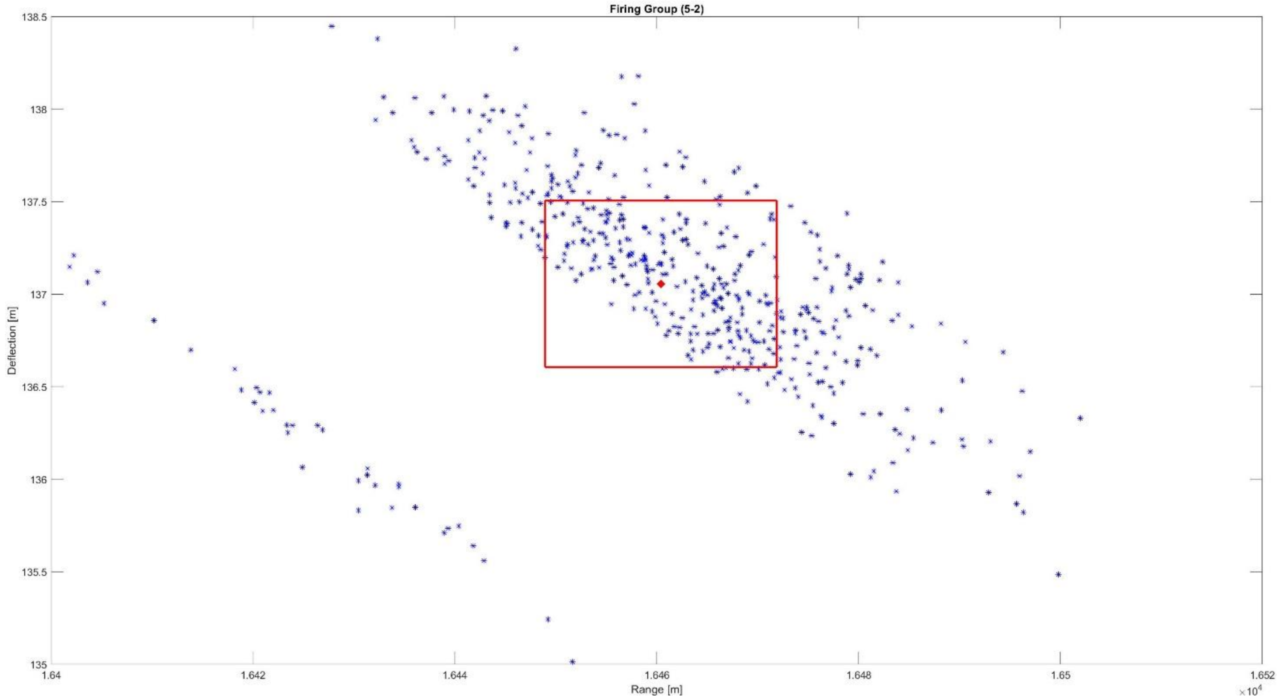

Figure B-19 Firing group zone 5 – elev. 2

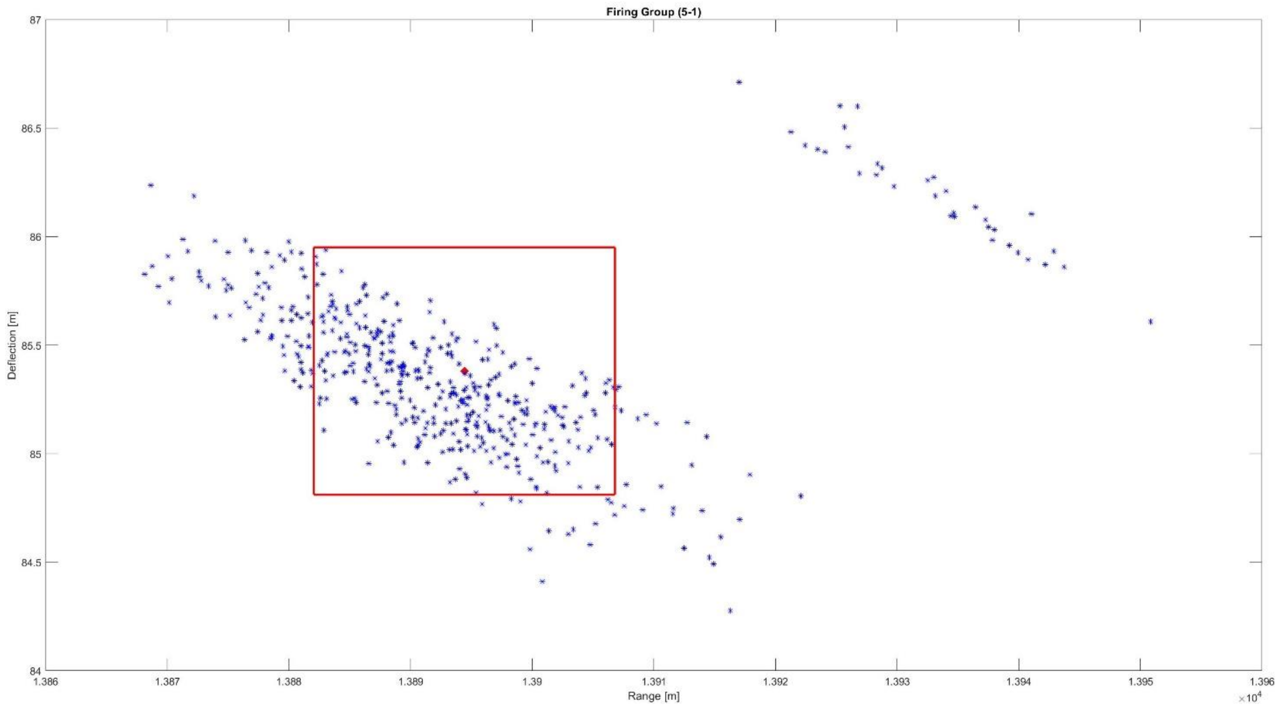

Figure B-20 Firing group zone 5 – elev. 1

B.3 Probable error plotting for zone 4.

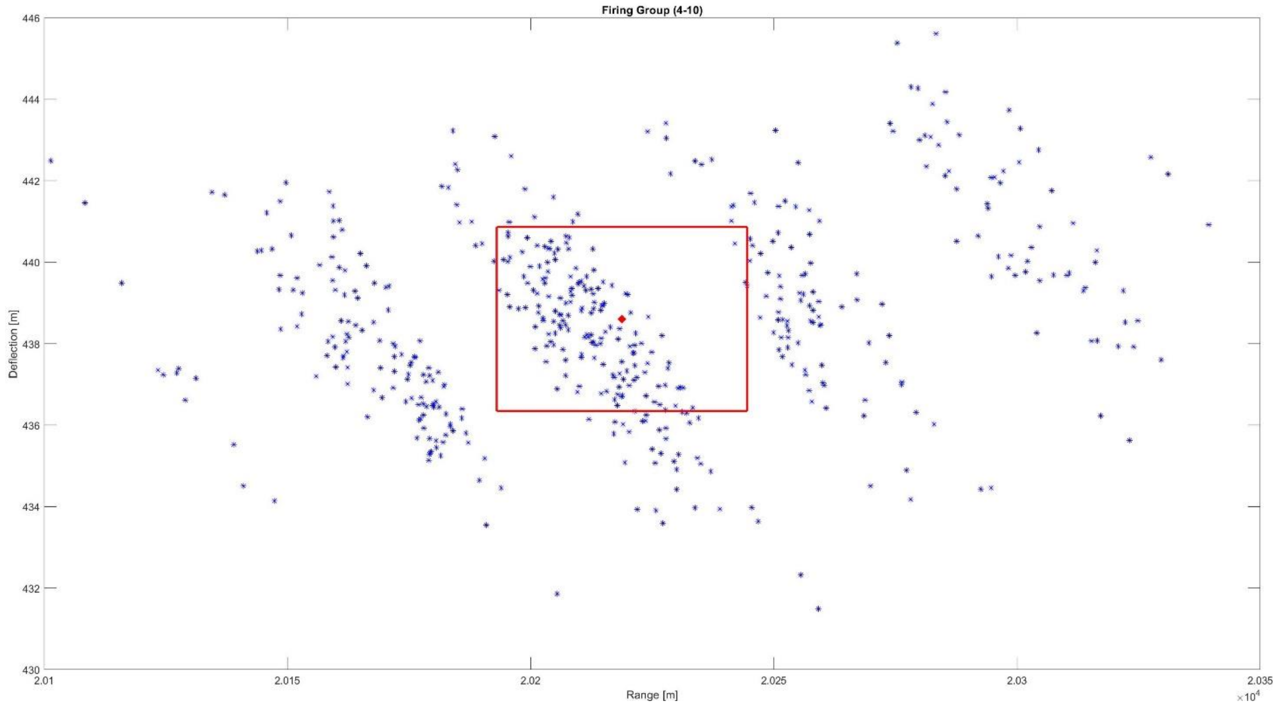

Figure B-21 Firing group zone 4 – elev. 10

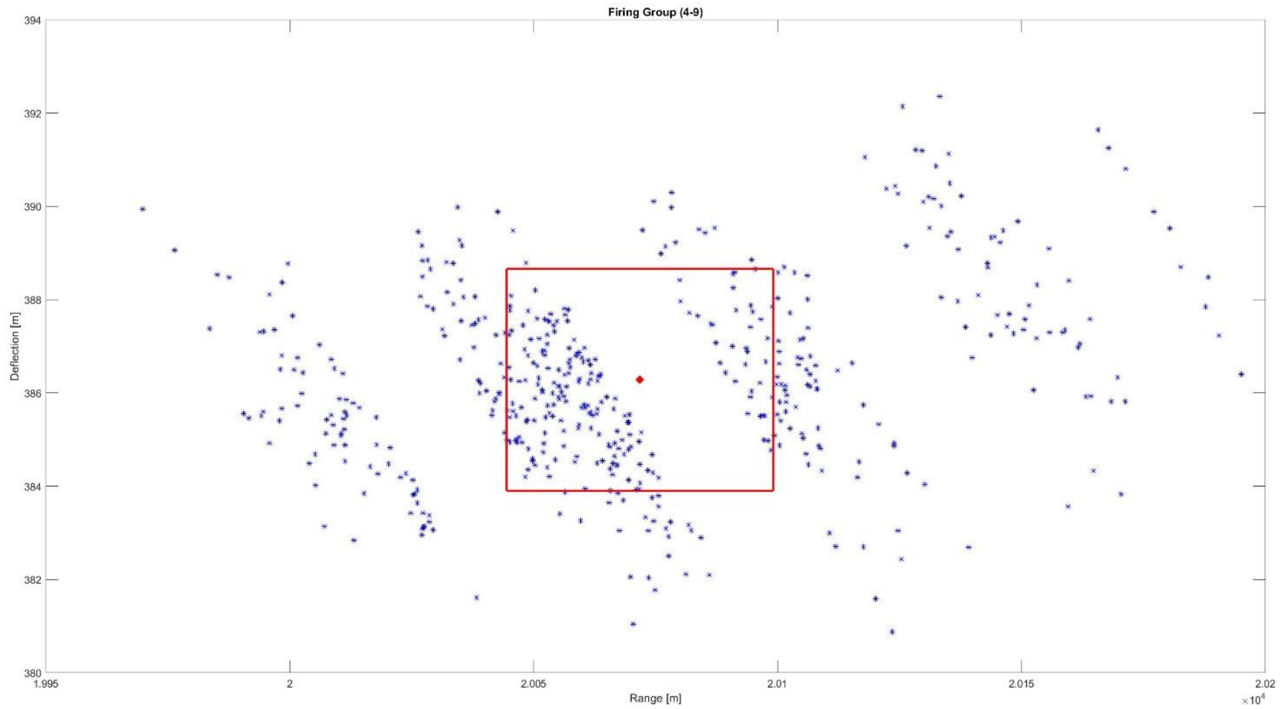

Figure B-22 Firing group zone 4 – elev. 9

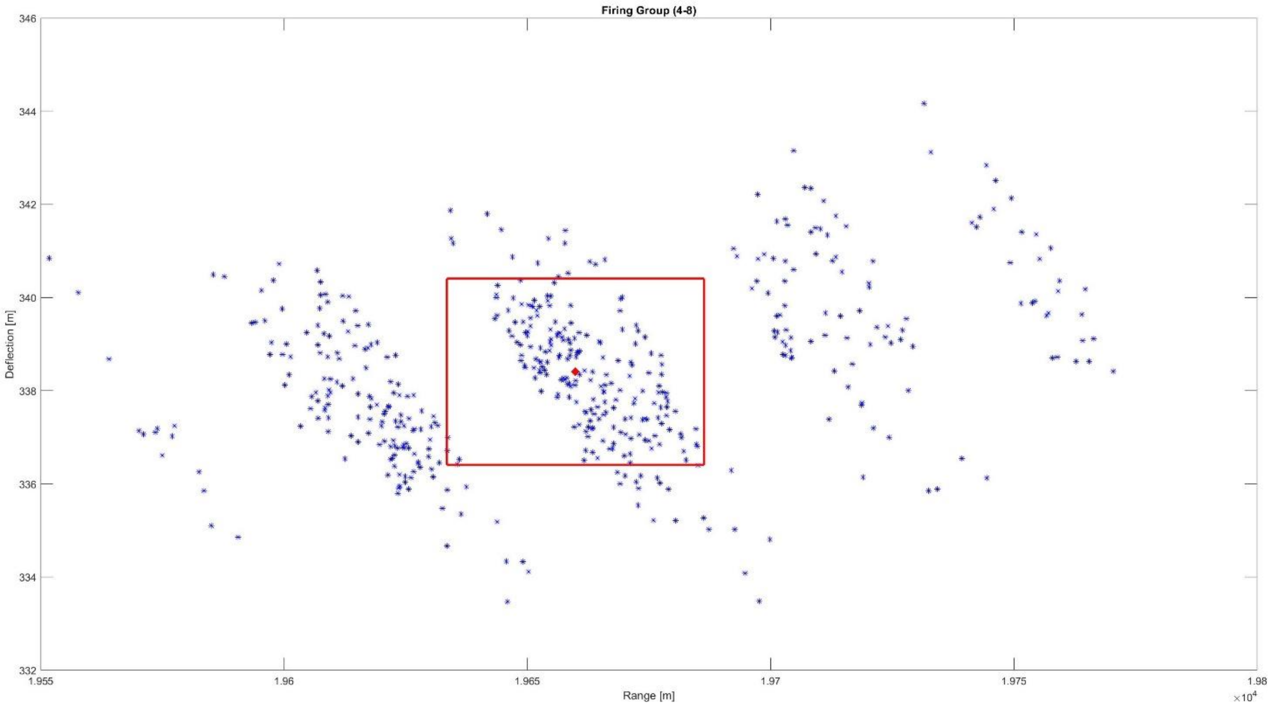

Figure B-23 Firing group zone 4 – elev. 8

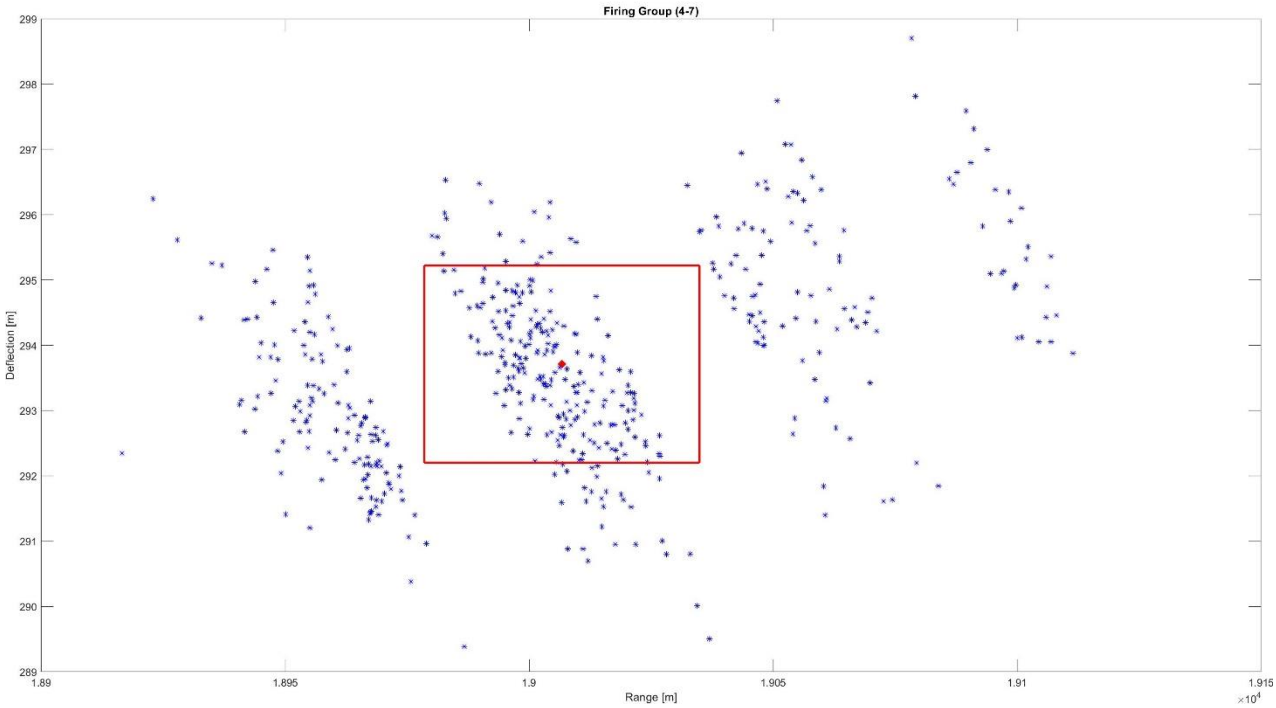

Figure B-24 Firing group zone 4 – elev. 7

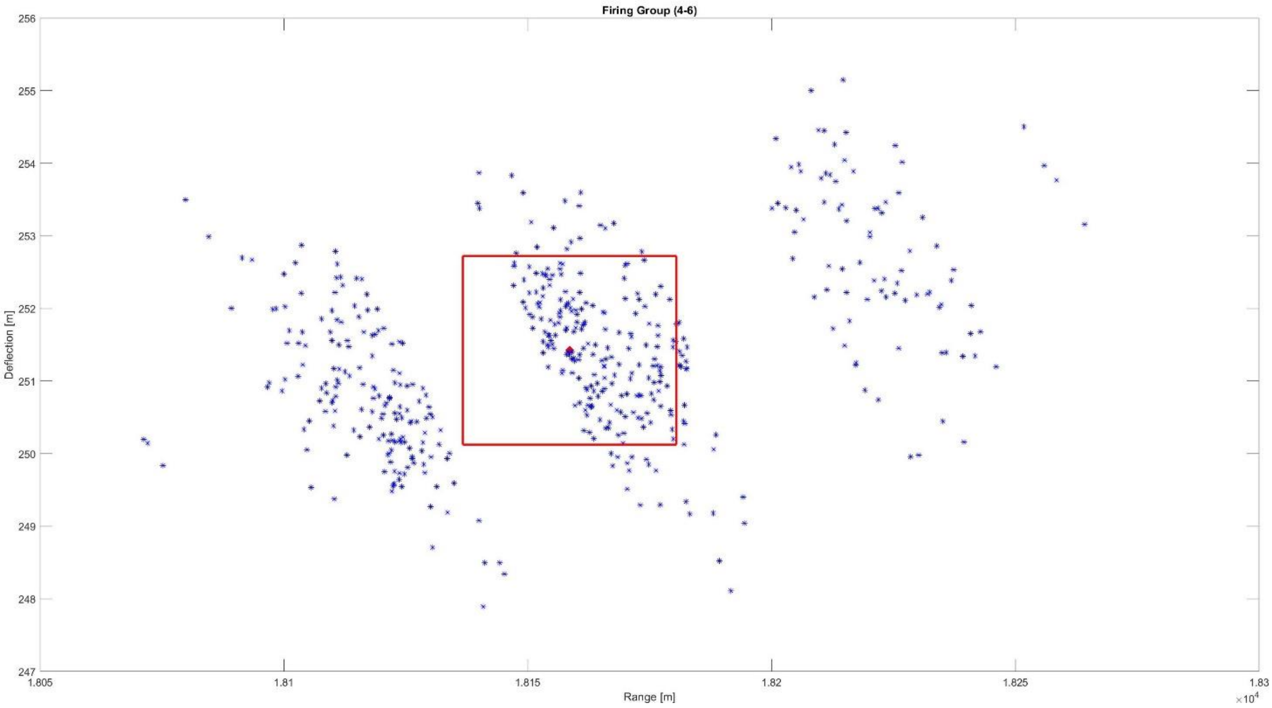

Figure B-25 Firing group zone 4 – elev. 6

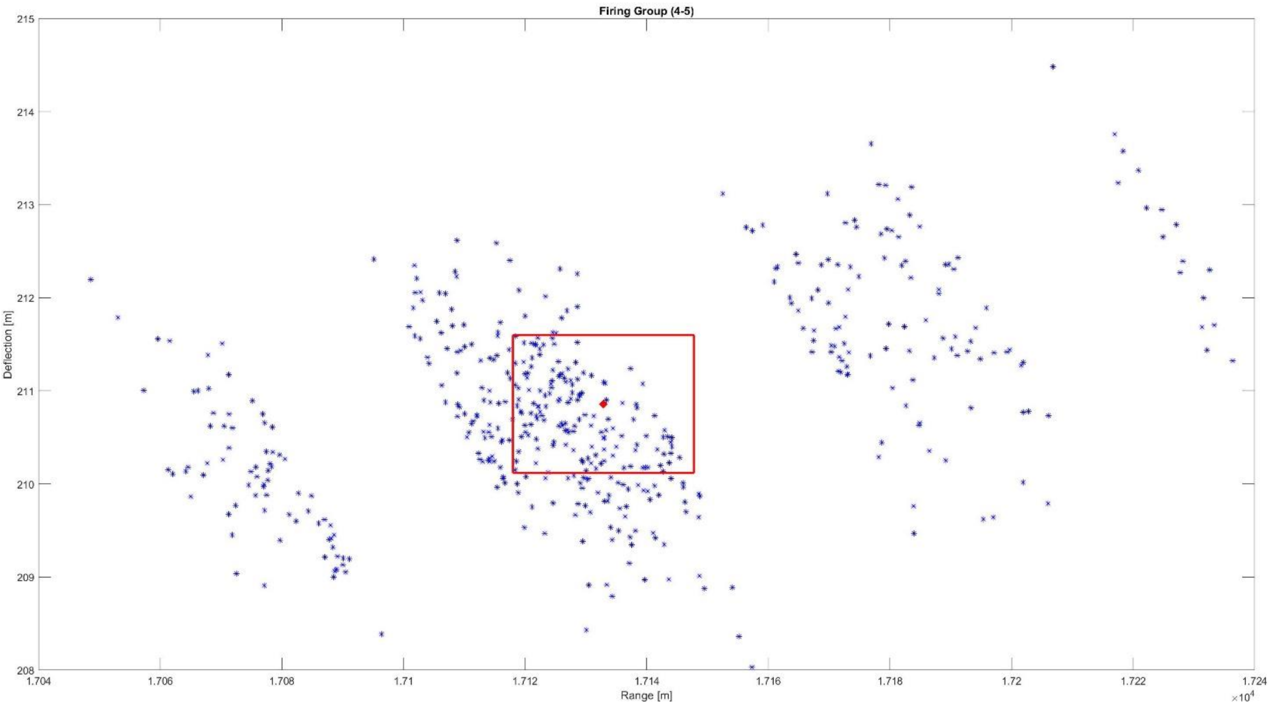

Figure B-26 Firing group zone 4 – elev. 5

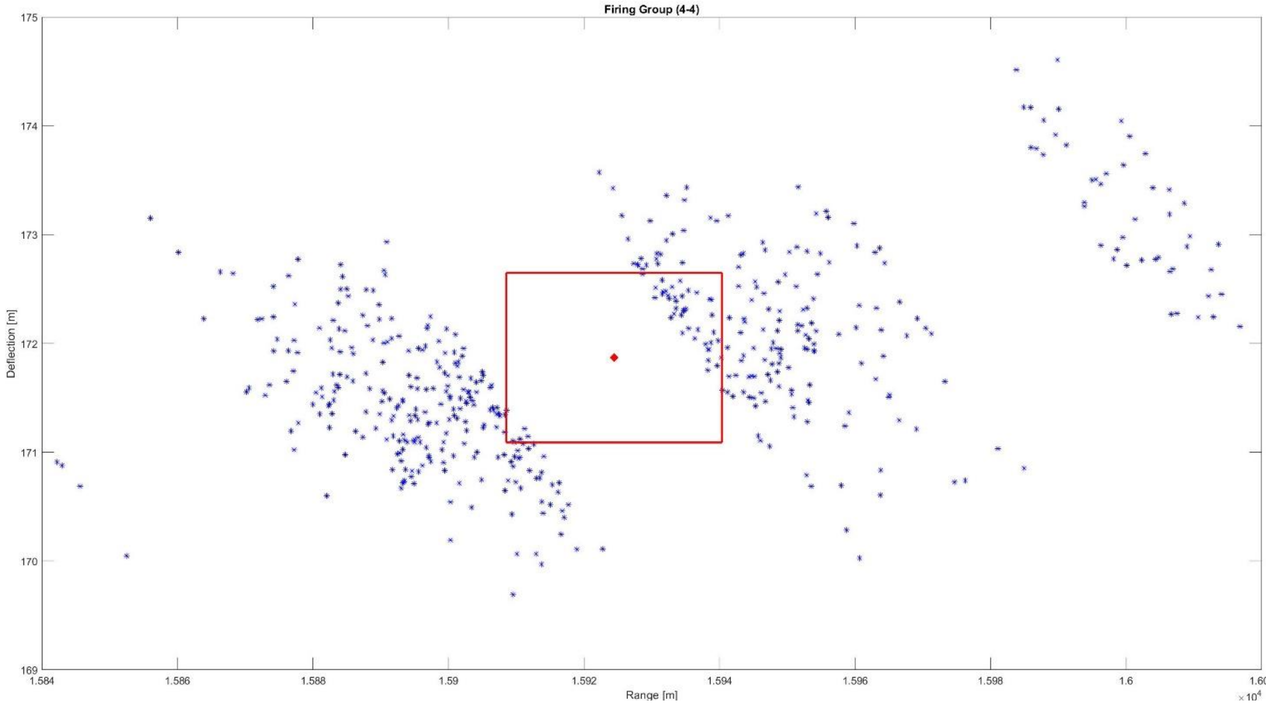

Figure B-27 Firing group zone 4 – elev. 4

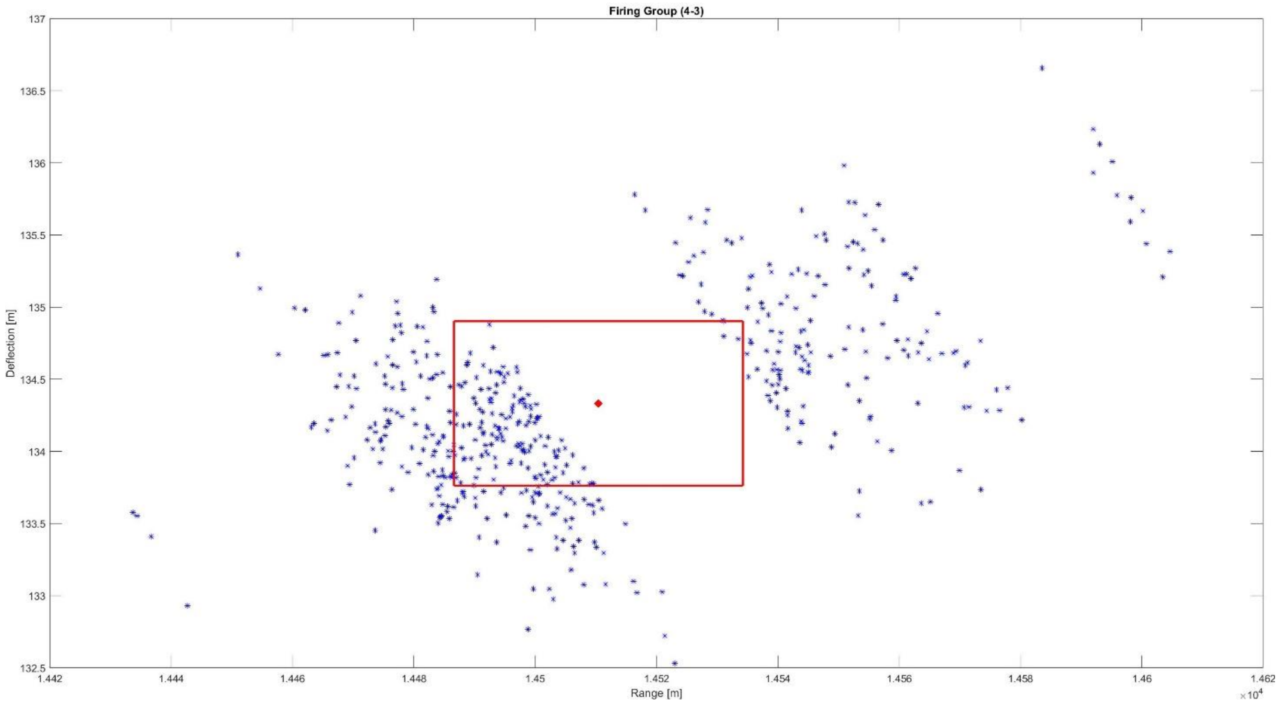

Figure B-28 Firing group zone 4 – elev. 3

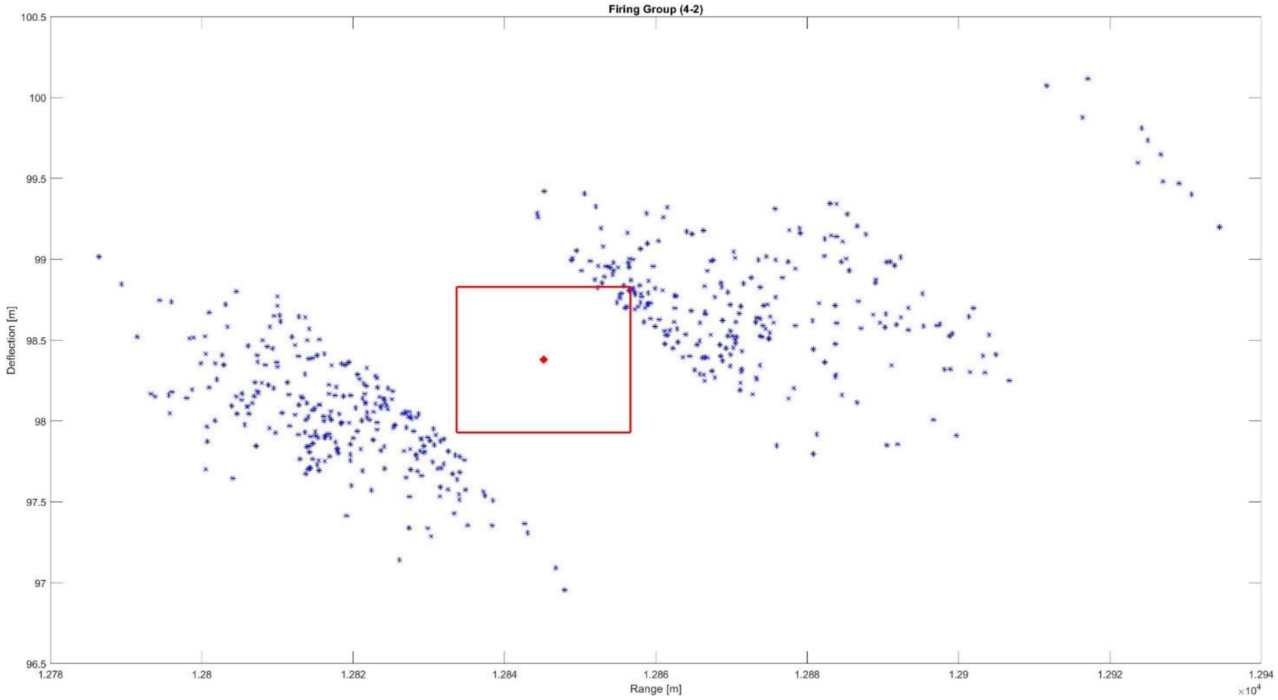

Figure B-29 Firing group zone 4 – elev. 2

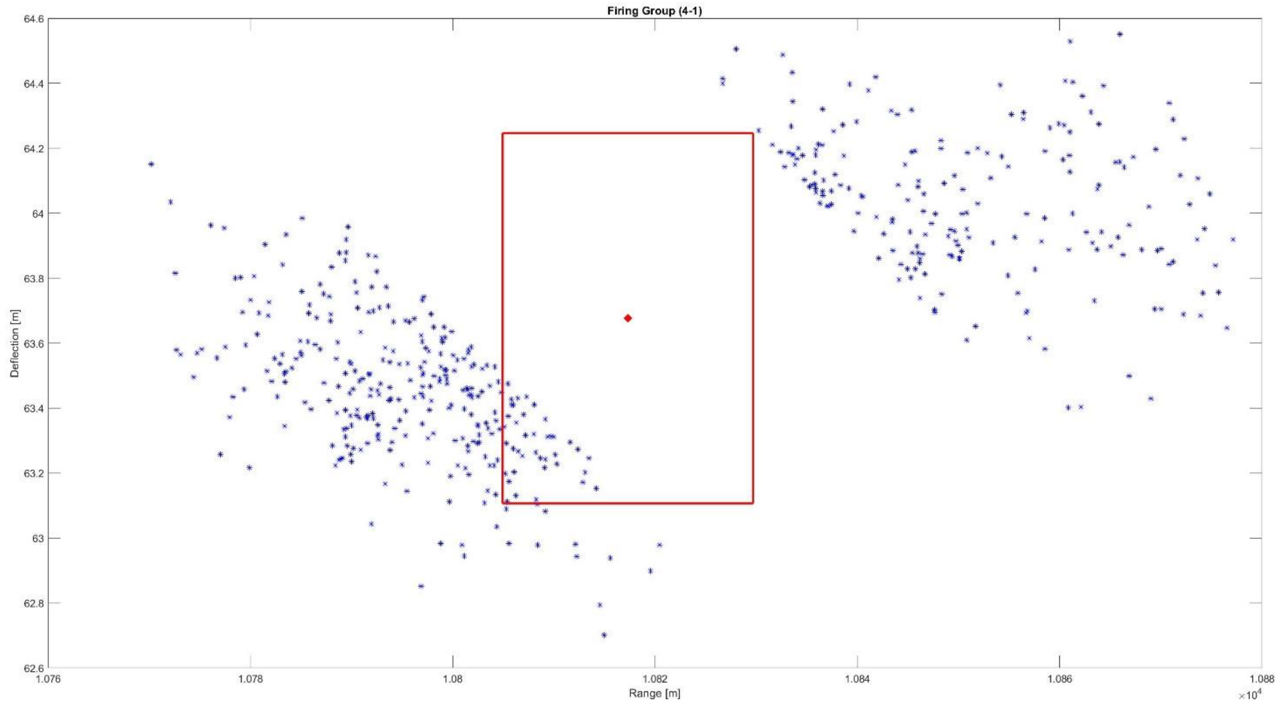

Figure B-30 Firing group zone 4 – elev. 1

B.4 Probable error plotting for zone 3.

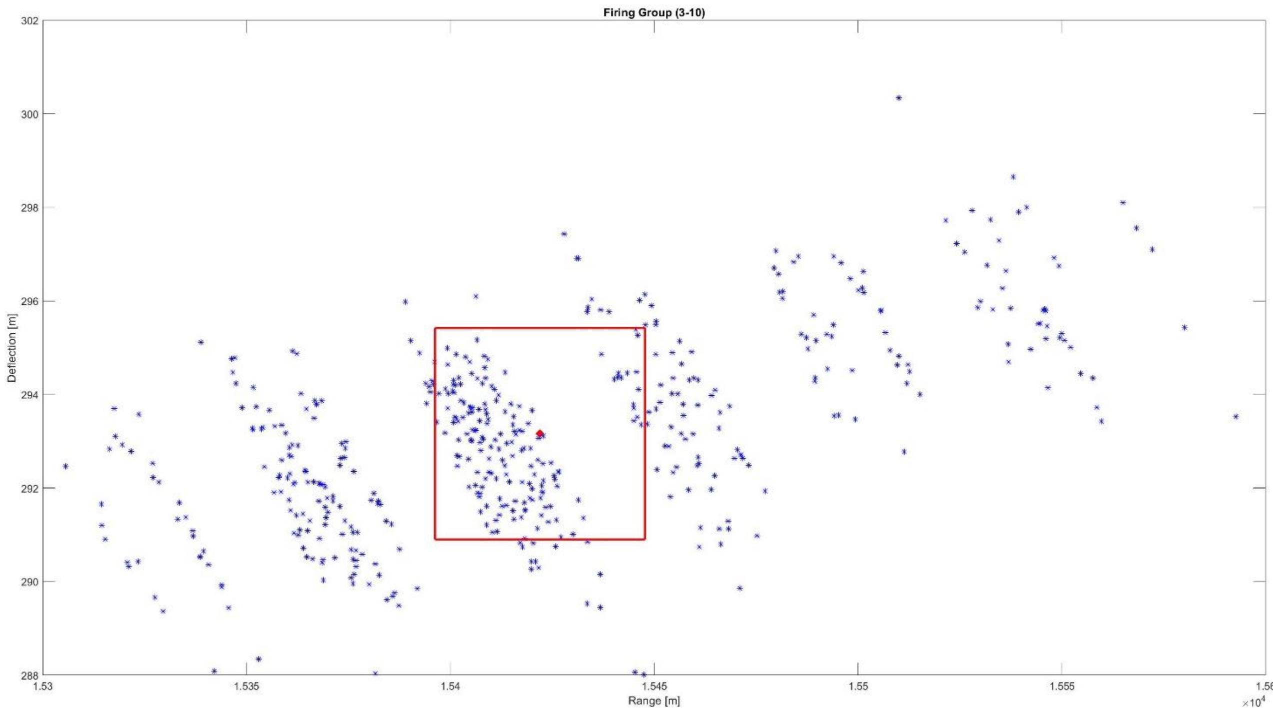

Figure B-31 Firing group zone 3 – elev. 10

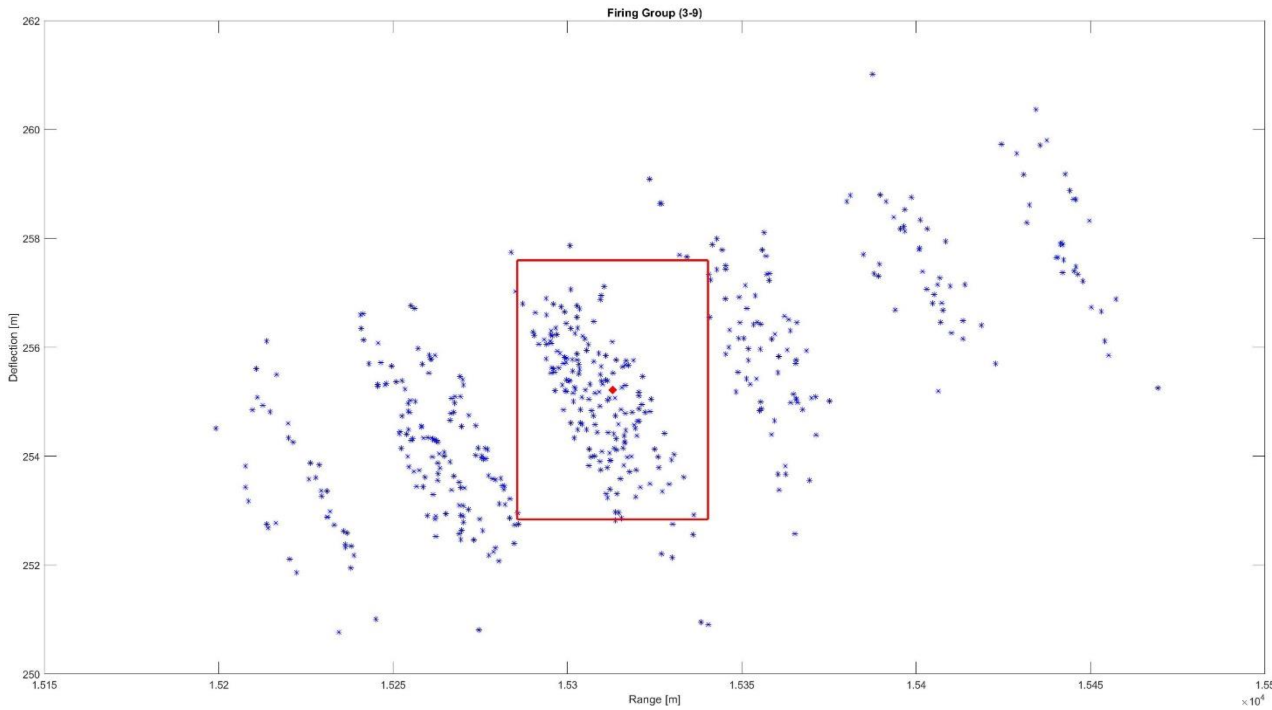

Figure B-32 Firing group zone 3 – elev. 9

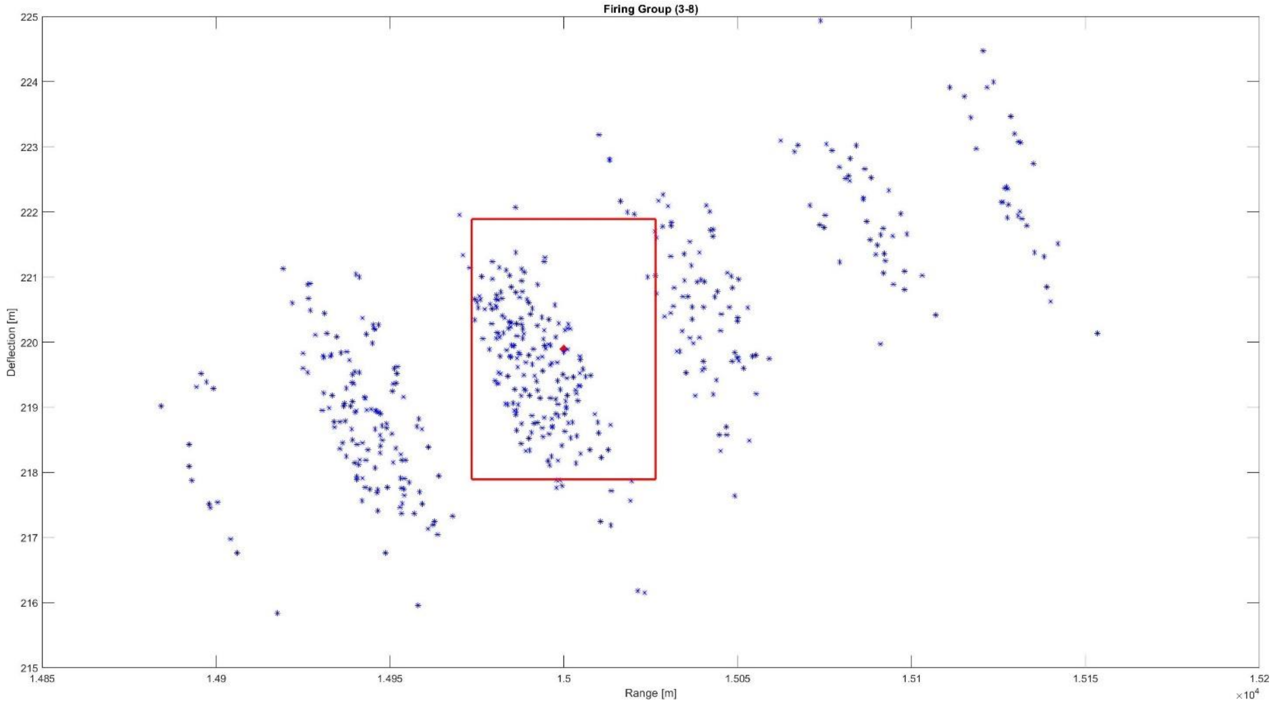

Figure B-33 Firing group zone 3 – elev. 8

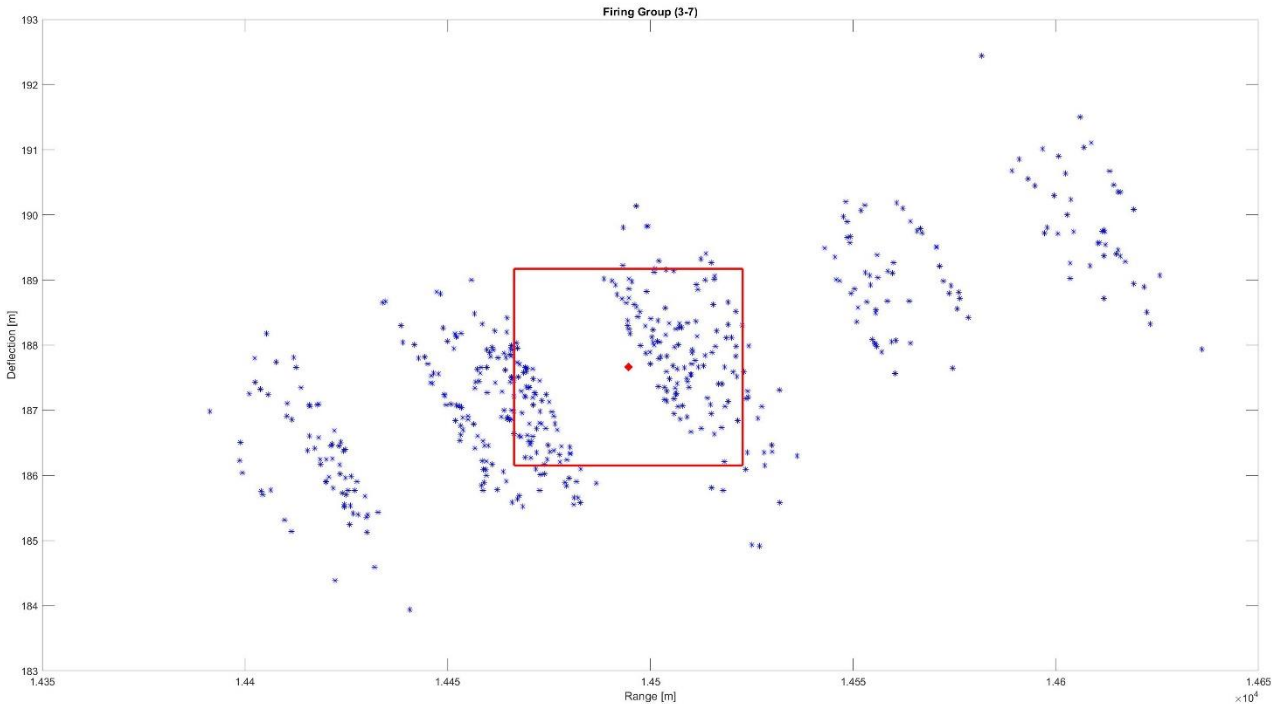

Figure B-34 Firing group zone 3 – elev. 7

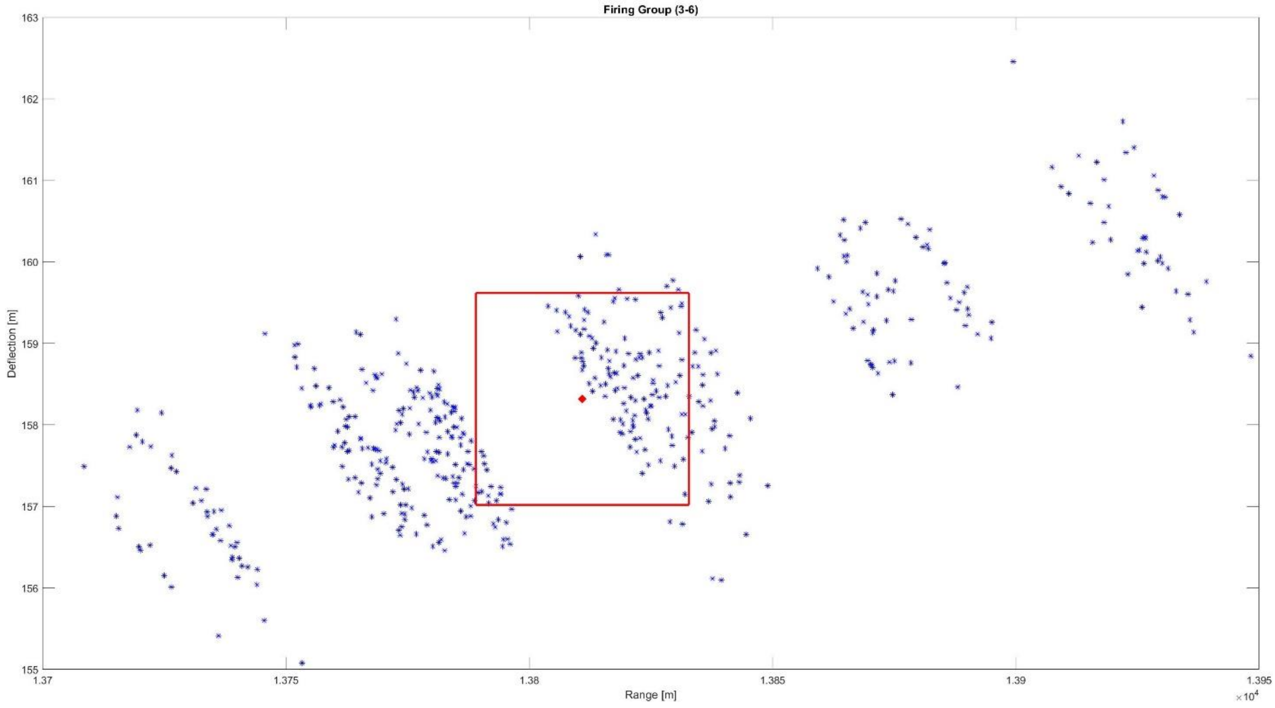

Figure B-35 Firing group zone 3 – elev. 6

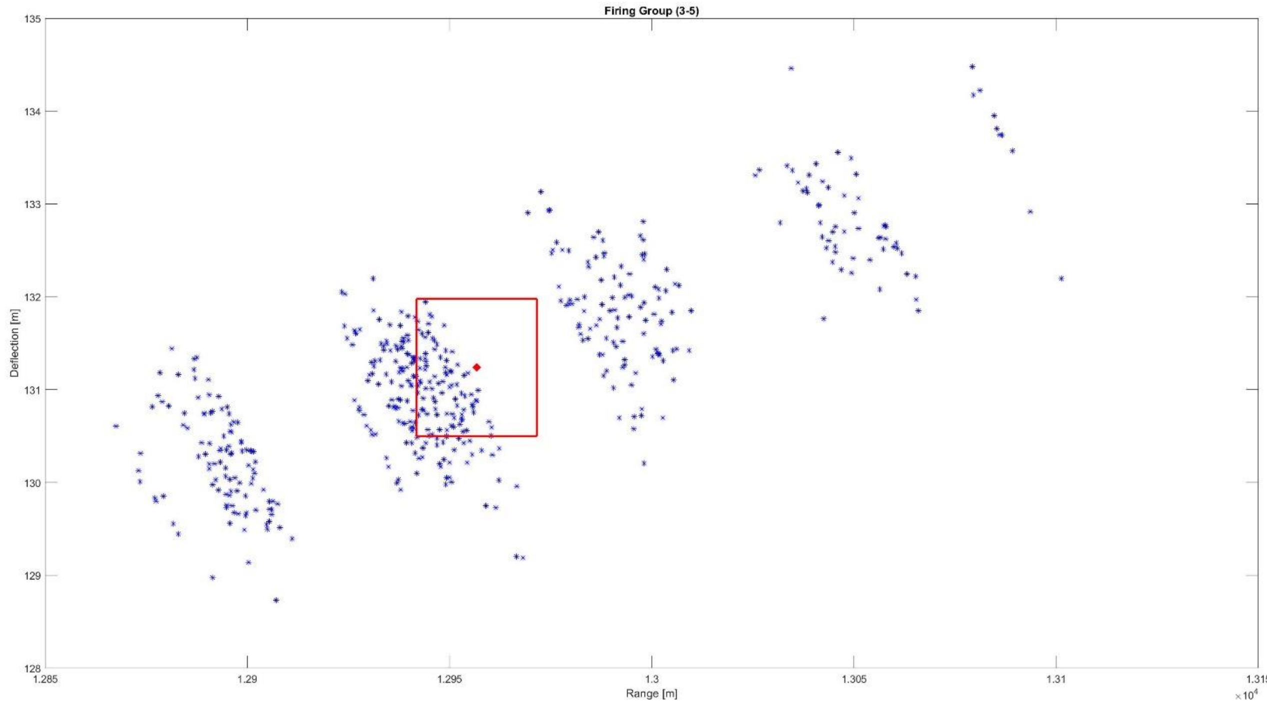

Figure B-36 Firing group zone 3 – elev. 5

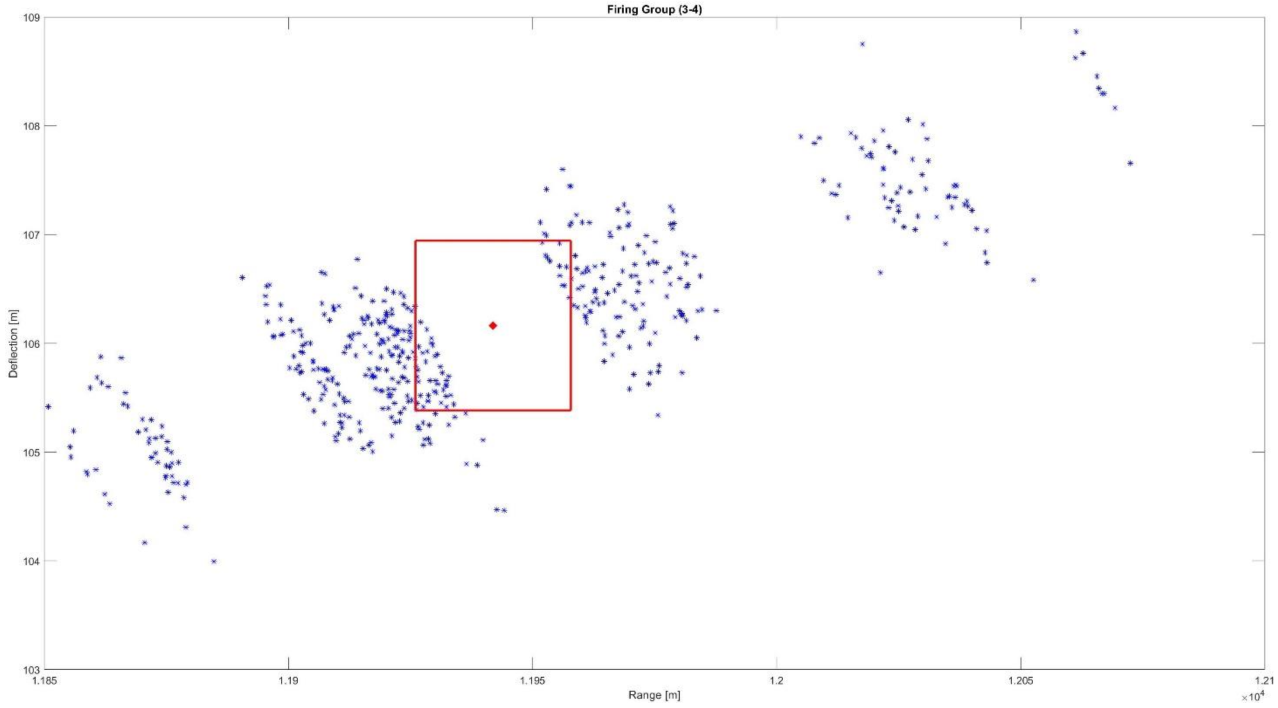

Figure B-37 Firing group zone 3 – elev. 4

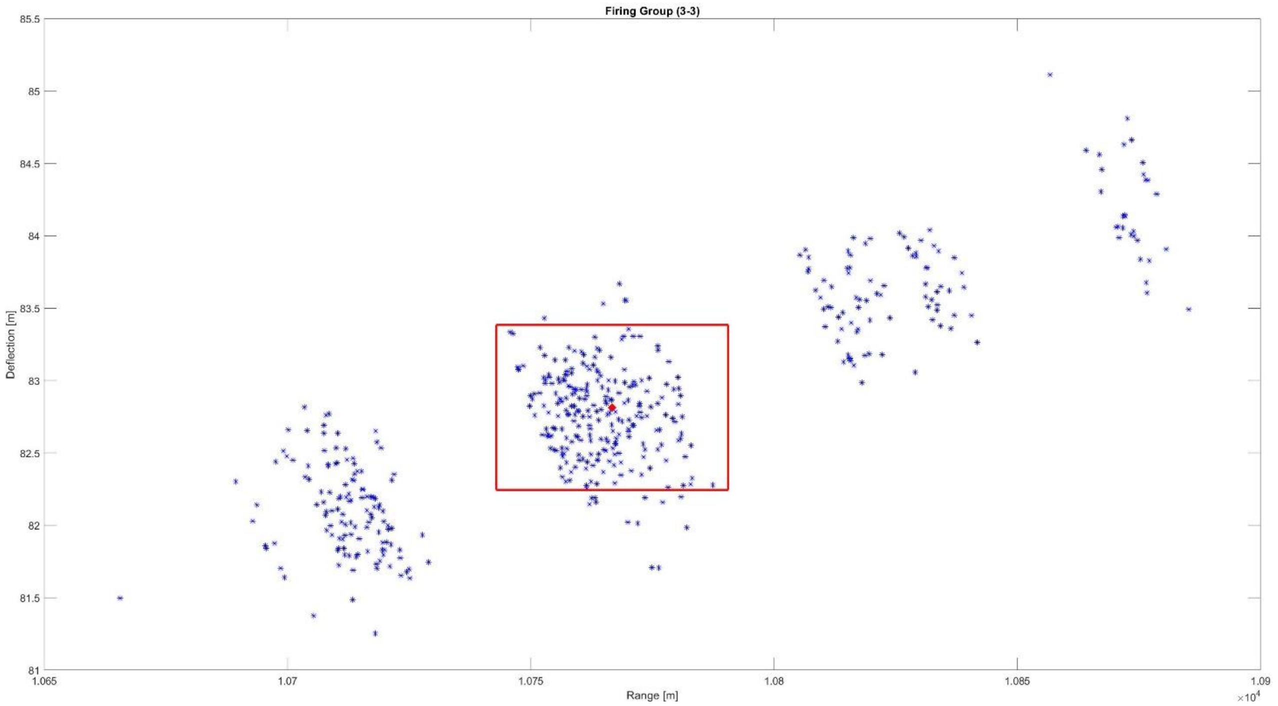

Figure B-38 Firing group zone 3 – elev. 3

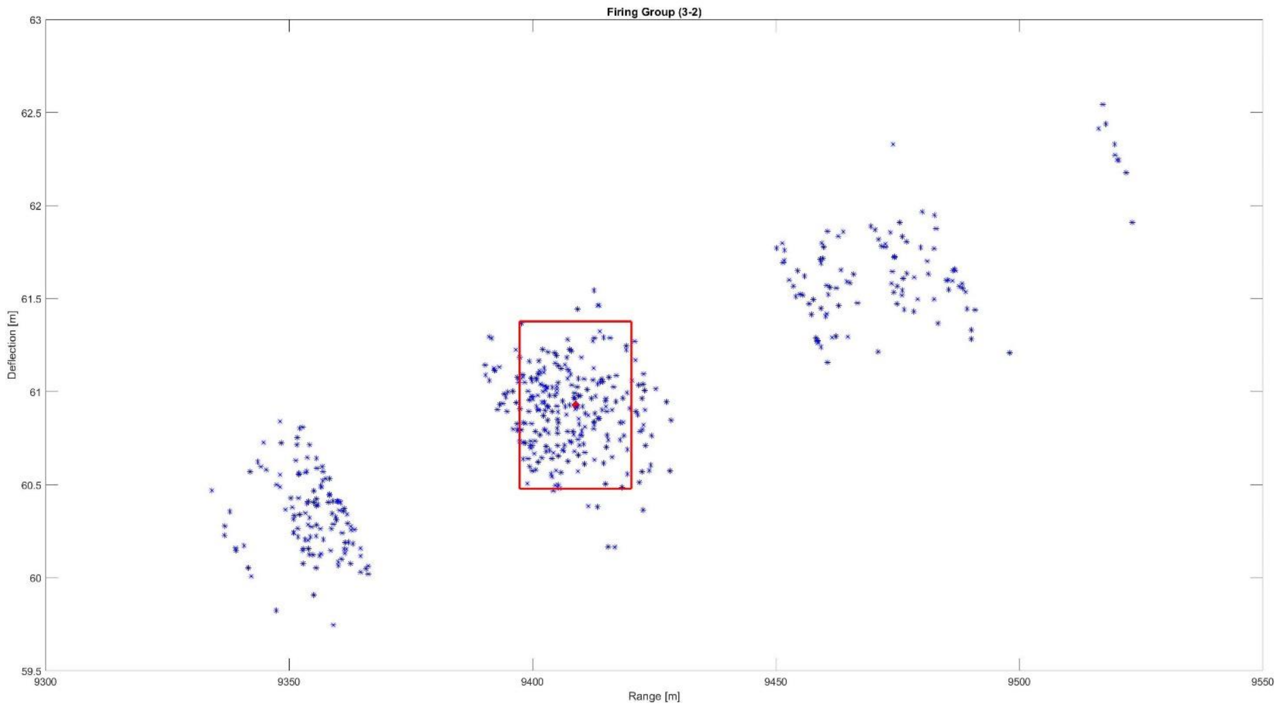

Figure B-39 Firing group zone 3 – elev. 2

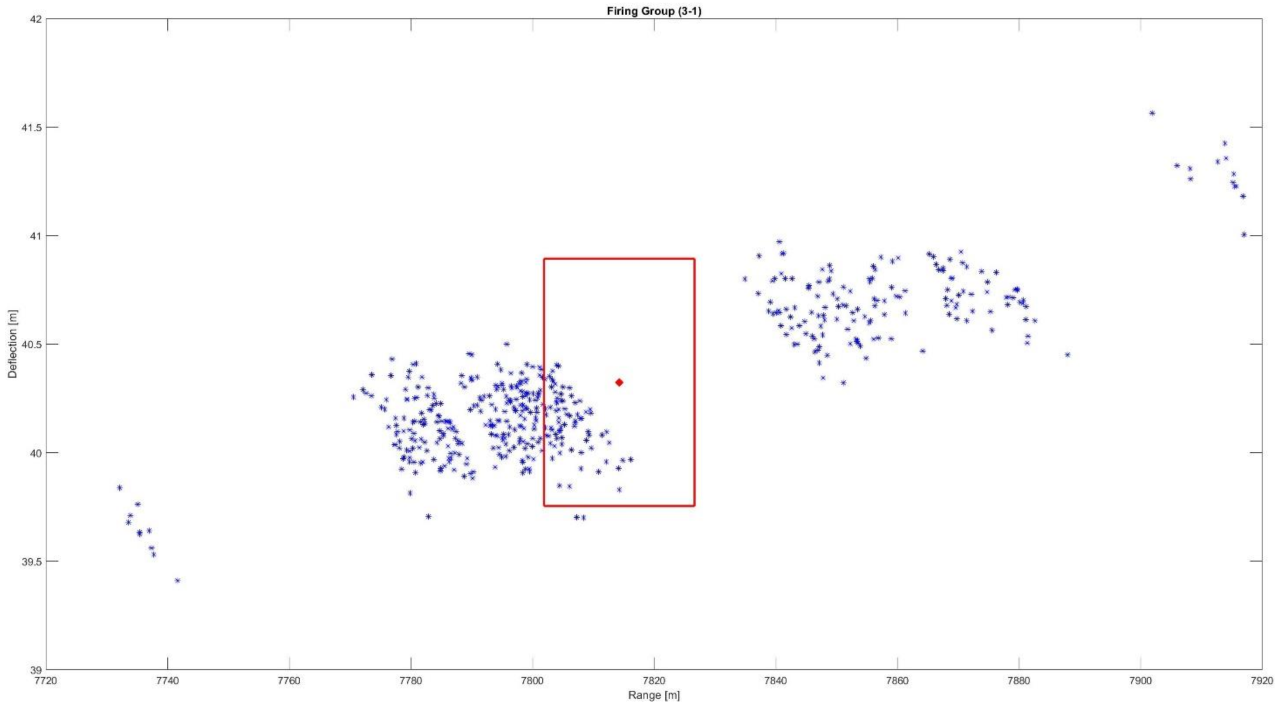

Figure B-40 Firing group zone 3 – elev. 1