



Defence Academy
of the United Kingdom



Mr Daniel Knight BEng (Hons) AMIMECHE

Effect of Wind Turbulence on Wind Ballistic Trajectory of a Medium
Calibre Weapon System

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Supervisor: Mr Dave Simner
Associate Supervisor: Dr Hugh Goyder, Dr Aimee Helliker
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ABSTRACT

Current ballistics and Fire Control Systems (FCS) use the assumption that crosswind located at the firing point will be constant between firing point and target location. The single constant crosswind value is then used to calculate the ballistic drift offset required to correctly engage a target at range and maintain an accurate firing solution. Variations in crosswind speed and direction are not considered by FCS but are known to cause drift errors in flight and offset the resulting impact point, the error is commonly known as gustiness.

Applying a variable crosswind drift correction for both time of flight and projectile height could produce an improved result by considering variations in the crosswind dynamics. Using multiple crosswind sensors at difference heights, a wind gradient curve can be produced to model wind turbulence and speed variations in reference to the projectile trajectory height. Similarly, changes in the crosswind can be modelling against the engagement timeline to show gustiness in relation to the time of flight of the projectile.

The accuracy and performance of the new ballistic model can be measured against the NATO standard coincidence window, which is used to evaluate FCS accuracy. The NATO error window of 0.3 mrad can be used to measure the probability of hit between the current constant crosswind and the new variable crosswind FCS model (US Army Aberdeen Test Center, 2009b). Using a reference tank target at a nominal distance of 2,000 meters, gives a coincidence window requirement of 60 cm square located on target centre mass.

The thesis found for the reference projectile used, a 40CTAS 40 mm round (CTA International, 2018b), that the FCS accuracy could be improved by 10.95% when including variations in the crosswind. The probability of hit inside the NATO coincidence window is improved to 56.16% when using crosswind at the instant of firing, compared to holding a single constant value during the engagement timeline.

It was also found that dynamic crosswind conditions can be included and modelled into a Point Mass Ballistic Model. Variations in the crosswind gradient

curve can be used to assess turbulence and change in wind conditions. The wind gradient curve also demonstrates that wind conditions are not constant in relation to both time and height above ground, during an engagement sequence.

Keywords:

Ballistics, Meteorological Wind, Fire Control (FC), Fire Control System (FCS), Gun System Control (GSC), Armoured Fighting Vehicle (AFV), Trajectory and Coincidence.

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Finally, my family and friends who have had to cope with my endless talking about ballistics and tanks. A big thank you to my mum, who turned my Vulcan into English.

"Failure is only the opportunity to begin again. Only this time, more wisely."

Iroh, Avatar: The Last Airbender.

Note for the reader; I have dyslexia and dyscalculia; this work has been proof-read but will most likely still have some grammatical errors, apologies in advance.

I'm #MadeByDyslexia – Expect big thinking & small typos.

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LIST OF ABBREVIATIONS

Table 1 – List of Abbreviations

Acronym	Explanation
AFV	Armoured Fighting Vehicle
AMIMechE	Associate Member Institute of Mechanical Engineers
AN	Analysed
APS	Active Protection Systems
APFSDS / SABOT	Armour-Piercing Fin Stabilised Discarding Sabot
A.R.D.E	Armament Research and Development Establishment
ARL	Army Research Laboratory
AT	Anti-Tank
ATGM	Anti-Tank Guided Missile
BL	Breech Loader
BMP	Boyevaya Mashina Pekhoty (Russian)
BRL	Ballistic Research Laboratory
C.E.P.	Circular Error Probability
Coin	Coincidence
C-Kill	Catastrophic / Complete Kill
cm	centimetres
CT40 / 40CTAS	Case Telescoped 40 / Case Telescoped Armament System
CW	Crosswind
Deg	Degree
Dir	Direction
Diff	Difference
DoF	Degrees of Freedom
Dr	Doctor
DTIC	Defense Technical Information Centre
DS	Data Set
ERA	Explosive Reactive Armour
ENE	East Northeast
E	East
ESE	East Southeast
FC	Fire Control
FCC	Fire Control Computer
FCS	Fire Control System

Acronym	Explanation
F-Kill	Firepower Kill
FM	Field Manual
ft/sec	Feet per second
FV	Fighting Vehicle
GCE	Gun Control Equipment
GPS	Global Positioning System
GSC	Gun System Control
Hit_L	Hit Lase (FCC solution at lase)
Hit_F	Hit Fired (FCC solution at firing)
HMMWV	High Mobility Multipurpose Wheeled Vehicle
H.M.S.	Her Majesty's Ship
hrs	Hours
ID	Identification
IFCS	Improved Fire Control System
IFV	Infantry Fighting Vehicle
in	Inches
IRT	Inertial Reticle Technology
KF	Kettenfahrzeug
kg	Kilograms
kg/m^3	Kilograms per Metre cubed
km	kilometre
LAHAT	Laser Homing Anti-Tank
Lb	Pound weight
L-R	Left to Right
m	Metres
M	Model
m ²	Metres squared
MBS	Boresight Mark
MBT	Main Battle Tank
MBE	Member of the Most Excellent Order of the British Empire
MET	Meteorological
M-Kill	Mobility Kill
Mill	Millimetre (NATO mill)
Mk	Mark
MLRS	Multiple Launch Rocket System
mm	millimetre

Acronym	Explanation
mph	Miles Per Hour
MPI	Mean Point of Impact
mrاد	Milli radians
m/s ⁻²	Metres per second
n/a	not applicable
NATO	Northern Atlantic Treaty Organisation
N	North
NNE	North Northeast
NE	Northeast
NW	Northwest
NNW	North Northwest
P-Hit	Probability of Hit
PhD	Doctor of Philosophy
P-Kill	Probability of Kill
Pndr	Pounder
QF	Quick Firing
R	Results
RARDEN	Royal Armament, Research and Development Establishment and Enfield
Ref	Reference
Rh	Rheinmetall
R-L	Right to Left
S / sec	Seconds
STANAG	Standardisation Agreement (NATO)
SE	Southeast
SSE	South Southeast
S	South
SSW	South Southwest
SW	Southwest
TOW	Tube-launched, Optically Tracked, Wire-guided
TP-T	Target Practice - Tracer
TV	Television guidance
UAS	Uninhabited Air System
UGS	Uninhabited Ground System
UK	United Kingdom
UTC	Coordinated Universal Time
U.S.	United States

Acronym	Explanation
USA	United States of America
U.S.N.	United States Navy
U.S.S.	United States Ship
V	Version
vs	versus
WW1	World War 1
WW2	World War 2
WSW	West Southwest
W	West
WNW	West Northwest
WTI	Wind Input Table
yd	yard
6DoF	Six Degrees of Freedom
.csv	Comma Separated Values
.txt	Text File
.jpg	Photo file

NOMENCLATURE

Table 2 – Nomenclature

Parameter	Symbol	Unit
Projectile mass	m	kg
Vector Velocity	$\vec{V}$	m/s
Vector acceleration	$\frac{d\vec{V}}{dt}$	m/s ⁻²
Force	F	N
Gravity	g	m/s ⁻²
Time (time of flight)	t	sec
Velocity (Initial Velocity, Axis x, y, z)	V, V_0, V_x, V_y, V_z	m/s ⁻²
Angle (launch angle, angle of flight)	ϕ_0, ϕ	deg
Projectile Diameter	d	m (meters)
Projectile reference area	S	m ³
Drag coefficient	C_D	Non-dimensional
Air density	ρ	kg/m ³
Distance in x, range	X	m
Distance in y, height	Y	m
Distance in z, drift	Z	m
Wind speed (direction)	W (x,y,z)	m/s
Range	R	m
Initial Speed (Muzzle velocity)	$u_0, MZ,$	m/s
Height	h	m
Height reference	h_{ref}	m

Chapter 1 Introduction

1.1 Wind variation effect on ballistic coincidence

One of the commonly known errors in calculating a ballistic solution of a projectile between firing position and target is the effect of wind. The speed and direction of the wind along the firing line can influence a projectile in flight and offset the impact point. This is commonly referred to as drift or wind deflection [**Figure 1**] and can be present as both a crosswind and a tail/head wind (Litz, 2015).

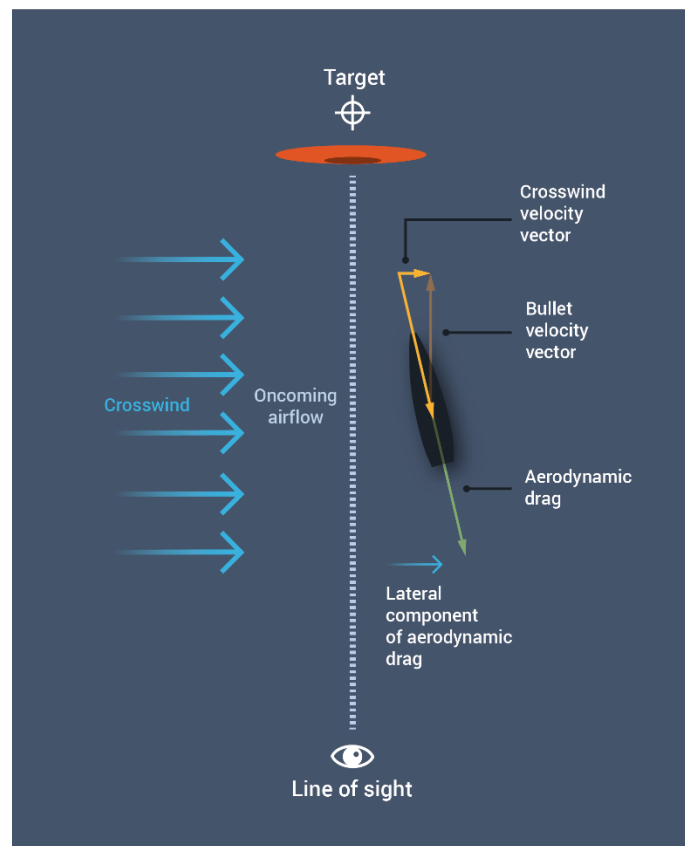


Figure 1 – Wind Deflection on projectile (Litz, 2015)

A crosswind is the effect of wind speed deflection across the left to right plane of the projectile in flight and can offset a projectile impact point. A head wind acts against the projectile flight and tail wind act with the projectile flight. The focus of this thesis is to understand the effect of variations in the crosswind domain, tail/head wind will be ignored.

Crosswind influences the drift or deflection of a projectile in the 'Z axes' of a general coordinate system, this is the traverse or left to right arcs **[Figure 2]**.

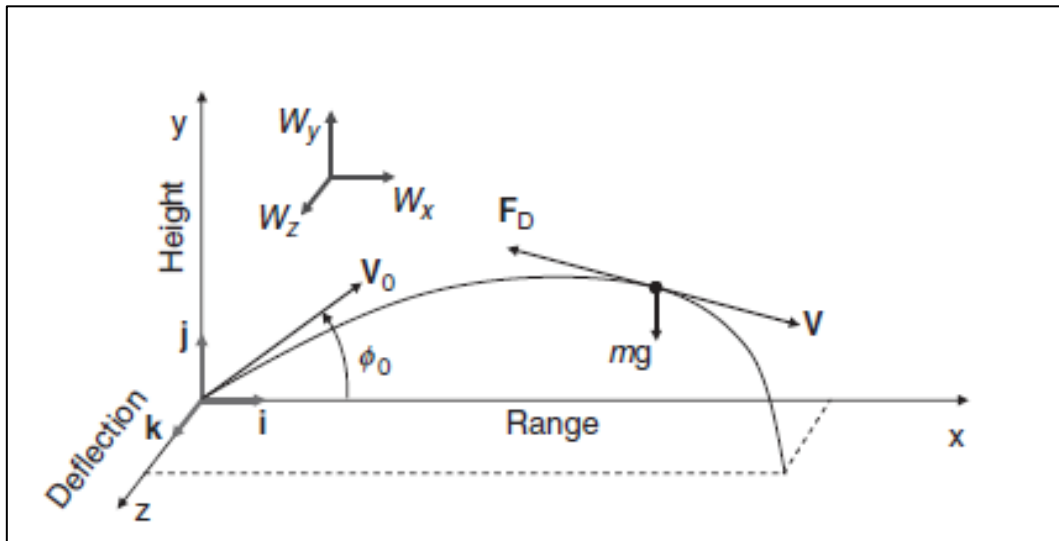


Figure 2 – Coordinate system for a Point-Mass Trajectory with Wind (McCoy, 2012)

In **[Figure 2]** above the projectile is subjected to a drift or deflection which moves the impact positively in Z axis or to the right of the firing line. Depending on the amount of drift caused by the crosswind this would cause the projectile to miss its target point.

To calculate the wind speed and direction that is used in the ballistic solution most modern Main Battle Tanks (MBT's), or vehicles use a wind sensor attached to the top of the vehicle. This sensor measures the wind speed and direction at the point of firing or the vehicle location and uses the assumption that the wind conditions are identical along the firing line and at the target **[Figure 3]**.

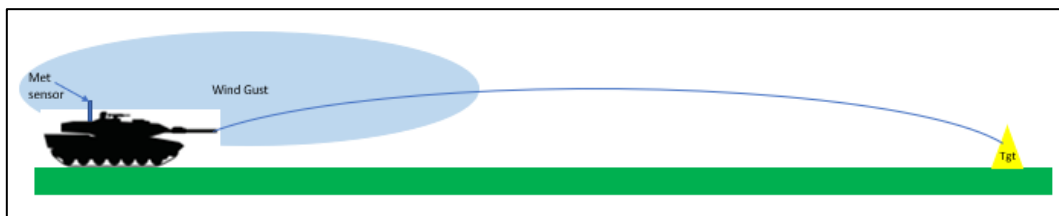


Figure 3 – Wind Gust at MBT Location

This assumption in the collection of the wind data processed by the Fire Control System [FCS] presents two issues, firstly the wind conditions are identical along the firing line between shooter and target. Secondly wind conditions do not change between data collection and firing.

For the first assumption there is an argument commonly held between sports shooters in the difference between 'near wind' and 'far wind'. As described by Litz book (Litz, 2015) near wind is deemed as the shooters location and far wind as the target location, with the argument as follows;

“Argument for near wind

Near wind is more important because it's the wind that affects the bullet earliest in its flight. The bullet will spend the rest of its flight on a deviated path according to how the near wind affected it. On the contrary, the far wind doesn't affect the bullet until its closer to the target, and by then, the bullet's flight is almost over.

Argument for far wind

Far wind is more important because the bullet is going slower when it's far downrange and is more susceptible to the effects of wind. The bullet spends more time covering the last half of its flight than the first half, so wind has more time to act on, and deflect the bullet. When the bullet is near the shooter, it's going so fast that the wind barely affects it at all.”

The definitions can be expanded on in textbook examples where 10 miles per hour (mph) [4.47 m/s] (McCoy, 2012; Litz, 2015) crosswind is applied continuously along the ballistic flight's entire length. The constant crosswind from the firing point does not consider changes or variation due to terrain, time-lag, air pressure and distance between firing and target point. The same can be said in reverse taking wind only from the target point and applying the drift at the firing point.

Many shooters and scientists will argue for and against different aspects of the wind effect; these are the common statements and assumptions for real-world effects (McCoy, 2012; Litz, 2015).

1. There is no constant wind in the real world.
2. Near wind, far wind, the mid-range wind are all valid.
3. Wind gradient affects the wind speed and will slow the projectile down near the ground due to surface friction from grass and bushes. Higher up from the effect of trees and hills until the free-flowing air takes effect.
4. Gustiness or the change in wind conditions between areas along the flight path will affect the projectile drift.

To accurately account for all wind conditions in the ballistic solution, effect of terrain and range to target should be considered as part of the wind conditions.

The assumption that the wind conditions do not change between the point in time when the data was collected and when the projectile is fired is incorrect. The wind speed and direction are a constantly changing variable, so the delay between data collection and projectile impact becomes important.

The Chieftain MBT Improved Fire Control System (IFCS) (Forty, 1979), has the following engagement timeline of 9.7 seconds [s] **[Figure 4]**.

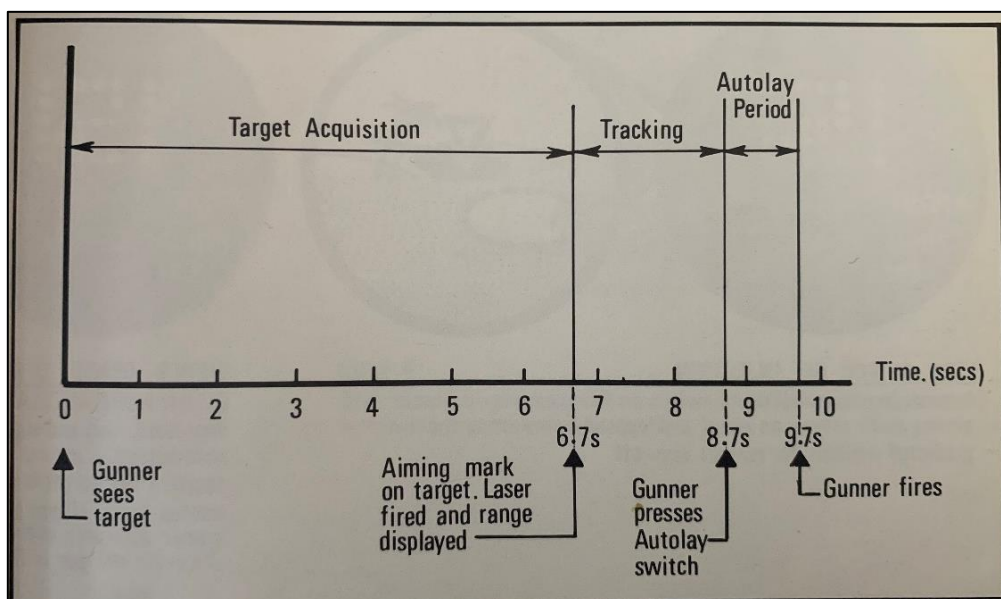


Figure 4 – Chieftain MBT IFCS, Engagement Timeline (Forty, 1979)

At the point of 6.7 s into the engagement timeline, when the laser is fired by the Gunner, the wind sensor takes a snapshot of the conditions at that point in time. The wind conditions along with the range distance and vehicle telemetry are inputted into the IFCS to calculate the new aim mark for the Autolay function. At 9.7 s in the timeline the Gunner will fire the weapon and 3 s later the projectile will impact a target at a nominal 2,000 meters [m].

The IFCS holds the wind and other firing data for nearly ~3 s prior to the projectile being fired, with a further ~3 s for target impact. The system cannot be relied on to have an accurate ballistic solution with variable data that is ~6 s old at the time of impact. In a static vehicle vs static target scenario, not considering vehicle movement, with a wind speed of 4.47 m/s [10 mph], the wind conditions have moved 13.41 m away from the vehicle by the time the projectile has fired [Figure 5].

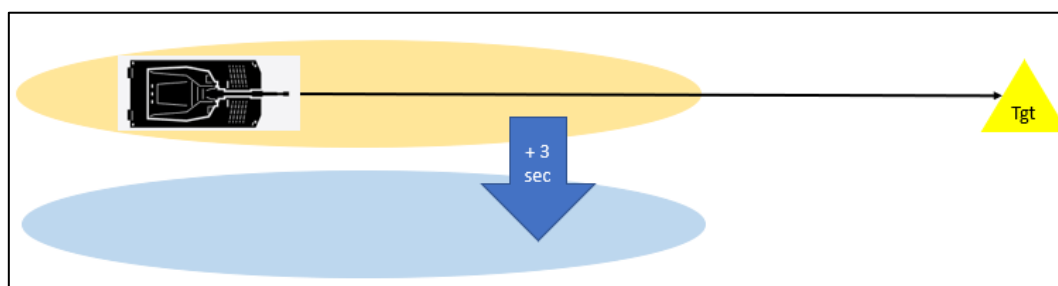


Figure 5 – Wind conditions offset against the Firing line.

For a static vehicle vs static target typical engagement at 2000 m (Forty, 1979), with a total of ~6 s delay on firing solution to target impact. This size of error in the ballistic solution could cause a miss to occur due to incorrectly measuring the wind variable drift effect. The errors are collected to be assessed for a FCS design as part of the “Error Budget”, which accounts for the errors as probability factors that influence the hit performance (Terry *et al.*, 1991).

1.2 Ballistic Error Budget

The Ballistic Error Budget is a probability table of factors that will influence the ballistic hit performance of either a projectile or FCS design (Terry *et al.*, 1991; Moss, Leeming and Farrar, 1995). Both a projectile and vehicle Error Budget

need to be understood and considered when understand the firing performance of a system.

Most of these Error Budget's for current vehicles and systems are closely guarded as they detail key performance factors on the vehicle and weapons systems. For this study an example Error Budget **[Table 3]**, has been used from (Terry *et al.*, 1991) which shows the percentage of each system error for a mean point of impact at 2000 metres, with each error in standard deviation percentage terms.

Table 3 – Example Error Budget (Terry *et al.*, 1991)

Error Source	Traverse Axis (%)	Elevation Axis (%)
Ammunition Error	23%	24%
Sight Error	23%	22%
Weapon Error	19%	19%
Environmental Error	15%	14%
Operator Error	11%	11%
FCC Error	8%	10%
Total Error Budget	100%	100%

It can be seen in the table that the “Environmental Error” (Wind) makes up 15% of the overall error budget, making this the fourth largest to affect the Traverse z-axis. System errors (Ammunition/Weapon/Sight) have been well defined through performance testing and can be detailed from equipment manuals (Jane's Information Group, 1992, 1997). These manuals and databases can be used to reliably model the system performance in an FCS design, however there is little understanding on the effect of wind conditions to this level of detail.

A general understanding of how wind behaves can be achieved through wind engineering design (Kaltschmitt and Streicher, 2007) and fluid mechanics. The principles that effect gunnery and ballistic performance have been taken into account over the years to define these errors as improved mathematic equations (McCoy, 1976, 2012). Other variables that effect the change in wind conditions in a direct flat fire plane can be modelled and considered to reduce the effect of the variable error. Known influencing factors on wind conditions between two known points, include (Moss, Leeming and Farrar, 1995; Litz, 2015):

1. Terrain height changes.
2. Skin Friction from terrain features – grass, trees, hills, and buildings.
3. Turbulence from changes in temperature and pressure.

The Skin Friction effect from terrain features on the ground can be modelled using fluid mechanics to create the wind gradient curve. Using multiple wind sensors at different heights and linear interpolation equation (MATLAB, 2023a) the wind gradient can be created. The wind gradient curve represents the skin friction effects of air as its moved across the ground features compared to height **[Figure 6]** (Litz, 2015).

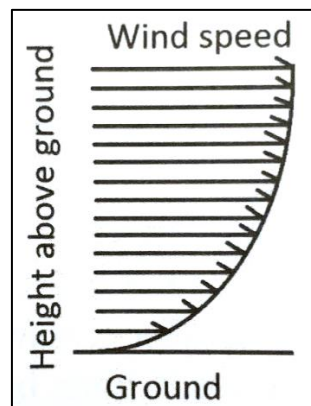


Figure 6 - Wind Gradient (Litz, 2015)

Most direct fire weapon systems used by MBTs will be affected by this low level change in wind conditions caused by wind gradient and low level turbulence. The projectile would be affected in its flight trajectory as it passes by terrain features such as buildings, hills, and dense trees and hedgerows, causing changes to the projectile velocity, drift, and stabilisation.

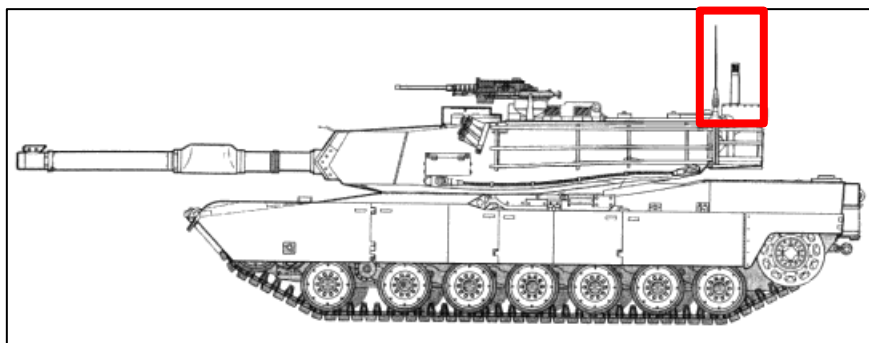


Figure 7 – Abrams MBT, with wind sensor highlighted (Gary, 2008)

Another issue to consider is the fact that the wind sensor on the vehicle is also affected by turbulence caused by features on top of the vehicle, as shown in **[Figure 7]**. The wind sensor is placed to gain best exposure to crosswind but can be easily affected from vehicle factors such as, applique armour or stowage clustered around the sensor.

The average MBT crosswind sensor sits at about 2.5 m in height from ground level (Taylor, 2018; Cecil and Shackleton, 2020), with a limit in height due to bridges and railway restrictions. This limits the crosswind data collection to a single data point to calculate the ballistic correction from.

1.3 Scope of Work

The scope of this thesis is to understand the effect that variations in the wind conditions used in a ballistic solution has on the end impact point. This will be determined by analysing the impact of variation in the wind speed in the ballistic solution, and how this will move the impact point out of the coincidence window. The coincidence window is a tolerance factor (error bar) used to measure the influence of the error budget on hit performance (US Army Aberdeen Test Center, 2009a).

The coincidence window is a NATO standard test measurement condition that is used to analyse the performance of Fire Control Systems (US Army Aberdeen Test Center, 2009a). The coincidence window is a 0.3 mrad x 0.3 mrad window used to measure the alignment between the sight and gun during an engagement window. The window is created for each axis by converting the distance of the engagement into the mrad window, NATO mils is also equivalent to the following $1 \text{ mil} = 1 \text{ mrad}$ (Department of Defense, 1961). The conversion is as follows for each 100 m in range, the 1 mrad is equivalent to 10 cm (1/1000), or 1000 m is 1 m **[Figure 8]** (Department of Defense, 1961).

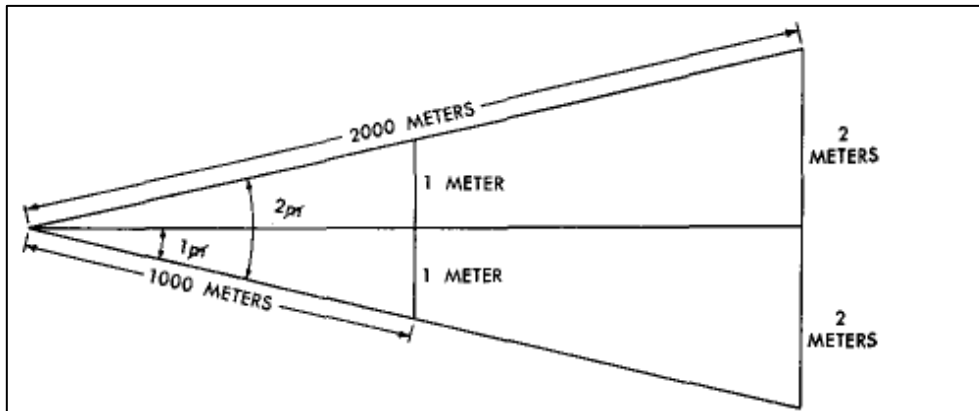


Figure 8 – NATO Mil's window calculation (Department of Defense, 1961)

For a standard engagement distance of 2,000 m, where 2 m equals 1mrad, the coincidence window of 0.3 mrad is 0.6 meters or 60 cm wide in both axis (elevation and traverse). When applied to a NATO standard tank target H-1, which represents a T-72 Tank Head-on (US Army Aberdeen Test Center, 1998), the coincidence window looks like the following **[Figure 9]**.

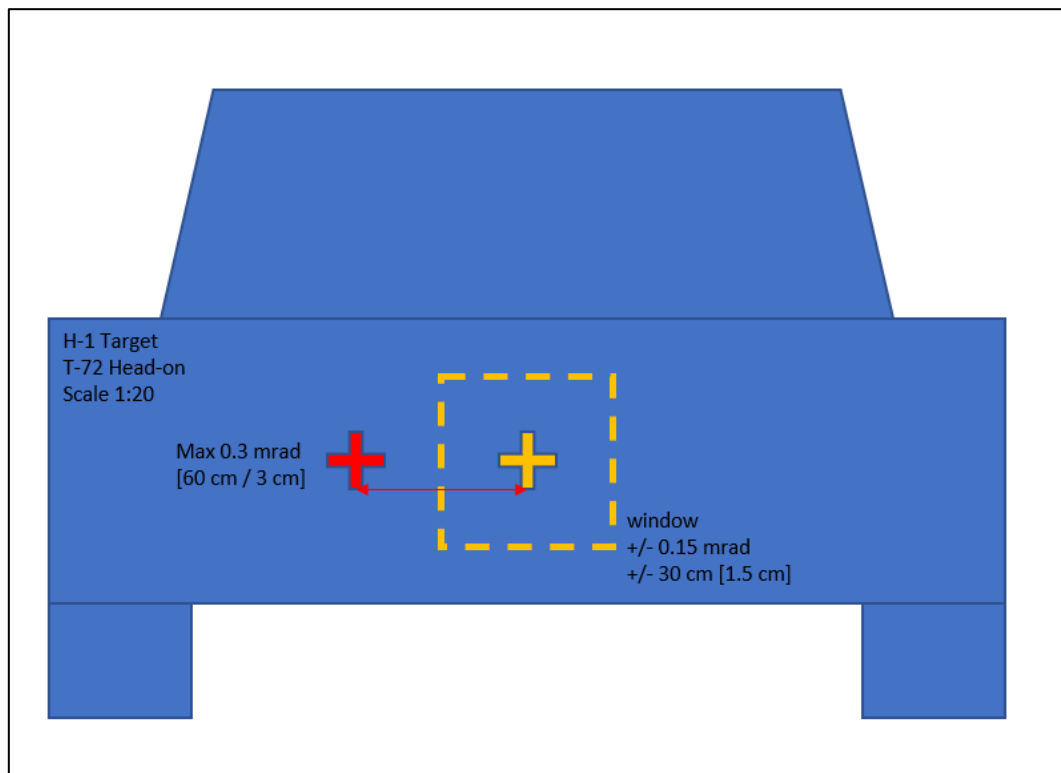


Figure 9 – Coincidence Window applied to a H-1 Target

The target and the window have been scaled to 1:20, so the coincidence window has become a 3 cm x 3 cm square, to a correctly scaled target image. This will be used to demonstrate a visual evaluation of the impact points generated from the ballistic code. **[Figure 9]** shows the H-1 target with its centre aiming mark designated by a yellow cross, the coincidence window a yellow hatched square. Finally, the ballistic impacts will be shown by red crosses, offset in the traverse (Z axis).

The impact points will be shown against two factors of the coincidence window:

1. The 0.3 mrad x 0.3 mrad box as described by the NATO standard which will be marked against the centre mass of the H-1 target. This will be +/- 0.15 mrads in each direction of the traverse and elevation axes.
2. And a 0.3 mrad tolerance between the two results of the ballistic model, to understand which is the worst case.

1.4 Aims and Objectives

This thesis's main objective is to understand the effect of varying wind conditions on the coincidence window in a ballistic solution. Using a standard ballistic model to assess different crosswind conditions during the FCS engagement timeline and there corresponding effects on the downrange flight ballistics.

Does the crosswind used in the FC ballistic solution have an effect on the performance of the 40 Cased Telescoped Armament System (40CTAS) reference projectile.

Chapter 2 Literature Review

2.1 Introduction

This chapter details the literature review in a thematic approach, approaching each of the central themes of ballistics, gunnery, and fire control. Specific focus is presented on the effect of meteorological wind on each of the subject areas.

Limitations and data restrictions applied to research information on ballistics and military technology as current/in-service systems are not freely obtainable and detailed. Details on in-service systems are protected by national security caveats and for the United Kingdom, the Official Secrets Act (UK Government, 1989). The information presented in this literature review will detail the background on the subject areas up to near modern times, as shown there is a knowledge gap of about 15 to 30 years due to no or minimal information released on modern systems and their developments.

2.2 General Background

2.2.1 Ballistic Modelling

The literature review focuses on recent ballistic development relating to Fire Control (FC) and vehicle based warfare, as the overall ballistic field is varied and detailed subject. Detail on modern system development and approaches is restricted but most general principles are applicable through all the mathematics and systems modelling used in ballistics.

The ballistic model used in this thesis is the Point Mass Model, which was developed from the Bernoulli's Flat Fire model, using standard planes of reference (McCoy, 2012) **[Figure 10]**. Further expansion on the equations of wind effect, gyroscopic (spin) and Coriolis equations explored the effect of the planet rotation on the ballistics flight models (McCoy, 2012).

The Flat Fire model method was used in the early ballistic modelling and development during the 1800s. The United States military used the Flat Fire models as their primary ballistic and fire control modelling method in the 1800s to 1900s (McCoy, 2012).

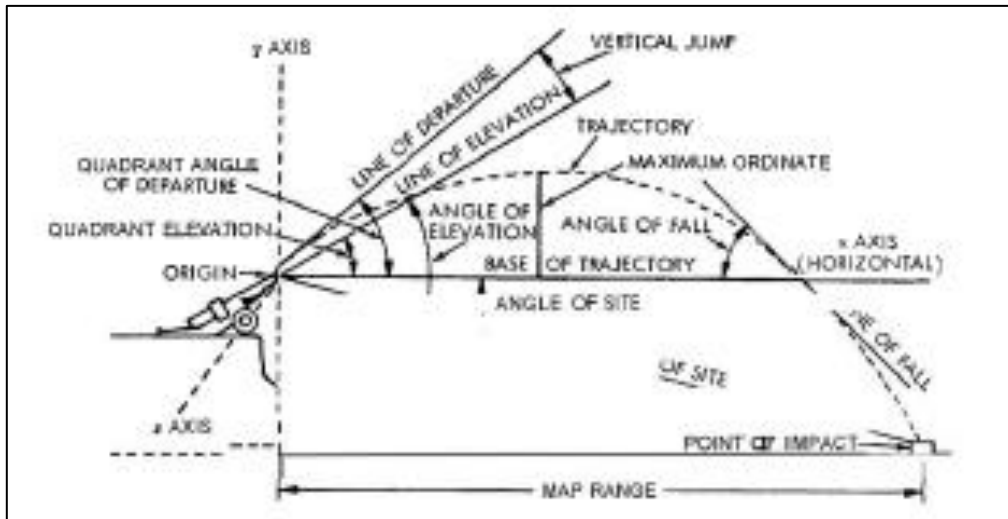


Figure 10 - Aspect of Trajectory (U.S. Army Material Command, 1968)

Improvements in mathematics and modelling from tests in the mid 1900's, produced the Point Mass Model, which was developed into three models. The Point Mass Model became the primary model of choice; the model was further developed into the Modified Point Mass Model as an expanded solution. As computer modelling and power increased, further data points could be analysed, creating the 6 Degrees of Freedom (6 D.O.F) Point Mass Model.

Each of the three Point Mass Models has been slowly developed to include further detailed information on the scenario under test. The Point Mass Model requires only 7 input variables for the model to work compared to 21 variables for the 6 D.O.F model (Moss, Leeming and Farrar, 1995).

The restrictions on information available mean that the most appropriate model for analysis is the Point Mass Model **[Appendix B]**. The model will be able to demonstrate the effect of wind on the drift of the projectile in flight and can be referred to other ballistic models for comparison. The computational speed of the Point Mass Model is also reasonable on a modern computer, compared to high computational requirement of the 6 D.O.F model.

2.2.2 Wind Modelling

Wind Engineering is a new engineering discipline that covers both structure and fluid mechanic engineering areas. The study of wind and turbulence effects on

structures has generated its importance from the building of skyscrapers and use of wind turbines to generate power. The engineering area looks into the effect of the fluid mechanics effects of wind and eddies at a lower level, compared to aeronautical fluid mechanics.

In this thesis the concept of Frozen Turbulence (American Meteorological Society, 2012; Brune, 2020) will be used to understand the movement of the wind variance during the flight of the projectile. The concept of Frozen Turbulence is that the wind experience effect is moving as a frozen bubble at the speed of the wind record [Figure 11].

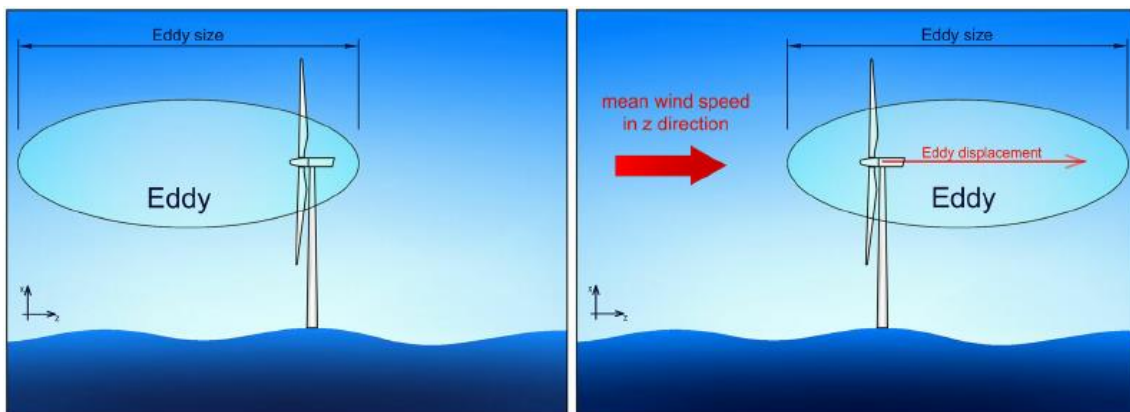


Figure 11 – Frozen Turbulence effect on a Wind Turbine. (Arany *et al.*, 2014)

[Figure 11] shows how the wind eddy move as the wind speed recorded in relation to the static wind turbine. The eddy bubble of the wind conditions moves in relation to the wind speed,

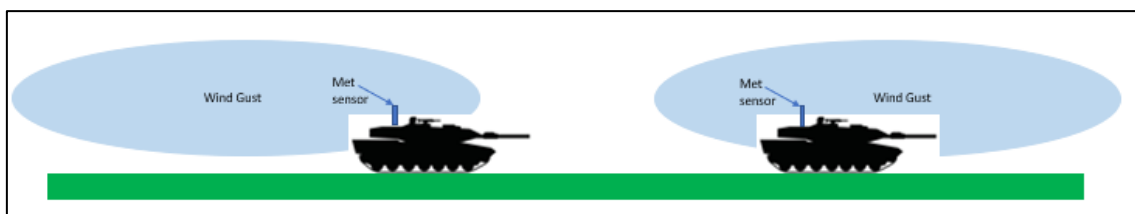


Figure 12 – Wind Eddy movement in reference to vehicle wind sensor

[Figure 12] shows how this would relate to an armoured vehicle or MBT, the wind sensor on the vehicle would record the wind conditions that would then travel away from the vehicle's location.

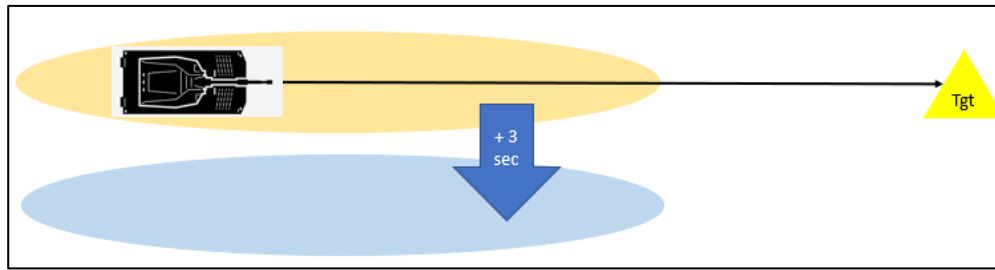


Figure 13 – Wind conditions offset against the Firing line.

The vehicle would continuously experience new wind conditions that would no longer be relevant to the Fire Control system once captured. The wind moving across the vehicle in relation to the crosswind conditions, would be offset from the vehicle **[Figure 13]**, compared to range wind that would be more relevant **[Figure 12]**.

The other main wind condition that will be examined in this thesis is the effect of wind gradient, which is the effect of boundary layer conditions close to the ground. Aerodynamic boundary layers are normally only examined at high altitude conditions where the changes in aerodynamic density and fluid mechanics become most relevant **[Figure 14]**.

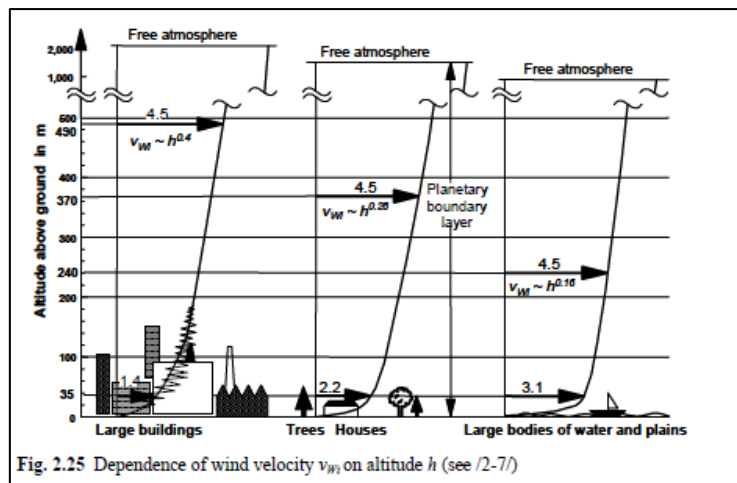


Figure 14 – Wind Gradient across different terrains (Kaltschmitt and Streicher, 2007)

Boundary layer conditions changing at the lower end of the spectrum are mostly ignored as the curve **[Figure 14]**, in the wind gradient and layering effect is much slower (Kaltschmitt and Streicher, 2007). But it has been raised by many

ballisticians that the effect of wind gradient can influence projectiles at a lower level, from aspects of the terrain (Moss, Leeming and Farrar, 1995; McCoy, 2012; Litz, 2015).

It is noted by nearly ever shooter when conducting rifle shooting that the local terrain has effects on the wind drift experienced by the projectile. This is easily seen during outdoor archery shooting, where the low speed arrow drifts at an angle to the wind. Conducting both outdoor archery and shooting myself, I have seen these effects on my projectiles in flight, with arrows nearly flying at a sideways angle to the line flight due to the effects of crosswind. Whilst a slow longbow arrow will have an increase reaction to wind drift, a ballistic projectile will still be subjected to the same effects.

The wind gradient **[Figure 15]** also effects the projectiles drift at a lower level, the curve in the gradient still applies. As can be seen in **[Figure 14]**, there are changes in the wind gradient curve between open terrain and closed terrain. Features including trees, hills and buildings can have a large effect on the lower altitude section of the wind gradient (Kaltschmitt and Streicher, 2007; Litz, 2015).

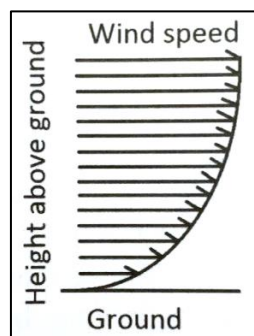


Figure 15 - Wind Gradient (Litz, 2015)

The wind gradient will be modelled using interpolation (MATLAB, 2023a) between the points given from the meteorological data (Reading University, 2020). The data sensor set provide by Reading University records wind at 2, 5 and 10 m in height, which can be used to build a wind gradient model **[Section 4.2]**.

2.3 Fire Control System Development

Fire Control Systems [FCS] and modern Fire Control Computers [FCC] have been mainly developed from research conducted in the Artillery and Naval Gunnery domains. In the 1900's artillery ballisticians and naval gunnery teams started to use complex system to conduct engagements over longer distances with larger weapons systems.

Development of these new combat systems installed on the early dreadnought ships used multiple fire control elements to engage targets. These developments in turn were transferred across to field artillery during the first world war as large calibre weapons and longer engagements were paramount.

Battlefields in the first world war were no longer limited to the 100 paces between the two armies but spread in depth and length engaging across thousands of kilometres. The artillery systems used also increased in size and calibre, with the Paris Gun being able to fire a shell across 120 kilometres (McCoy, 2012).

Naval engagements increase in distance and weapon system calibre, in 1906 the British Navy new Dreadnought class ship equipped with 12-inch [304.8 mm] guns had a maximum engagement range of 16,450 yards [15 km]. This new system required one of the first full fire control system to be installed into a battleship, enabling accurate engagements (Wikipedia, 2023b).

Ballistic development was also conducted separately by different departments with the focus being on unique application compared to any overall joint development of systems. This has changed over the end of the last century as budget restrictions and joint equipment procurement require joint development systems.

2.3.1 Artillery System Developments

Artillery ballistics and FC methods have been in continuous development since the late 1800s. Artillery systems used line of sight and range finders similar to the period's naval gunners to engage targets.

During the late 1800s and early 1900s artillery, FC and ballistics changed; the British in the Anglo-Boer War developed new tactics to direct fire. The “creeping barrage, where a curtain of shellfire proceeded just in front of the advancing troops” (Schlenoff, 2014) was used at a distance, and required coordination to engage targets that were out of the line of sight. Japan used artillery in the Russo-Japanese war 1904-1905 to bombard Port Arthur and the Russia fleet stationed there (Schlenoff, 2014). This longer more direct control firing before WW1 required meteorologists' support to support the ballistic calculations.

Meteorology was still in its early science during this period but rapidly developed during WW1. Artillery batteries used balloons **[Figure 16]** to capture meteorology readings to correct their firing trajectories. Later in the war, other units also provided weather data from balloons and aircraft regularly during the day to support ballistic corrections, nominally around every 4 hours. (Evans, 2014a)

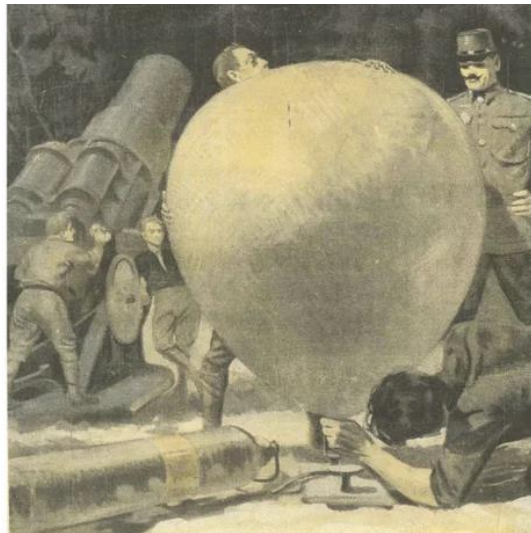


Figure 16 - WW1 Artillery Wind Measuring with a balloon (Schlenoff, 2016b)

Combining balloon and aircraft wind readings with ground stations improved the overall ballistic calculations for the artillery batteries. The wind across the shell

path through different atmosphere levels could be corrected in the range tables. Technology development in between wars which added radar and radio technologies into these solutions provided further improvement.

Balloons would carry a radiosonde to record data which was sent back via radio waves to a ground station. The lighter radiosonde fitted to balloons reduced the overall weight, which prolonged their flight time and increased possible altitudes. Radar tracking of the balloons would measure their drift from reflectors, which provided additional information (Evans, 2014a).

Sound ranging and radar was used to track incoming and outgoing shells to provide down range correction measurement to a target position (Evans, 2014b). Combining these systems provides artillery with long-range tracking of projectiles that enabled wind to be corrected along the flight's entire length. The downside was that they were large and labour intensive to implement, this was possible for artillery behind the mainline, but not for forward units.

The development of missile technology has led to the decline of long-range artillery systems. The equivalent Circular Error Probability (C.E.P) error of hitting a target is more accurate with a missile system compared to a shell. The M270 Multiple Launch Rocket System (MLRS) (Lockheed Martin, 2020), shown in **[Figure 17]**, is one of these advanced missile systems.

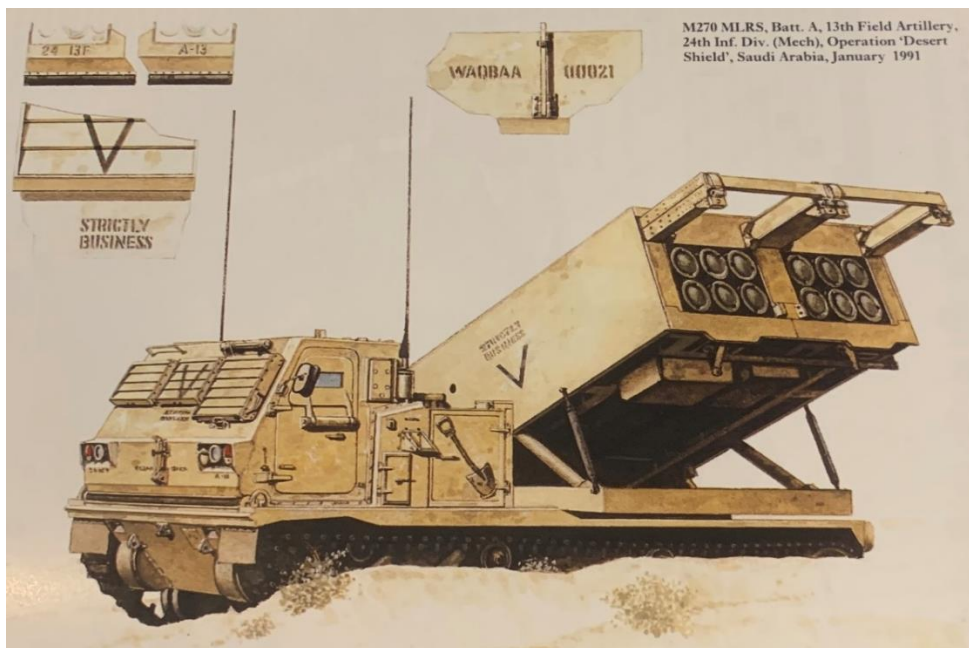
The missiles are guided by the Global Position System (GPS) which can provide accurate long-range artillery. One of the system's nicknames is the '70-kilometre sniper rifle' due to the guided rockets' accuracy. Despite the improved accuracy of guided missiles, these are less cost-effective than conventional 'dumb' unguided artillery projectiles. The development of guided projectiles has increased to correct for errors and improve the C.E.P in line with guided missiles accuracy.

Table 4 – Circular Error Probability (C.E.P) Comparison

Projectile	Guidance	Accuracy C.E.P	Range
M982 Excalibur 155 mm ^A	GPS / Inertial Nav Laser guided	5-20 m	la-1 = 23 km la-2 = 40 km
M795 155 mm ^B	None	50 m	M795 = 22.5 km M795E1 = 28.7-37 km

^A(BAE Systems Bofors AB, 2007), ^B(Wikipedia, 2020e)

[Table 4] compares the C.E.P of two 155 mm munitions the XM982 Excalibur guided round (BAE Systems Bofors AB, 2007) and a standard M795 155 mm shell. The guided capability has reduced the C.E.P error and increased the possible range. With guidance systems attached, munitions can improve their ability to counter wind drift but are at the cost of space and weight. The improvement is limited to large calibres with one of the smallest being the PERM 120 mm mortar round (Raytheon, 2020).

**Figure 17 – MRLS (Zaloga and Sarson, 1996)**

2.3.2 Naval System Development

Naval FC has developed across the last 200 years from rudimentary sighting along the gunmetal to advanced fire control systems. Early naval engagements were across a very short distance of 50 to 500 yards (Bureau of Naval Personnel Training Division, 1966). These short engagements were completed using 'by the metal' sighting, looking along the gun case to line up with a target.

Development in the early 1900s and WW1 further increased the effectiveness of naval cannons. Targets could now be reached out to 6000 yards in 1905 and then to 12,000 yards in 1910 (Bureau of Naval Personnel Training Division, 1966, 1971). The new FCS used a scientific method combining the following:

1. Range Finder
2. Rate of change of range projector
3. Range clock
4. Plotting and tracking boards
5. Communication improvements

(Bureau of Naval Personnel Training Division, 1954, 1966)

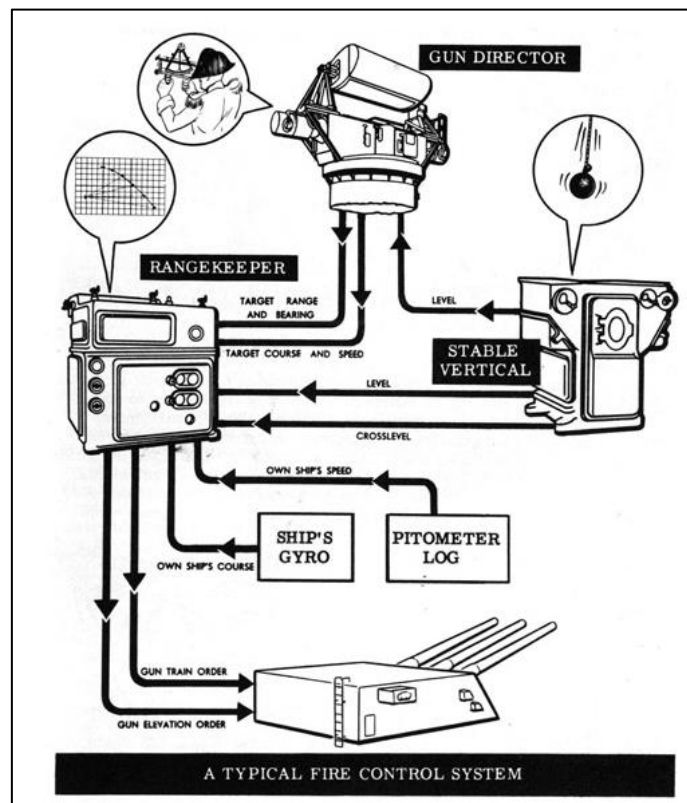


Figure 18 - Example Fire Control System (FCS) (U.S. Navy, 1953)

An example system layout is shown in **[Figure 18]**, displaying each of the above components. Due to the system's complexity, the system was only installed into early battleships and dreadnoughts ship class before WW1. The FCS replaced many manual tasks and ballistic calculation with mechanical computer systems.

The ballistic data from an FCS on board a battleship allowed it to engage out to an averaging between 18,000 to 24,000 yards at maximum elevations of 15 degrees. (Bureau of Naval Personnel Training Division, 1971).

In the 1920s, advanced Gun Directors and Rangekeepers system were installed across all vessels, not only battleship classes. Rangekeeper acted as plotting boards and mechanical computers that calculated the ballistic trajectory. Gun Directors used parallax to confirm the range to the target ship. Together with wind measures and gyros for the ship's position, accurate long-range targeting was completed.

The FCS were able to control and direct the movement of multiple turrets on the larger battleship to aim at a single target. Developments in WW2 allowed a ship to have multiple FCS on board at once and control different sets of batteries (Bureau of Naval Personnel Training Division, 1956, 1966).

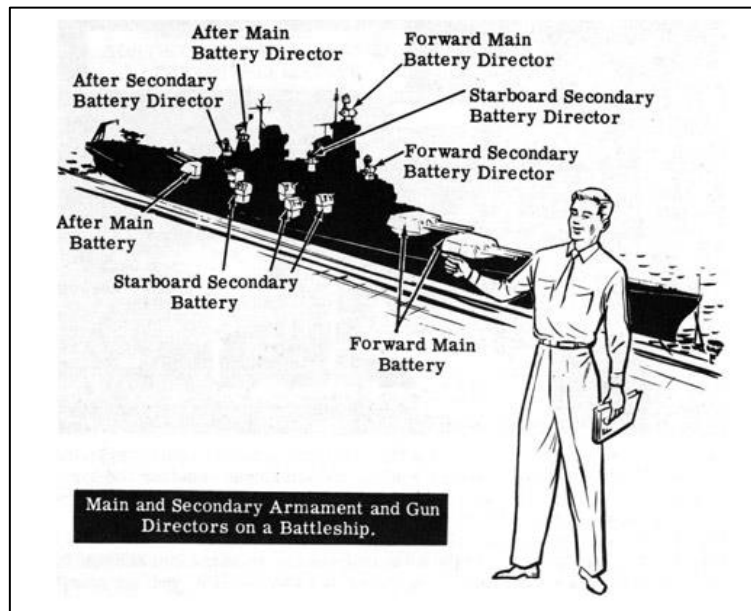


Figure 19 - Fire Control System Layout for Main and Secondary systems (U.S. Navy, 1953)

[Figure 19] shows the layout of a battleship class with multiple batteries and fire groups. The primary and secondary systems would allow different targets to be engaged or full ship simultaneous engagements. Secondary FCS also controlled the anti-aircraft guns into effective combined batteries. [Table 5] below shows the weapons and ranges of WW2 battleships classes.

Table 5 – Naval Weapon System Characteristics

Weapon	Maximum Range	Ship Class
14 in 45 Naval ^A	35,450 m (38,730 yd)	Kongo class
BL 12 in ^B	22,860 m (25,000 yd)	H.M.S. Dreadnought
BL 14 in ^C	38,600 yd @ 40 deg's	King George V class
BL 16 in ^D	39,780 yd / 35,000 yd @ 32 deg's	Nelson class
BL 15 in ^E	37,870 yd @ 30 deg's supercharge	H.M.S. Hood
16" / 50 calibre ^F	41,622 yd 660 lb charge	U.S.S. Iowa class
40 cm / 45 cm type 94 ^G	42 km @ 45 deg's	Yamato class

^A(Wikipedia, 2017), ^B(Wikipedia, 2019a), ^C(Wikipedia, 2020c), ^D(Wikipedia, 2019b), ^E(Wikipedia, 2020d), ^F(Wikipedia, 2020a), ^G(Wikipedia, 2020b)

Battleship class ships with 3-gun turret batteries would apply mechanical offsets in increase range and drift [Figure 20] dispersion. Each gun could be offset from the other to change the dispersion pattern; this would counteract drift errors. Wind drift would still affect each projectile flight, but the dispersion would counteract and increase the chance of impacting a target (U.S. Navy, 1953).

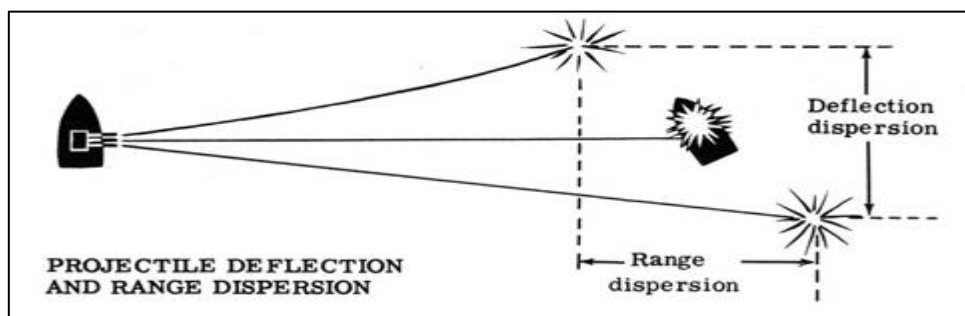


Figure 20 - Drift Dispersion (U.S. Navy, 1953)

The projectiles' dispersion enabled correction for errors in the ballistic flight at long range; another primary way was using spotters. Spotters would watch for

where the projectile landed near the target and inform the FC team what to correct (U.S. Navy, 1953; Bureau of Naval Personnel Training Division, 1971).

Spotters provided a long-range sensor using crew eyes and skill to provide additional information into an FCS. An equivalent in modern-day would be using a radar sensor or a drone at long range with these sensors attached. Modern sensors enable further data input into the FCS compared to a crew spotter.

In WW2, it was discovered that changes in wind conditions in atmosphere layers could affect long-range engagements. As shown in **[Figure 21]**, wind direction and speed can be opposite to lower atmospheres levels.

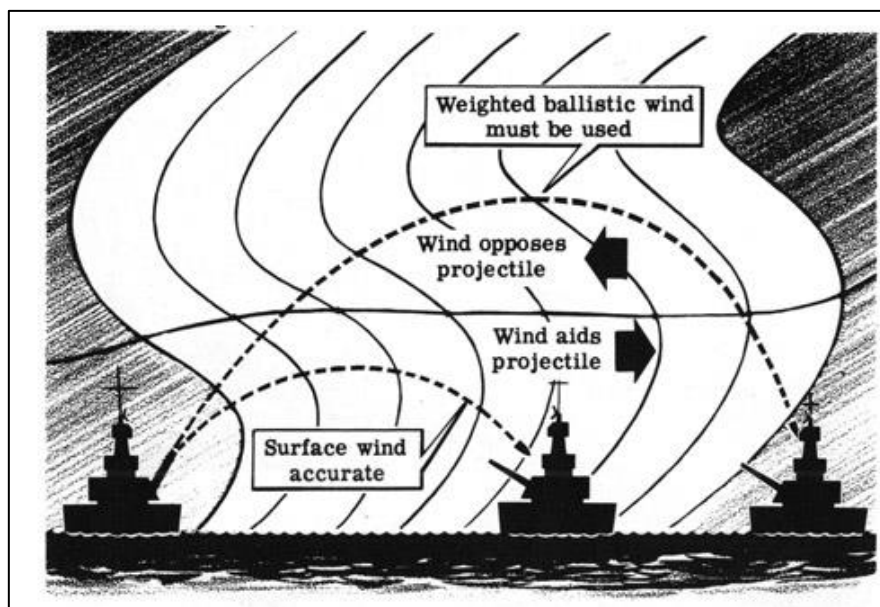


Figure 21 - Effect of wind with altitude (U.S. Navy, 1953)

Average wind values and weighted wind values were used to correct for ballistic errors in flight. Balloons and spotters were used to collect data on downrange wind conditions for each of the atmosphere layers so that corrections could be made to the FCS. The advance of radar was used to track the round in flight as it travelled to the target.

Radar provides real-time feedback of corrected information for a projectile trajectory into the FCS for the next projectile. Even correcting by this method, the correct wind data is still old and incorrect for the next projectile fired.

Radar and digital computer developments did improve the calculation process speed and complexity of FCS. The MK37 FCS shown in **[Figure 22]** was an early electrical and mechanical FCS solution. Radar improved the tracking and ranging of the Gun Director, compared to parallax sights, and enabled long-range tracking of a projectile.

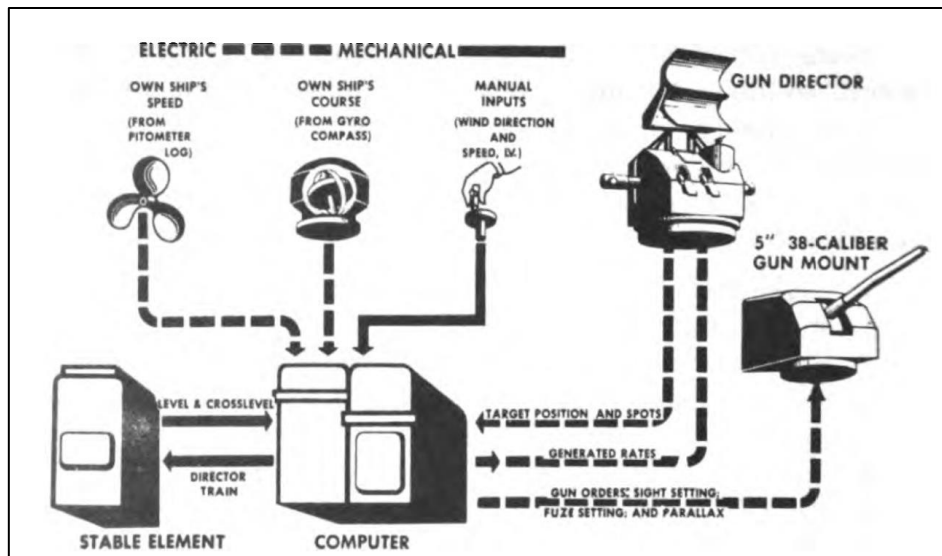


Figure 22 - Mk 37 Fire Control System (FCS) Layout (Bureau of Naval Personnel Training Division, 1954)

Developments during the 1950s and 1960s into missile technology changed naval engagements away from large calibre guns. Missiles used guidance technology to correct for downrange errors in flight including radar-, TV-, laser-guidance systems. These guidance systems were either manually controlled or computer-controlled to fly the missile to the target.

Missile systems have taken over as the main armament for naval vessels, with gun systems taken a back step in technology development. The C.E.P and flight errors are small for a missile compared to a large calibre traditional projectile.

Guided projectile developed for artillery systems are moving across to naval gun systems technology. Traditional cannon projectiles are cheaper than missile systems and with a guidance system added can perform similarly to missile systems in projectile accuracy.

2.3.3 Snipers and Sport Shooting

Significant developments in ballistics technology and ballistic mathematics have come from sport targeting and small arms shooting. Military snipers and sport shooters commonly shoot across varying terrain and out to extreme distances. The longest kill of 3,540 m by a Canadian sniper in 2017 (The Straits Times, 2017) shows that ballistic accuracy is highly required. Crosswind drift becomes an essential consideration on the trajectory of the projectile from the rifle.

In rifle shooting, it becomes essential to consider the terrain's effect on the projectile's wind condition in flight. Trees and hills affect the wind conditions due to surface friction which impacts wind gradient. Sniper and spotter teams can use various equipment to measure wind at the shooter's location and target location.

Snipers use traditional skills or training to measure the wind conditions by watching grass along the trajectory to the target. Skilled shooters can read the wind conditions to "+/- 1 mph" in estimating wind speed (Litz, 2015). This process still has errors, including human error in reading the wind and still only correcting for a single point either near wind or far wind.

Supporting spotters can add their wind reading into the calculation process and monitor the wind activity. The spotter can continuously update the sniper with changes in the wind conditions. The spotter can also decide which set of wind conditions is more critical and then correct if shooting across complex terrain. Miniature laser range finders and doppler radar units can provide environmental information to the sniper team to assist with wind reading.

This thesis aims to understand whether the human process in reading the wind conditions and correcting multiple points can be developed into the FCS. Military snipers apply different methods of correcting and estimating the crosswind correction to their trajectory. (Wahlde and Metz, 1999)

1. Manual Training – Sniper on his/her own will measure the crosswind by an estimate from training. The sniper measures manually by feeling the wind on their skin or watching trees and bushes around the area.

2. Paired (Baseline) – Sniper and Spotter will correct the crosswind; the spotter will read the wind and compare to range tables and notes. They communicate the corrections to the shooter. A combined spotter and sniper team is more effective compared to a solo sniper as the spotter can control the correction much like a fire control computer. Whilst the sniper is focusing on the target, and the spotter can manually work out corrections.
3. Windage Crosswind – using sensors at the firing point such as an anemometer device and training can better predict the crosswind and counter it. Additional technology also allows for better corrections to a sniper/spotter team, with laser range finders and supporting scopes.
4. Fire Control System – having a fire control computer either separate for the spotter to use or inbuilt into the sniper's scope to provide a real-time correction value.

The advancement in electronics has enabled rifle FCS to be developed to correct for the crosswind conditions. A fully trained sniper and spotter team are extremely effective for engaging targets but are still limited in their skills and information capacity. These teams mostly work on estimating the effect of crosswind during an engagement.

The USA Army Research Laboratory (ARL) have conducted several tests and experiments over the years to trial and develop FCS to correct for crosswind conditions. Error budget analysis (Wahlde and Metz, 1999) and the White Feather: Fire Control and Crosswind Sensing for Sniper Applications (Wahlde, 2008) reports details these results.

The ARL conducts a series of sniper error budget tests to understand the standard sniper engagement process (Wahlde and Metz, 1999). The report detailed the errors affecting the ballistic flight focused mainly on the crosswind correction. The crosswind correction applied was from the previous projectile reading; however, the current crosswind velocity was different, so the delta between the two values was not corrected.

The personnel manual corrected and rounded their estimates on wind speed to intervals of 5 mph for ease of mathematics (Wahlde and Metz, 1999). The rounding added additional inaccuracy into the correction method applied to the rifles. Using an FCS or even crosswind sensor did improve the accuracy of the wind speed values being corrected for but was still rounded to 5 mph intervals.

Two advanced crosswind measurements were tested in the reports, the first a doppler velocimetry sensor. This measured the velocities of the atmospherics across two divergent laser beams. The two beams along the sides of the firing line measured the difference in the crosswind components. The system is accurate down to '0.5 m/s' but with the disadvantage of the beams being impinged by clutter.

The second crosswind sensor works by measuring the average weighted distortion (scintillation method) in a single reflected laser beam (Wahlde and Metz, 1999). This type of sensor can read down to '1 m/s'. W.K. Graber has also conducted similar tests into scintillation based sensors to measure crosswind and atmospheric turbulence across hundreds of meters (Graber and Furger, 1994).

In the White Feather Trials (Wahlde, 2008) conducted by ARL, the crosswind wind correction processes mentioned above have been added to an automatic FCS. The Inertial Reticle Technology (IRT) works by giving the shooter a corrected reticle in their sights calculated by the IRT to aim to, **[Figure 23]**.

ARL used a Remington 700 Sniper Rifle with IRT fitted which when fired by a test engineer, was able to maintain a '10-round group' out to 800 m on an E-type silhouette target (Brosseau *et al.*, 2000b). An Army sniper could not achieve the same grouping at the 800 m, but the author noted that a sniper and spotter team would have been expected to maintain the grouping.

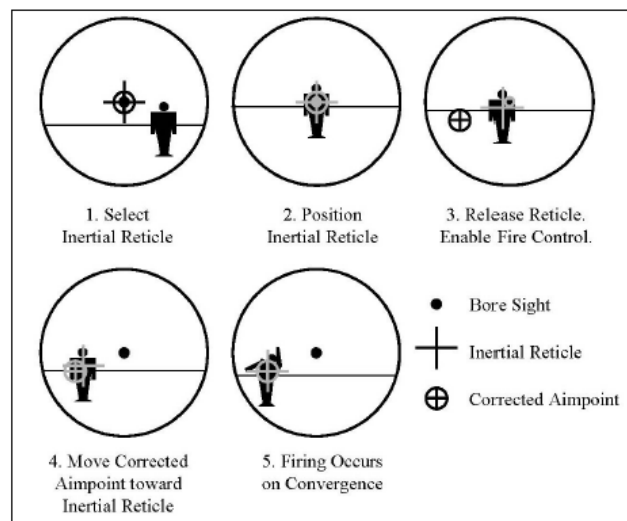


Figure 23 – Operation of Inertial Reticle Technology system (Wahlde, 2008)

The IRT system fitted to a turreted .50 calibre machine gun system on an Humvee (HMMWV) vehicle was also tested (Brosseau *et al.*, 2000a). The IRT system showed an improvement in accuracy. However, this study focused on the FCS and stabilisation, not the crosswind effects compared to the sniper test.

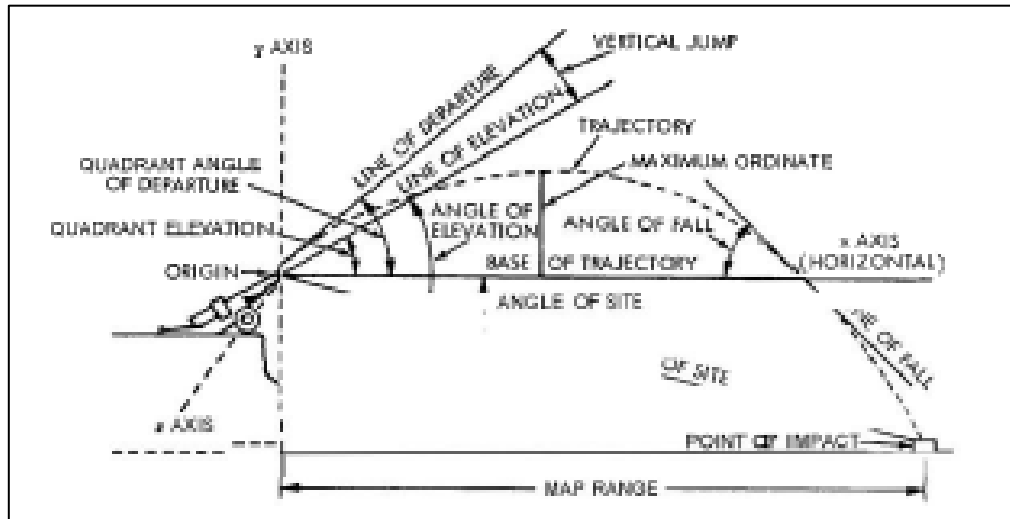


Figure 24 - Aspect of Trajectory (U.S. Army Material Command, 1968)

[Figure 24] above displays the aspects of a projectile's ballistic trajectory flight, taken from the engineering design handbook on fire control (U.S. Army Material Command, 1968). The fire control problem shows all aspects that need to be

solved to have an accurate projectile launch onto a target during an engagement.

The research conducted by ARL and Aberdeen Proving Ground as well as other military institution is collected into the overall Point Mass model and FC systems. Most western development use this information collected together in the NATO standard model for ballistic study as detailed in STANAG 4355 (NATO Standardization Agency, 2009). The STANAG details the version of the Point Mass model to be used during testing, which this thesis follows.

2.4 Fighting Vehicle Development

2.4.1 Armoured Vehicle Development

Armoured Fighting Vehicles (AFV) can trace their development back to WW1 with the first generation of Tanks and AFV. These vehicles were designed to support the infantry and break through the trench warfare deadlock, with a similar design to siege engines. Early British tanks like the Mother [Figure 25] were designed to cross no-man's land to breach trenches and provide supportive firepower. The vehicle design was based around the idea of 'land ships' or 'land cruisers' (Schlenoff, 2016a).



Figure 25 – British Tank used in the Battle of the Somme 1916 (Schlenoff, 2017)

The early tank battles of WW1 had an engagement range of 100-200 m (Cross and Willey, 2016) across trench fields. FC was similar to the early warship aiming to be “by the metal” of the gun barrel or basic fixed gun sight.

In the inter-war years, multiple different types of AFV's or tanks were designed to meet different requirements placed by different regiments, Infantry tanks were designed to be slow and support the infantry. Cavalry tanks were faster and lighter designed to break through and manoeuvre around the enemy positions (Cross and Willey, 2016).

Modern Armoured manoeuvre warfare was developed from the German Army early experiences in the 1930's with their armoured Panzer Corps and Blitzkrieg tactics. These were manoeuvre combined arms units including mechanised infantry and armoured divisions. The new style of manoeuvre warfare was

devastating and extremely effective in during WW2. Tactics moved away from static trench warfare to manoeuvre warfare which brought tanks and AFVs to the forefront of military strategy, and into direct conflict with each other.

The British Army tactics were in turn completely different from the new German Army tactics, with different British units using specialist vehicles. The Infantry regiments were supported by heavier Churchill tanks compared to Tank Regiments using medium [Cruiser] or light and faster tanks. This created issues for the British Tank Regiments being based around a cavalry format, using light tanks with smaller QF 2-pndr [40 mm] guns for most of the war **[Figure 26]**.

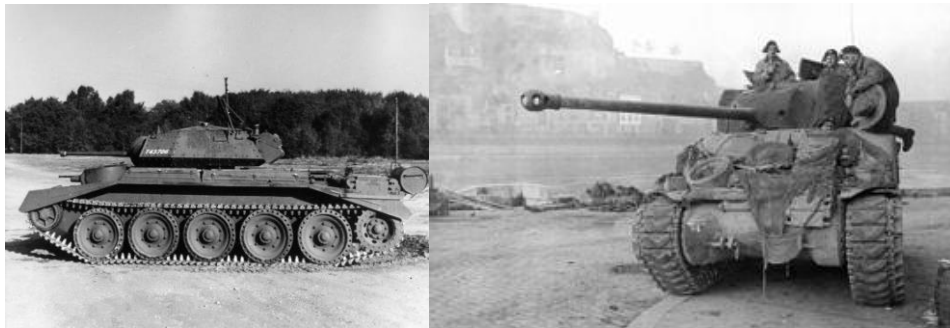


Figure 26 – Cruiser Mk I, with QF 2-pndr and Sherman Firefly, with 17-pndr.

With the introduction of the M4 Sherman from the USA, the standard armament changed from the QF 2-pndr to the 75 mm gun. This increase in firepower was demanded due to the introduction of Panzer IV and Tiger 1 tanks. The British then introduced mounted on the Sherman Firefly the British 17-pndr anti-tank gun [76.2 mm] (Cross and Willey, 2016).

The increase in firepower and the standardisation of the tank in the later part of WW2 was due to the tank moving from a fire support vehicle to primary a tank destroyer. The increase of armour on the new tanks required large gun to engage and destroy another tank in combat. This also increase the requirement to hit and destroy the other vehicle at distance, increased accuracy and even on the move.

The average engagement ranges increased to high hundreds of metres; the Cruiser tanks could reach 600 m (Cross and Willey, 2016). These ranges were reached with stadiametric fixed sights alongside manual hand controls for the gun

traverse. Electrical motors were only introduced in later tank development near to the end of the war.

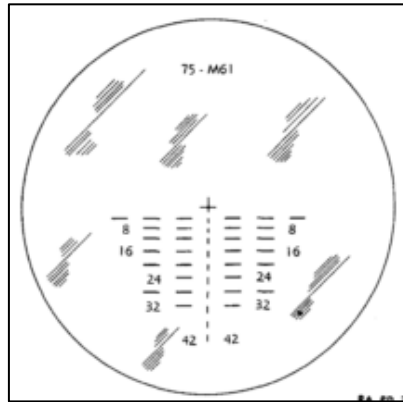


Figure 27 – M4 Sherman Tank, M70F Telescopic Sight Reticule

Initial advance gunsights, used on the M4 Sherman vehicles used an etched fixed sight reticle pattern **[Figure 27]** (The Sherman Tank Site, 2016). Advance recticle pattern could have different type of rounds on either side of the main vertical line, for example for High-Explosive and Discarded Sabot, due to the difference in projectile ballistic flight. This was the limit of the FC methodology during the war, with the process of steam gunnery used, which was “sight, fire, correct and fire again”.

By the end of the war the first of the “Main Battle Tanks” [MBT] was created and deployed in the form of the Centurion MBT **[Figure 28]** (Dunstan and Sarson, 2003), which only saw a very brief deployment. These new post war design focus on the principle of a tank goal was to engage another tank, with FC focusing on the first hit kill probability.



Figure 28 – Centurion MBT Mark 3, First Fully Stabilised system.

But the FC of these early MBT was still rudimentary compared to modern systems and even naval systems of the period. Range finding was an educated guess using the reticle pattern; turrets were stabilised but limited and no weather data was collected to provide an input. The firing solution was calculated by the gunner using the systems on board and was reliant on their skill.

With engagement distance increasing during the Cold War years due to increase in gun system design and the introduction of Anti-Tank Missiles. A gunner's skill at engagement could not be relied upon, so the FC systems were updated.

Manual stadiametric range finding was initially supported by a ranging gun, which fired long burn tracer and a projectile head would provide a 'flash' when impacting a hard object. The rounds would be fired at intervals until reaching the target of a known distance, the main gun was then fired after impact. Ranging rounds could also be used to estimate the crosswind, by observing the flight of the trace (Forty, 1979; Dunstan and Sarson, 2003).



Figure 29 – Chieftain MBT, (Wikipedia, 2023a)

The initial introduction of the Chieftain MBT **[Figure 29]** from 1967 the vehicle was fitted with a Marconi FC/GCE Mk 4, using a .50 in ranging gun, giving an effective range out to 2,400 m. This was replaced in the 1970's with the Barr and Stroud LF-2 laser rangefinder **[Figure 30]**, with an effective range of 10 km. Later models in the 1980's was upgraded with the Marconi Improved Fire Control System [IFCS] which was the first digital ballistic FCC (Taylor, 2016; Wikipedia, 2023a).



Figure 30 – TLS No 7, Laser Rangefinder, fitted to Chieftain MBT.

[Figure 30] (Taylor, 2016) Laser Range finders were introduced to replace ranging guns, which fired a laser pulse to calculate the distance to the target, initially just providing distance feedback independent of the stadiametric ballistic display. The TLS No 7 Sight, fitted to Chieftain provided the laser range feedback in the left eye and the ballistic graticule to the right eye (Taylor, 2016).

The IFCS fitted to the Chieftain MBT provided a corrected ballistic solution to the gunner, with corrections for range, crosswind, and vehicle position as an overlay onto the graticule sight. The advancement of this system enabled the gunner to have improved first hit chance onto the required target **[Figure 31]** (Forty, 1979).

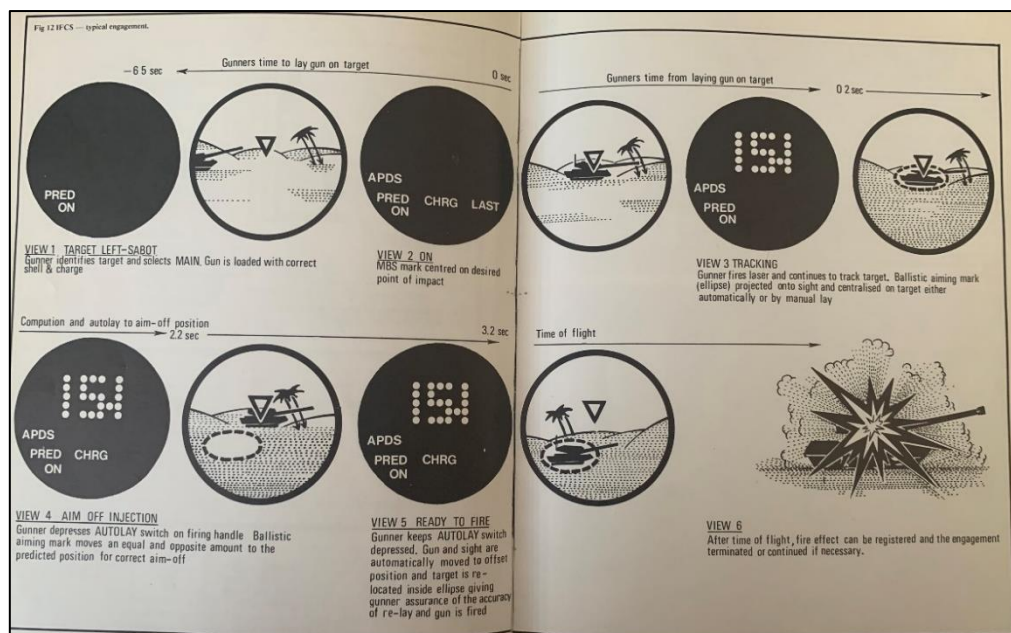


Figure 31 – Chieftain MBT IFCS Process

The IFCS process shown in **[Figure 31]** is examined further in **[Section 2.4.3]** on the engagement timeline in FCS. The engagement timeline process has been further refined in modern MBT's, with improvements across the full system. The simple overlay shown in **[Figure 31]** has now been replaced with digital display with auto-correct the system and do not require a re-laying of the new sight mark **[Figure 32]** (GD, 2023).



Figure 32 – General Dynamics Display Unit

Other systems have also been incorporated into the latest 4th Generation MBT's, with the inclusion of thermal sights and advance optics being the main difference in Cold War to Modern MBT's **[Figure 33]** (Galgano and Tillinghast, 2012).

	50's	60's	70's	80's	90's	2000 to Present
FIRE CONTROL COMPUTER	Ballistic Reticle ▲	Mechanical Computer ▲	Analog Computer ▲	Digital Ballistic Computer ▲	Digital Architecture Hunter/Killer ▲	Ammo Data Link (VSMC) ▲
SENSORS						
• RANGE	Optical ▲		Ruby ▲	NdYag ▲		
• ENVIRONMENTAL			▲	Optical (Manual) ▲		
• MUZZLE REFERENCE						
• TRACKING			Rate ▲			
ACQUISITION	Hard Optics ▲	Image Converters ▲	Image Intensifiers ▲	Thermal ▲	1st Gen. FLIR ▲	2nd Gen. FLIR ▲
STABILIZATION			Gun ▲	Sight (1 Axis) ▲	Sight (Dual Axis) ▲	

Figure 33 – U.S. Army, Vehicle Fire Control development timeline

Further improvement to modern MBT and AFV is the inclusion of either drone and Active Protection Systems (APS) using either passive or hard-kill counter measures. The latest European development system the Panther KF51 (Rheinmetall Defence, 2022) **[Figure 34]** is equipped with all these technologies and more.



Figure 34 – Panther KF51 MBT

The vehicle is intended to replace the 3rd Generation vehicles like the Leopard 2 which include many of the latest systems as add-on rather than full integration from the beginning. Similarly designed vehicle includes the Merkava Mk 4 Windbreaker which has systems like APS and thermal optics integrated from the initial design level.

The latest generation of vehicles are looking towards a future network integrated battlefield with a dependence on information and sensors being integrated. The KF51 includes a digital system design **[Figure 35]**, including a network integrated system to link with other vehicles and remote drone technologies (Rheinmetall Defence, 2022).



Figure 35 – KF51 Panther crew station

Advanced data and communication would enable a vehicle FCS to gather data from other vehicles and systems in its local environment. The FCS would then not be solely dependent on a single set of sensors to inform the FCC ballistic solution. A networked FCS could collect local area meteorological data from different vehicles to better inform the ballistic calculation.

2.4.2 Vehicle Fire Control Development

Vehicle Fire Control Systems (FCS) and Fire Control Computers (FCC) were developed mainly from the preceding naval gunnery and artillery technology. The early tanks in WW1, through to Cold War vehicles in 1970's, the main FCS relied on stadiametric range finders **[Figure 36]** (U.S. Army Material Command, 1968).

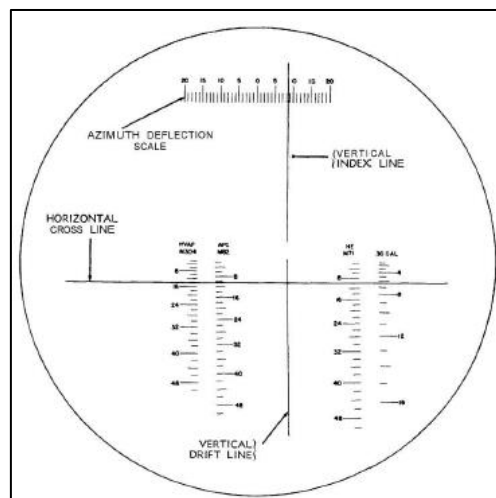


Figure 36 - Example stadiametric range finder layout

The stadiametric design in the sighting systems enabled engagements to be conducted over short to medium distances using the fixed intervals in the sight's index lines. Manual FC and stadiametric sights provided adequate engagement systems for WW2, static vs static vehicle combat. These were found to not provide as useful support for vehicles engaging moving vehicles.

For late WW2 tank engagements where tanks moved from infantry support vehicles to conducting tank vs tank engagement, improved FCS were needed. The ability to track and engage a moving target became paramount, and in order to destroy the other vehicle prior to it destroying your vehicle. The stadiametric sight and the manual ballistic calculations made by the crew needed to be improved to increase the 'first hit' probability of the systems.

To improve the 'first hit' probability of the FCS, both new tactics and equipment were needed. Developments in the 1950-1980's in sighting, control, data and digital FCC were slowly added to vehicles **[Figure 33]** (Galgano and Tillinghast, 2012). Mechanical control of the vehicle and turret systems were replaced with digital supported and then digital replacement systems.

The new FCS were based around a computer system that could calculate all aspects of the ballistics solution on behalf of the crew. This would include the following aspects:

- Moving and tracking a target,
- Meteorological effects of air temperature and pressure
- Meteorological effects of wind speed and direction
- Range finding
- Control of gun position in reference to the vehicle

The first part of the FCS that was replaced was the manual ranging of the system via the stadiametric sight. Changes included ranging machine guns with tracer projectiles to verify the engagement distances, which had previously been estimated by the crew. The crew could fire lower cost rounds compared to firing the main armament projectile at a target to find the range.

In the 1960's, laser range finders **[Figure 30]** provided an improved reading for ranging to a target. This type of system replaced the ranging machine guns on vehicles arising due to the average engagement distance increasing from 500-1000 m during WW2 to 1000-3000 m during the cold war.

The acceleration of development during the cold war in vehicle technology led to an increase in the average engagement range. The use of Anti-Tank (AT) missiles increased the scale of vehicle engagements, as the AT missiles outmatched the range of a standard cannon projectile. The increased range furthered the stand-off distance requirement in weapon system development, as shown in **[Table 6]**.

Table 6 – Tank/AFV Weapon Ranges

Vehicle	Cannon	Range (meters)	Missile	Range
Panzer IV ^A	7.5 cm KwK 40	7700 m (max)	n/a	
Sherman ^B	75 mm gun M3	3000 m	n/a	
M60 ^C	Gun 105 mm Tk L7	4000 m	n/a	
M1A1 Abrams ^D	120 mm Rh-120	4000 m	LAHAT	8000 m
T72 ^E	2A46 125 mm gun	4000 m	ATGM	5000 m
Challenger 1 ^F	Gun 120 mm Tk L11	APDS 3000 m HESH 8000 m	n/a	
BMP-2 ^G	30 mm autocannon 2A42	2000 m (effective)	9M113 Konkurs	4000 m
Warrior IFV ^H	30 mm L21A1 RARDEN	2000 m	n/a	
Bradley IFV ^I	25 mm M242 Bushmaster	3000 m	BGM-71 TOW	3000 m

^{A,B}(Cross and Willey, 2016), ^C(Lathrop, McDonald and Laurier, 2003), ^D(Forty, 2005), ^E(Zaloga and Bryan, 2009), ^F(Dunstan and Sarson, 1998), ^G(Zaloga and Sarson, 1994), ^H(Foss and Sarson, 1994), ^I(Zaloga and Sarson, 1996)

Further integration of electrical and mechanical systems would enable vehicles to reach full FCS similar to the development of battleship FCS in the early 1900's. The principles of both naval and vehicle FCS worked on the same principles of control but different aspects of control of individual systems **[Figure 37]** (U.S. Army Material Command, 1968).

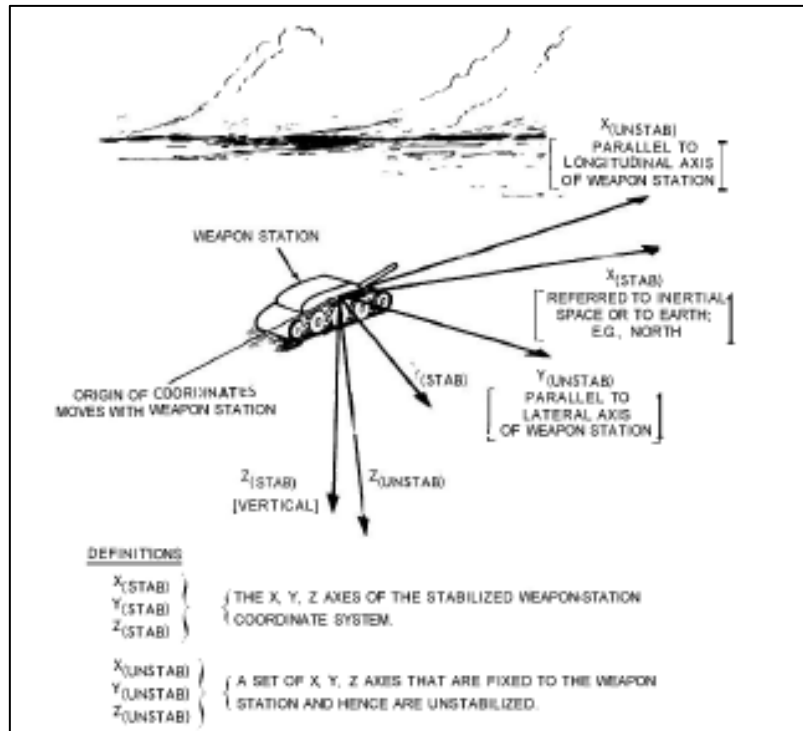


Figure 37 - Aspect of Fire Control (U.S. Army Material Command, 1968)

Fully stabilised and controlled vehicle systems didn't complete development until the late 1990's [Figure 33] (Galgano and Tillinghast, 2012). With the latest generation three vehicle Leopard 2 and Challenger 2 demonstrating the capability (Taylor, 2018). The new digital FCS enable massively improved 'first hit' probably from the vehicle which would increase the chance of a vehicle kill.

The aspects of a full FCS were demonstrated in Gulf War 1 in 1990's, as modern western MBT came into conflict with older Russian MBT's in Iraq (Dunstan and Sarson, 1998). The improved FCS, thermal sights and equipment on the vehicles being quote as enabling the western MBT to effective knockout the Iraq MBT's.

A limiting factor of the modern FCS is the calibration and accuracy in maintaining the capability of the system. Each element of the FCS requires regular calibration and the system as a whole calibrated mainly via Boresighting the core elements. Boresighting is the process of aligning the barrel to the sights and inputting the correct vehicle offsets into the FCC [Figure 38] (U.S. Army Material Command, 1968).

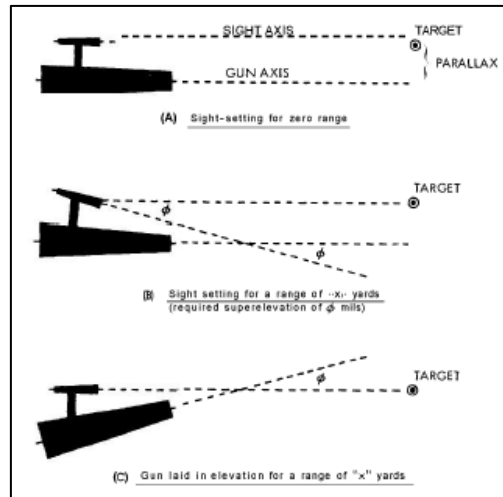


Figure 38 - Boresight alignment

The FCC requires the offsets mainly between the barrel and sight to make sure that where the sight is aiming, the barrel correctly follows. Additional offsets between the gun, sights, turret layout and metrological sensor also form part of the ballistic equations. The accuracy and reliability of these systems form part of the overall FCC calculation and the error budget [Table 3].

Boresight and FCS calibration is conducted through the measurement of the vehicle ballistic Mean Point of Impact (MPI) [Figure 39]. The MPI is the comparison between the point of aim and the impact dispersion of the rounds on a target. The MPI offsets in the X & Y grid will be inputted into the FCC to align the impact and aim points together.

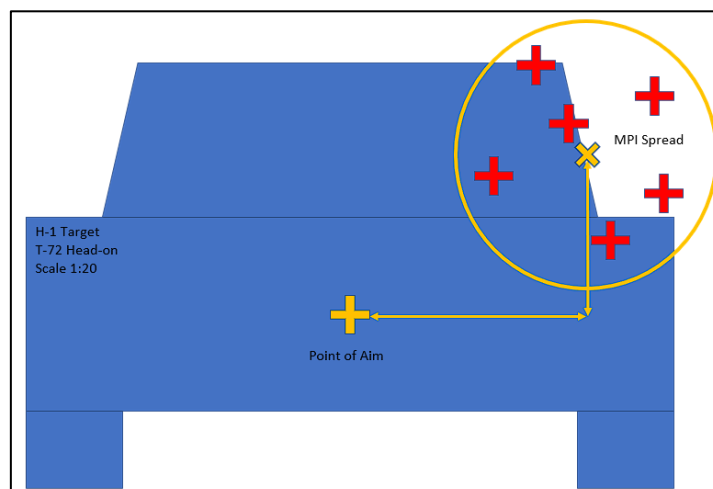


Figure 39 – Mean Point of Impact definition

The issue with aligning the vehicle FCS around the MPI is that all influences on the projectile flight will be shown in the MPI dispersion. If the projectile is heavily influenced by wind drift and the system is re-aligned to the MPI offsets the next time the system is fired the MPI will be different.

These aspects are summarised in the Error Budget **[Table 3]**, which is used to develop and control the importance of the influences to the FCS. **[Table 7]** shows an expanded environmental errors in the Error Budget (Terry *et al.*, 1991) that will influence the MPI.

Table 7 – Example Error Budget for Environmental Error

Error Source	Traverse Axis (%)	Elevation Axis (%)
Charge Temperature	0%	30%
Air Density	0%	5%
Crosswind at Tank	50%	0%
Headwind at Tank	0%	5%
Downrange Gusts	20%	0%
Optical Refraction	0%	30%
Jitter	30%	30%
TOTAL	100%	100%

The errors that will most likely cause the greatest influence on the MPI at the target point are the environmental errors. **[Table 7]** shows that Meteorological wind makes up 70% of the traverse axis environmental errors: 50% from crosswind and 20% from downrange gusts. FCS using a single sensor on the platform will only account for the wind at the vehicle and not downrange.

(Terry *et al.*, 1991) mentions that onboard wind sensors are susceptible to disturbed airflow from the platform. A sensor is required to be at the height of around “1 m” to avoid disturbance. These sensors are not at these heights on modern tanks making them susceptible to clutter and interference **[Figure 7]**.

Research to expand the understanding of the meteorological and environmental influences on the FCS have been conducted by a few research institutes. British Armament Research and Development Establishment (A.R.D.E) was the leading research centre in the U.K in the 20th century for weapon and tank development.

A report from the 1960s talked about a statistical method of countering wind gustiness (Armament Research and Development Establishment (A.R.D.E), 1967). The report sought to understand and correct for the gustiness of wind on the Mean Point of Impact (MPI) drift of a weapon, as shown in **[Figure 39]**.

The error in the MPI detailed in the A.R.D.E report due to wind was calculated based on a 1-hour average of the Northern European wind environment, with a statistical drift offset applied to the vehicle's base calibrated MPI offset. The A.R.D.E team suggested that a statistical average wind drift offset to be applied to vehicles operating in Europe, instead of the crosswind sensors value.

The suggested would enable a vehicle with an FCS to conduct a shoot without the crosswind sensor being used and still have an offset applied that matched the local environmental conditions. The statical average was recorded across multiple sensors for considered gustiness and changes to the wind conditions, compared to a single point average.

The average statical wind velocity for northwest Europe having a standard deviation of gustiness value of 4.9 ft/sec [1.49 m/s] to 6ft/sec [1.82 m/s] (Armament Research and Development Establishment (A.R.D.E), 1967).

The Error Budget is included in the development and programme of a FCS to enable an accuracy system, which is calibrated via the MPI method. The purpose of having the precise FCS is to enable a high first hit performance of the system or P-Hit for short. Having a high P-Hit value would enable an MBT to destroy its target prior to being engaged itself (Cranfield University, 2020a).

The second part to the P-Hit calculation is that the weapon is enabled to get a probably of Kill [P-Kill], to remove the vehicle from combat. The P-Kill can be further defined into a Catastrophic/complete Kill [K-Kill] destruction of the target; Mobility Kill [M-Kill] removing the ability to move and Firepower Kill [F-Kill] removing the ability to fight.

The mathematical analysis of a system is then aligned with the performance of the system against a standard target, normally a NATO standard training target.

One of these is the H-1 T-72 target [Figure 40] set used by the U.S military in their training programmes (US Army Aberdeen Test Center, 1998).

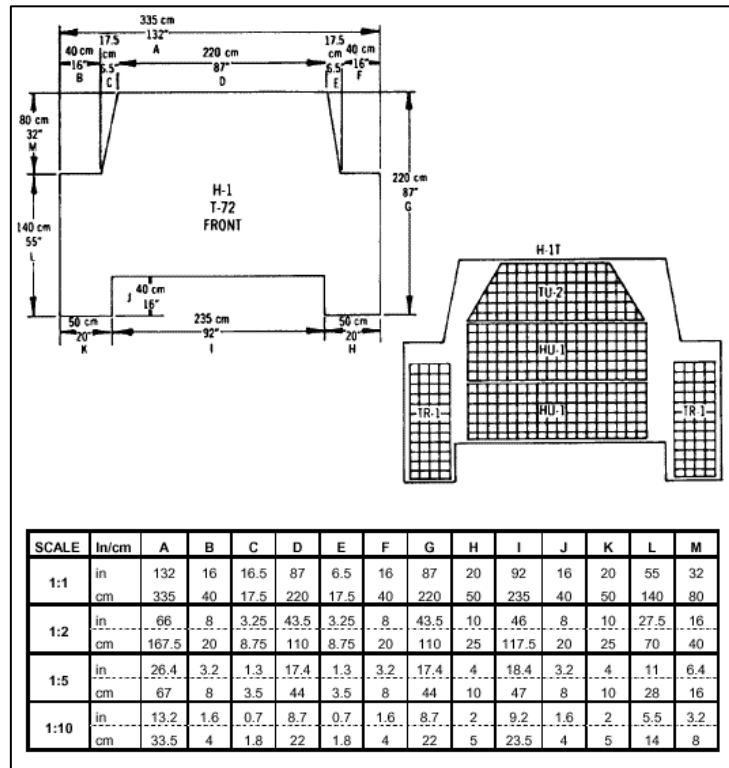


Figure 40 – H-1 and conversion chart for reference target creation

This standard H-1 T-72 MBT head-on reference target has been recreated to a corrected scale for 2,000 m engagement, at 1:20 scale [Figure 41].

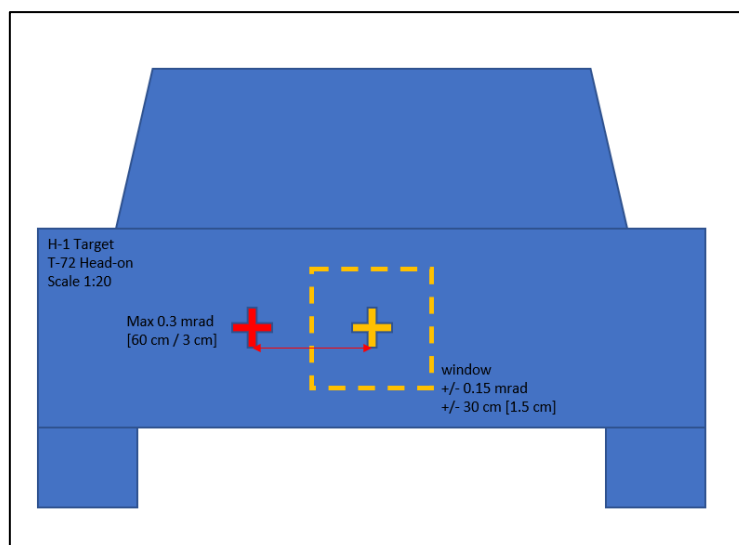


Figure 41 – H-1 T-72 Head-on scaled target, with Coincidence overlayed

The NATO standard Coincidence window has also been overlayed onto the target in both the main square window (yellow), against the centre aiming mark. As well as showing the maximum single direction error of 0.3 mrad [60 cm] at 2,000 m in a single direction (red).

2.4.3 Chieftain MBT IFCS

The Chieftain MBT Fire Control System, known as Improved Firing Control System [IFCS] developed by Marconi System [now part of BAE Systems] is the most modern system that is widely detailed in how the system works. The majority of modern MBT still in current service or development, are highly classified with extremely limited information on the FCS. The Chieftain IFCS is a modern designed FCS which is the basis for most modern FCS and MBT design, detailing the interaction between all the systems **[Figure 42]** (Forty, 1979).

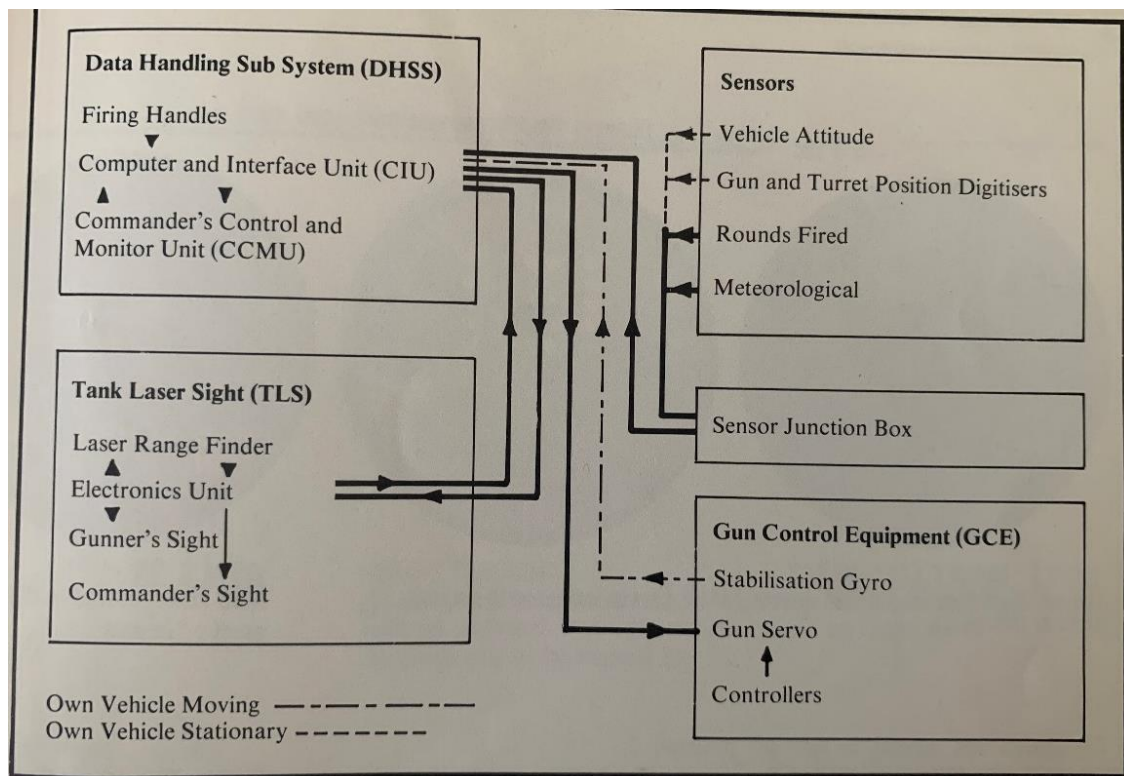


Figure 42 - Chieftain MBT IFCS Control Layout

The IFCS was a fully digitised and stabilised system for the MBT, incorporating many new systems including laser range finders, fire control computer and

thermal sights. The system input recorded all the hull and turret dynamics required to achieve precise fire on the move capability (Forty, 1979).

The IFCS has been further developed in new MBT designs but the overall principles of the system design and engagement timeline remain the same. The Chieftain engagement timeline has also been well documented **[Figure 43]** (Forty, 1979). The IFCS enabled the vehicle to achieve an engagement timeline of around 10-15 s.

The engagement timeline is as follows **[Figure 43]**: The Target is located and tracked by the Gunner **[Tile 1]**; The Target is located in the centre of the sight **[Tile 2]**. The Target is then lased with the range finder **[Tile 3]**, at this point the rest of the IFCS collects data for the ballistic solution, including crosswind and vehicle orientation. The IFCS provided a corrected ballistic solution as an offset aiming mark into the Gunner's sight **[Tile 4]**.

The Gunner then overlays the correct ballistic aiming mark onto the Target position in the sight, confirming to the Commander that they are ready to engage **[Tile 5]**. The Commander then gives the Gunner permission to fire at the Target, which is then destroyed after the flight of the projectile **[Tile 6]**.

The process from Target sighted to destruction is around ~12 s, this is a long space of time, in relation to meteorological wind and the movement of the crosswind. The IFCS holds the data for the ballistics solution for around ~3 s prior to the Gunner firing the weapon system. The IFCS ballistic solution is not updated or recalculated during this time. When the projectile impacts the target, the IFCS ballistic solution is ~6 s out of date for that engagement.

For a Static vs Static vehicle and Target, the change in relation to the held ballistic solution is low, but the crosswind has changed by the time the projectile is fired. This error is amplified when the scenario changes to a Moving vs Moving vehicle and Target, if the ballistic solution is not recalculated larger errors and drifts in the solution appear.

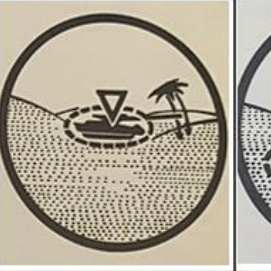
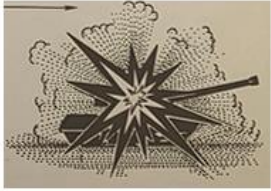
Tile	1	2	3	4	5	6
Sight Icon						
Title	Target – Left SABOT	ON	Tracking	Aim off Injection	Ready to Fire	Target
Timeline	- 6.5 s	0 s	+ 0.2 s	+ 2.2 s	+ 3.2 s	+6.2 s
Gunner action	Target Sighted and tracked	MBS centred on Target	Gnr, Fires Laser	Checks results	Gunner, fires gun once ellipse corrects.	
Fire Control System (FCS)			Ballistic Aim Mark projected (ellipse), Ballistic correction calculated	Ballistic correction applied, ellipse moves with correction aim-off results	Gun and sights re-locate to inside the ellipse window	
Met Data			Wind data collected			
Lase			Fired, distance reported			

Figure 43 – Chieftain MBT Engagement Timeline

The Chieftain MBT IFCS is a very detailed example of the FCS for an MBT and how the system engages a Static vs Static vehicle and target scenario. The principles in the FCS can be applied to modern vehicles as the FCS is identical in design. The main change in modern system is the use of improved computers and sensors to support the ballistic solution calculation (Dunstan and Sarson, 1998; Taylor, 2018).

The latest British MBTs, which followed on from the Chieftain are the Challenger 1 and Challenger 2, which share the same design heritage. Both modern MBTs use modern versions of the Marconi IFCS, with improved system design. The new FCS does not require the Gunner to re-lay the ballistic offset mark onto the target during the engagement sequence **[Tile 4-5] [Figure 43]** (Taylor, 2018).

The sequence has been shortened as the FCS directs the Gun Control Equipment [GCE] to auto-update and re-lay the gun and systems into the correct position based off the ballistic solution correction. The Gunner screen aiming mark stays in the same position on the target as the system updates, there then is a minor controlled delay if the Gunner fires the system before the GCE update is completed (Taylor, 2018).

The firing process detailed above is known as coincidence firing and is also dependant on the NATO coincidence error of 0.3 mrad (US Army Aberdeen Test Center, 2009a). The 0.3 mrad error check is present in the FCS to monitor the drift in the GCE movement compared to the FCS ballistic solution. The FCS is designed to keep the drift between the GCE and FCS solution to within the 0.3 mrad error window.

If there is a long pause between the initial lase onto the target and fire trigger being pressed, then there is a high probability that the drift between the FCS and GCE will exceed 0.3 mrad. Depending on the system design the FCS once exceeded 0.3 mrad in drift, will either not fire or conduct a recalculation of the ballistic solution to bring the drift back within 0.3mrad.

Meteorological wind is a constant changing condition there is a high chance that the FCS drift exceeding 0.3 mrad will be caused due to the crosswind error in a

static scenario. The is shown in the Error Budget values for the crosswind [Table 7].

2.4.1 Future Vehicle Technology

The error caused from meteorological wind data could be improved by the use of more sensors inputting into the FCS. There have been a number of developments by different companies into this area of vehicle design. Examples of extra sensors being integrated into a vehicle platform or provided from other platforms, include remote Uninhabited Air Systems (UAS) or other MBTs.

The French firm Nexter (ADIT - The Bulletin, 2019), has developed an aerial wingman (UAS) for MBT, which can carry a number of sensors. The main feature of the UAS is a remote sight/camera to enable the crew to view a larger area around the vehicle [Figure 44]. The UAS would allow the MBT to stay out of the line-of-sight and provides additional firing information to the FCS and crew.



Figure 44 – A Render of a Leclerc tank with UAS

The UAS could be operated as a network solution, so multiple vehicles in a platoon or battlegroup could use multiple UAS as extended range sensors. Regarding this research, the UAS or UGS could also carry a meteorological

sensor to capture wind conditions between the vehicle and targets or across a much larger area of exposure.

By combining multiple vehicles and UAS/UGS platforms, a larger area could be covered to determine the wind conditions accurately. Networks of local sensors would enable different vehicles to use other platform sensors that are not on their own (Eshel, 2018). The article by Eshel details the possible combined platform networked systems that would be available. Using a mixture of different sensors and systems across an operational group could provide multiple options to future commanders.

Improving the vehicle system is another option that could be considered. Work by an Israeli team (Bar-Tal, Tsadka and Azoulay, 1998) on an improved crosswind sensor system could be incorporated into a vehicle system. The rifle FCS uses a laser beam between rifle and target to analyse the turbulence induced spatio temporal power fluctuation to produce a crosswind reading. The diffraction pattern of the beam drift along with the crosswind between the two positions, providing an improved crosswind reading, accounting for the full length of flight.

The author noted current system do not consider the analysis of crosswind 'over the total line of sight' between a firing position and target. It was also noted from the analysis that effect of wind on projectile 'accuracy is substantial'. New FCS will need to consider the effect of crosswind along the full length between a shooter and target.

2.5 Conclusion

The development of improved FCS that consider the effects of crosswind and gustiness in the ballistic solutions are required as the defensive systems of target vehicles equally improves. Modern MBT have increased protection systems in the form of Explosive Reactive Armour (ERA) packs and Active Protection Systems (APS) (Cranfield University, 2020b), which are all designed to protect the vehicle from a distance (Rafael, 2019).

APS is designed in two main forms, Soft-kill and Hard-kill systems, a Soft-kill system is designed to obscure the target or defeat the sensors of a weapon. Most

Soft-kill systems work in the electronic spectrum, compared to Hard-kill systems which are designed to physically defeat a projectile [Figure 45].

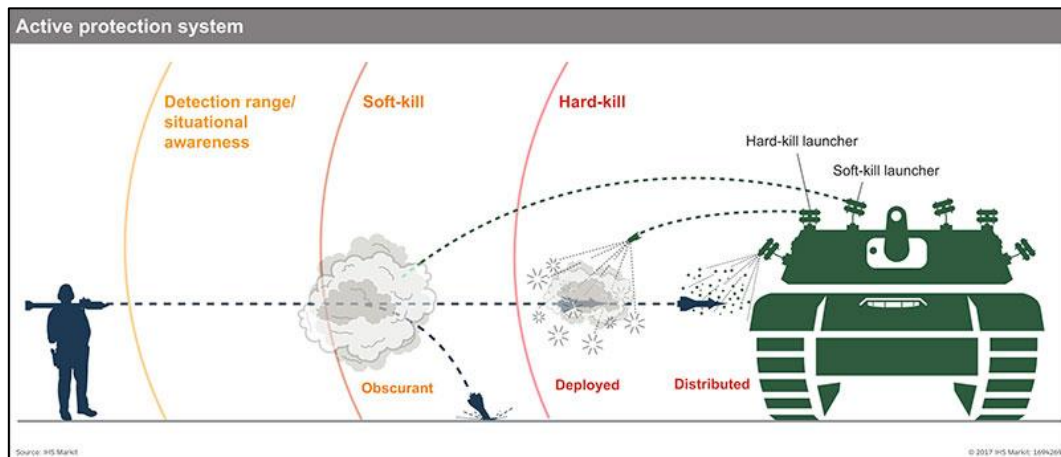


Figure 45 – Active Protection System (APS) function (Jane's, 2017)

A mixture of APS and ERA systems added to a MBT can defeat projectiles prior to impacting against the main vehicle. These systems are designed to increase the survivability of the crew and system as a whole but have a few down sides. ERA armour packs can only be added to specific areas of the vehicle so areas where the sights or other system protrude would not be protected. APS system provide a near 360 degree protective bubble around the vehicle but only if designed and installed correctly.

For example, T-80 and T-90 MBT, ERA is fitted to the frontal turret and hull armour only (Zaloga and Rodríguez, 2018), whilst western vehicles are designed with all round protection. APS coverage arcs are reduced due to other exposed systems on the vehicle for example, Sights and Electronic Counter Measures pods.

Previously not considering the effect of crosswind and gustiness across the full distance between a firing position and target would cause a drift that would still impact a target. For example, most MBT are 2 m wide in the frontal arc, a drift within the NATO 0.3 mrad at 2 km, would only be a drift of 60 cm. This being the allowable drift, the projectile would still impact the target. However, for a target fitted with these systems that drift distance could be the difference between impact ERA armour or an exposed area of an MBT.

To enable an improved FCS, the gustiness and crosswind across the full distance between target and shooter needs to be considered. Wind conditions that are constantly changing causing a gustiness error are not being measured or considered in a modern system calculation.

Advancement from other areas can be included in developing new vehicle FCS but have restrictions. Artillery system rely on improvements to the projectiles in the form of guidance kits these are too complex and large to integrate into MBT and vehicle projectile systems. Naval guns are of the same design and calibre as ground artillery system, incorporating guidance kits. Naval tactic also have moved to missile technology rather than conventional guns and fire control.

FCS development from sport and infantry rifle systems are still developing along similar avenues to vehicle based systems. Concepts proposed by the Israeli team (Bar-Tal, Tsadka and Azoulay, 1998) and ARL (Wahlde and Metz, 1999) can also be incorporated into vehicle FCS. Incorporating a mixture of additional sensors to provide increased information for an FCS to conduct calculations from could provide an improved solution.

Networking with other vehicles in a battlegroup or Uninhabited air or ground vehicles (UAS/UGS) to use their sensors could provide a big picture of the local meteorological conditions. These systems would allow for gustiness and changes in the wind conditions to be measured, either to provide an improved FCS solution or to provide an alert to show the drift away from the 0.3 mrad window.

2.5.1 Aims and Objectives

Refining the main aim of this thesis, to understand the effect of varying wind conditions on the coincidence window in a ballistic solution. The Point Mass Model ballistic calculation will be used to simulate the Fire Control System for the reference projectile. Along with further defining the objective into:

1. Do varying crosswind conditions affect the 40CTAS projectile drift in flight to a target?
2. Does the time delay in an FCS engagement timeline (Chieftain FC) affect the coincidence window?
3. Can the varying crosswind conditions move a projectile impact point outside of the NATO 0.3 mrad error window, referenced to the centre target mass?
4. Can the FC system conditions be improved to support an improved crosswind assumption for the ballistic solution?

Chapter 3 Theory

3.1 Introduction

This chapter details the equations and models used to process data used and undertake the ballistics calculations. The theory will focus on the relevant aspects that relate to the MATLAB code and ballistic assessment in this thesis.

The fundamental ballistics theory used for this research is primarily the Modern Exterior Ballistics (McCoy, 2012). Supporting information from Fundamental of Ballistic Course notes (Cranfield University, 2019); Applied Ballistics for Long Range Shooting (Litz, 2015) and NATO STANAG 4355 (NATO Standardization Agency, 2009).

3.2 Ballistic Theory

3.2.1 Equation of Motion

All ballistic models start from the initial condition of the projectile and firing platform, these are principally represented by the equation of motion which sums all forces acting on the projectile (McCoy, 2012).

$$m \frac{d\vec{v}}{dt} = \sum \vec{F} + m\vec{g} \quad (3.2-1)$$

Where:

$\vec{F} = \text{Force}$

$m = \text{Projectile mass}$

$\vec{g} = \text{Gravity}$

The second integration of the equation of motion produces the X and Y axis for range and height. These equations form the basic trajectory profile in a vacuum with no drag and only gravity affecting the projectile's flight.

$$X = \int v_x dt = v_0 t \cos \phi_0 \quad (3.2-2)$$

$$Y = \int v_y dt = v_0 t \sin \phi_0 - \frac{1}{2} g t^2 \quad (3.2-3)$$

Where:

v = Velocity

t = Time of Flight

ϕ_0 = Initial launch Angle

These equations produce a basic 2-dimensional ballistic trajectory plot. The projectile's drag reference area 'S' can be calculated from (McCoy, 2012).

$$S = \frac{\pi}{4} d^2 \quad (3.2-4)$$

Where:

d = diameter of projectile

3.2.2 Point Mass Model

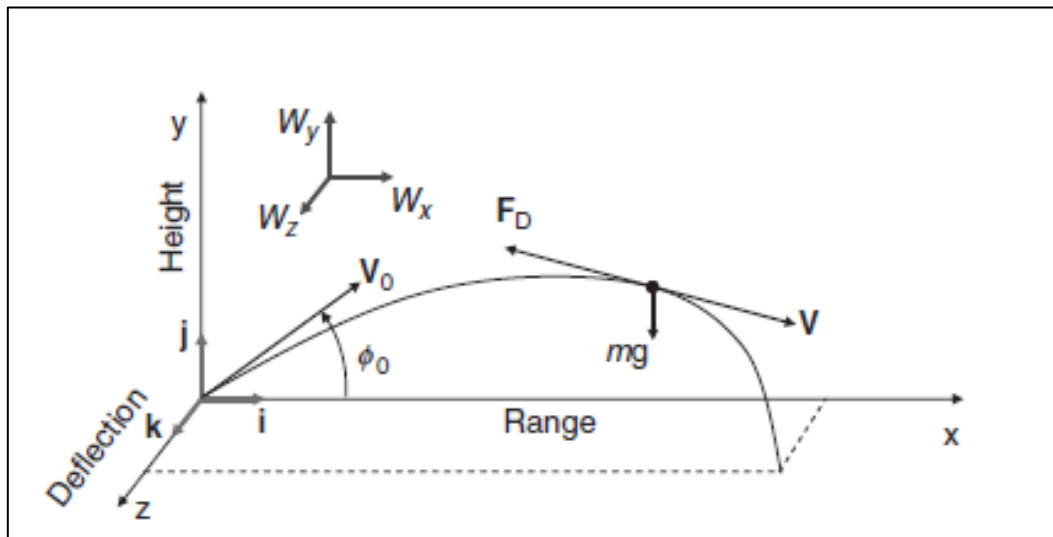


Figure 46 – Coordinate system for a Point-Mass Trajectory with Wind (McCoy, 2012)

The Point Mass trajectory model (McCoy, 2012) as shown in **[Figure 46]** expands on the primary equations of motion and was used to build the MATLAB code. The equation of motion can be expanded for all axis (X, Y, Z) to the following.

$$\dot{V}_x = \frac{dv_x}{dt} = -\widehat{C}_D^* \tilde{v}(v_x - W_x) \quad (3.2-5)$$

$$\dot{V}_y = \frac{dv_y}{dt} = -\widehat{C}_D^* \tilde{v}(v_y - W_y) - g \quad (3.2-6)$$

$$\dot{V}_z = \frac{dv_z}{dt} = -\widehat{C}_D^* \tilde{v}(v_z - W_z) \quad (3.2-7)$$

Where:

W = Wind Velocity, in each axis

V = Projectile Velocity, in each axis

C_D = drag coefficient

The Drag Force of the projectile is given from (McCoy, 2012):

$$\text{Drag Force} = -\frac{1}{2} \rho v^2 S C_D \quad (3.2-8)$$

Where:

ρ = air density

S = projectile reference area

As the Point Mass Model and assessment of the projectile is focusing on the projectile drift in the Z axis, a number of variables are not considered within the assessment. A direct fire flat trajectory removes the need to assess earth rotation via the coriolis effect, additional projectile spin damping will not be considered due to the ranges involved. Magnus and lift forces that mostly act in the Y Axis's will also not be considered in this assessment.

3.2.3 Crosswind Equation

The meteorological assessment will focus on the effect of crosswind variation on the projectile's flight, so rangewind acting in the X Axis will also not be assessed. The crosswind effect on a projectile in flight is shown in **[Figure 47]** detailing the components of the drift equation. The velocity of the crosswind and the projectile's stability affect how much the projectile will drift off course. Projectile gyroscopic spin value enables a projectile to return to the centre line of flight due to inertia.

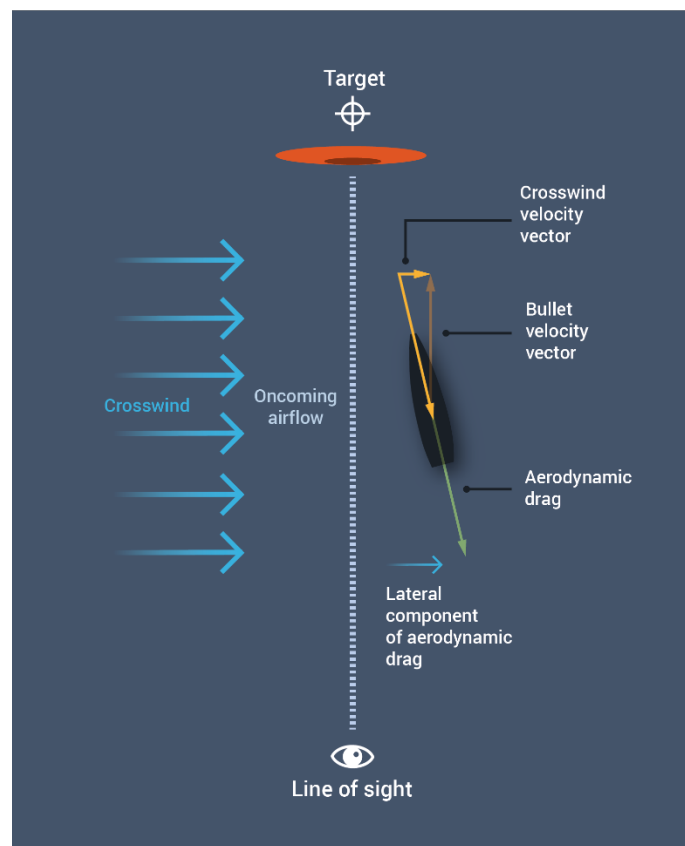


Figure 47 – Wind Deflection on projectile (Litz, 2015)

Equation (3.2-9) details the wind drift equation (McCoy, 2012):

$$Z = \int_0^t v_z ds_1 = W_z \left(t - \frac{X}{v_{xo}} \right) \quad (3.2-9)$$

Where:

W_z = Wind Velocity, in Z axis

$X = \text{range to target}$

$V_{xo} = \text{Muzzle Velocity}$

These equations have formed the basis of the Point Mass Model, full details of the MATLAB script can be found in Appendix B.

3.3 Coincidence and Hit Equations

To assess the effect of the trajectory results from the Point Mass Model against the NATO coincidence standard (US Army Aberdeen Test Center, 2009a) the results have been formatted into standard range tables (McCoy, 2012). The range table format enables quick assessment of the results and the calculation of the final hit point positions.

To calculate the hit point and coincidence values, the trajectory results are formatted into a set of processing equations outside of the Point Mass Model. The equations use the Model results to produce a linear polynomial line of fit along the trajectory of the projectile. The line of fit is used to smooth the trajectory output point from the input of the variable wind speeds intervals used **[Figure 48]**.

The polyfit equation uses the data stored in the firing table [data.3], as reference by the individual columns [Range_m & Drift_Lase_m] for each output value. The polyval equation then models the results from polyfit to the overall range, to give a line of fit (MATLAB, 2023a).

$$\text{BL_L} = \text{polyfit}(\text{data3.Range_m}, \text{data3.Drift_Lase_m}, 1); \quad (3.3-10)$$

$$\text{Z_lase} = \text{polyval}(\text{BL_L}, \text{data3.Range_m}); \quad (3.3-11)$$

The results from the two 'poly' equations can then be displayed in the correct line of fit equation format of $z = m \cdot x + b$ (MATLAB, 2023a).

$$\text{disp}(['\text{Equation is } Z1 = ' \text{ num2str}(\text{BL_L}(1)) '*x + ' \text{ num2str}(\text{BL_L}(2))']) \quad (3.3-12)$$

The line of fit or projectile trajectory line is calculated for the initial 'lase' firing above and the 'fire' point trajectory below, using the same equation set (MATLAB, 2023a).

$$\text{BL_F} = \text{polyfit}(\text{data3.Range_m}, \text{data3.Drift_Fire_m}, 1); \quad (3.3-13)$$

$$\text{Z_fire} = \text{polyval}(\text{BL_F}, \text{data3.Range_m}); \quad (3.3-14)$$

The result for the 'fire' result can then be displayed as $z = m \cdot x + b$ (MATLAB, 2023a).

$$\text{disp}(['\text{Equation is Z2= ' num2str}(\text{BL_F}(1)) '\cdot x + ' \text{num2str}(\text{BL_F}(2))']) \quad (3.3-15)$$

With these equations the line of fit or projectile line can be calculated for both trajectory sets. The results can then be plotted back onto the original trajectory plot to give the following results [Figure 48].

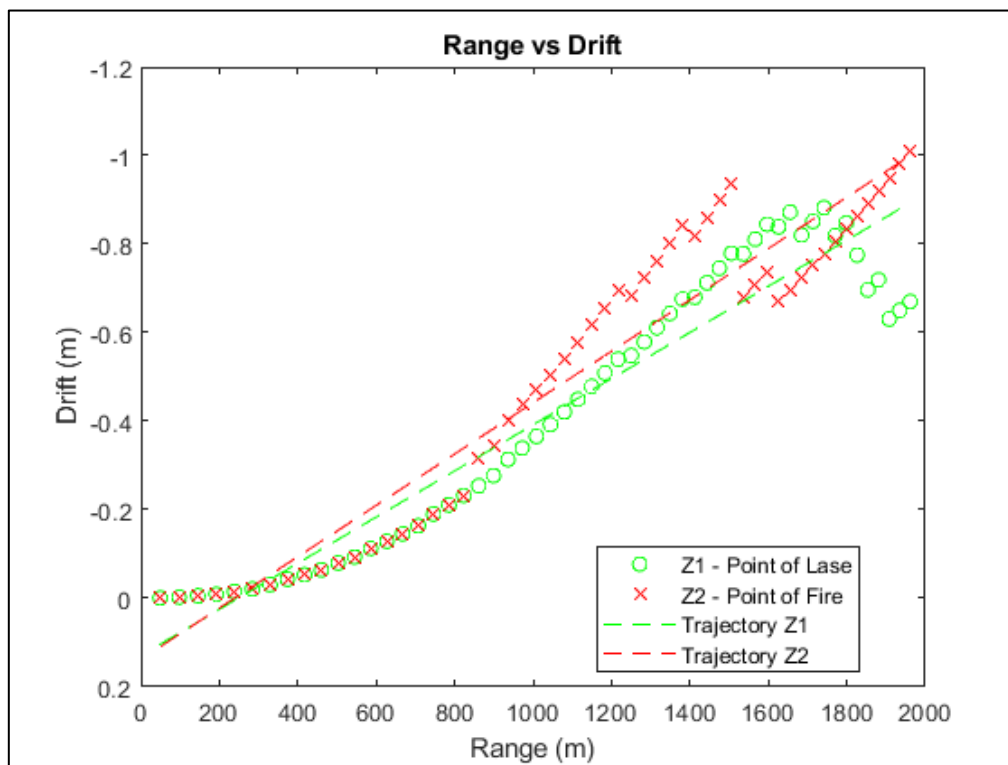


Figure 48 – Example Drift Trajectory Plot, with Line of Fit for each result.

The Line of Fit is used for the ballistic flight line instead of the plotted lines of Point of Lase (o) and Point of Fire (x) due to the segmented jump error seen in [Figure

48] The segmented jump error is particularly apparent in Point of Fire (x) curve where three distinct sections are seen. This is due to the stepping of conditions in the code between time of flight segments calculations (three 1 second sections are calculated), The code for each of these sections is shown in Section 4.3.2 Point Mass Model, the line of fit in **[Figure 48]** reduces the scattering error and jump error.

In the last segment of Point of Fire (x) curve a further scattering of the data points can be seen between ranges of 1600 to 2000 meters. The scattering is caused by variations in the wind gradient interpolation which causes the wind drift and overall drift of the projectile to deviate rather than maintain a single flight profile. This can be seen in the wind gradient **[Figure 54]**, as the gradient is not a simple linear curve of a statistical wind gradient profile **[Figure 6]**.

The line of fit reduces the scattering error and jump error, a further development of the code is required to integrate the time of flight sections, to remove the segmented error.

3.3.1 MATLAB Code

To calculate the coincidence values against the NATO target, the next set of equations are used in the model. First the two values from the line of fit equation are renamed and placed back into the fit equation ' $z = m*x+b$ ', as their respective values of 'm' and 'b' **[Figure 49]**. The target range of 2000 m is input as the 'x' value into the equation to provide the end point value.

```
% Coincidence window
% Calculating Lase Hit position at 2000 meters.
Hit_L1 = str2double(num2str(BL_L(1)));
Hit_L2 = str2double(num2str(BL_L(2)));
Hit_L = (Hit_L1*2000+Hit_L2)*100 % Lase Hit Coincidence Position in "CM"
```

Figure 49 – Coincidence Equations 1

The results of the equations are initially given in meters [m] [0.00 format], this is converted to centimetre [cm] by multiplying the result by 100. This has been done to enable easier comparison of the results against the targeted error value [60

cm]. The hit location results are then given in cm for both the initial lased wind value [Hit_L] and the at firing wind values [Hit_F] **[Figure 50]**.

```
% Calculating Fire Hit position at 2000 meters.
Hit_F1 = str2double(num2str(BL_F(1)));
Hit_F2 = str2double(num2str(BL_F(2)));
Hit_F = (Hit_F1*2000+Hit_F2)*100 % Fire Hit Coincidence Position in "CM"
```

Figure 50 – Coincidence Equations 2

The two trajectory hit locations can be compared to give the different between the two; at point of lase [Hit_L] and at point of firing [Hit_F], this gives the coincidence offset between the two locations. **[Figure 51]**, shows the final equation in the model, which outputs as displayed value of the coincidence offset [Coin] between the two results.

```
% Calculating the Coincidence Error
% Coincidence Error is 0.30 mil, or at 2000 meters, 0.60 meters, or 60 cm. in "CM"
Coin = Hit_F-Hit_L
```

Figure 51 – Coincidence Equations 3

The target value from NATO's requirement of 0.3 mrad x 0.3 mrad (US Army Aberdeen Test Center, 2009a), gives a window width for a target at 2000 m is 0.60 m or 60 cm's in each axis. The hit locations have been compared to the maximum offset of 60 cm's [0.3 mrad] in a single direction and located around the centre of an example target.

3.3.2 Visual Assessment

To assist with the visual assessment of the coincidence and hit performance of the projectile, the results have been plotted onto a scaled H-1 Target profile from Field Manual [FM] 17-12-1-2 Tank Gunnery (US Army Aberdeen Test Center, 1998) **[Figure 52]**. The H-1 Target is a silhouette profile of a head-on T-72 tank, which is mainly used as training target in exercises, and used as part of annual crew assessments during live firing exercises (US Army Aberdeen Test Center, 1998).

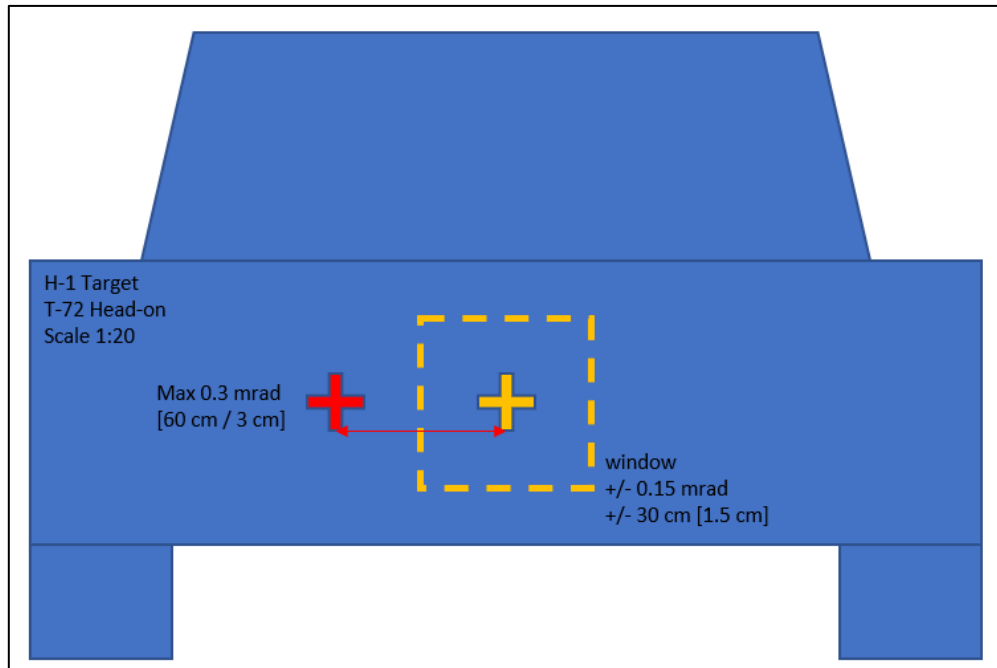


Figure 52 – Coincidence Requirement on a H-1 Target

The H-1 Target [Figure 52], has been scaled to a 1:20 scale to fit visually into this document. The firing results produced from the Point Mass Model have also been correctly scaled to align with the target model. The NATO coincidence requirements have been placed on to [Figure 52], to show the two error windows used during the test.

The first is the yellow dashed box around the centre yellow cross mark on the target, this represents a +/- 0.15 mrad window around the centre mass of the target. This corresponds with the NATO 0.3 x 0.3 mrad box (US Army Aberdeen Test Center, 2009a), the second is the red crosses and the red drift offset line shown a maximum offset between two results of 0.3 mrad or 60 cm's for a 2000 m target.

3.4 Wind Equations

The theory and equations used to assess the wind results produced have been provide by the following background and mathematics. Firstly, the drift equation (McCoy, 2012), has been used as the output of the wind effect on the projectile. To enable the use of this equation the raw wind data provided was required to be filtered into the correct set of results.

The raw real wind values were provided from a meteorological database collected by the Atmospheric Observatory at Reading University (Reading University, 2020). The database meteorological results from sensor sets on campus are collected into the METFiDAS-3 database which can be assessed by request (Reading University, 2020). The data can be extracted into .csv files which are converted into EXCEL Worksheet for analysis.

The database is fed from a set of variable height wind velocity sensors located at 2, 5 and 10 meters. The 10m height aligns with the maximum height of the trajectory of the reference projectile. Using the interpolation equation, the gaps between each reference wind sensor can be filled to achieve meteorological data at 0.5 m intervals across the height range.

Prior to interpolation of the data to provide the missing values, the reference height samples were split into Rangewind and Crosswind values. The raw real wind values are given as true speed and direction linked to a compass position, this required converting to the two ballistic wind values **[Figure 53]**.

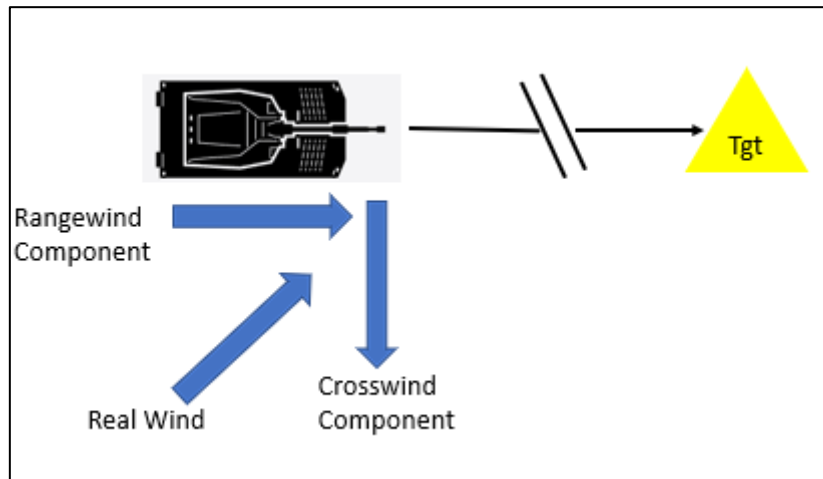


Figure 53 – Rangewind and Crosswind Component directions

The Rangewind will follow the direction of fire, heading positively towards the target, whilst the Crosswind will be positive heading Left to Right across the line of fire. A Sine and Cosine conversion table (VID 150259, 2020) **[Table 8]** taken from an aircraft simulator was used to split the real wind into ballistic wind components of Rangewind [cos] and Crosswind [sin].

Table 8 – Sine and Cosine Conversion Table (VID 150259, 2020)

α	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
$\sin \alpha$	0	0.17	0.34	0.5	0.64	0.77	0.86	0.94	0.98	1
$\cos \alpha$	1	0.98	0.94	0.86	0.77	0.64	0.5	0.34	0.17	0

The MATLAB equations and functions used to produce the usable wind data within the model are the following. The interpolation equation required a set of initial conditions to be set, first the reference height of the initial variables 2, 5 and 10 m.

$$\text{Height_Ref} = [2 \ 5 \ 10]; \quad (3.4-16)$$

Second, the reference variable, which were the recorded wind velocities in m/s at each height.

$$\text{Wind_R\#} = [a \ b \ c]; \quad (3.4-17)$$

The required interpolation range 0 to 10 m, covering the direct fire trajectory height. And the frequency of the results required, so height steps of 0.5 m.

$$xq = 0:0.5:10 \quad (3.4-18)$$

Each of the initial conditions was then placed into the interpolation equation (MATLAB, 2023b).

$$wq\# = \text{interp1}(\text{Height_Ref}, \text{Wind_R\#}, xq, 'linear', 'extrap'); \quad (3.4-19)$$

The equation outputted the results in a horizontal table, so a reshape function was used to convert the table to a vertical table, which matches the rest of the tables in the model.

$$\text{WH}/\text{W_R\#} = \text{reshape}(xq\#, [21,1]); \quad (3.4-20)$$

The data produced from the equations and functions was then saved into a table, with the following column conditions. Where 'WH' represents height, and 'W_R*' represents each of the wind variable conditions for a six second period.

$$\text{data1} = \text{table}(\text{WH}, \text{W_R1}, \text{W_R4}, \text{W_R5}, \text{W_R6}); \quad (3.4-21)$$

All the data was interpolated to provide input into the Point Mass Model script, with the initial focus on intervals at 1, 4, 5 and 6 s of the test profile. The first second is matched to the point at which the lase is fired and then +3 s in delay until the gun is fired at the fourth second. The flight period [3 s] of the projectile taking place during 4-6 s of the wind test profile.

3.4.1 Example Data Set 30-A

Using Data Set 30-A as an example of the wind data assessment, the initial variables covering intervals at 1, 4, 5 and 6 s are shown in **[Table 9]**, with their corresponding wind speed in m/s at each reference height [2, 5 & 10 m]. The ‘-’ negative indicator is reference of a left to right crosswind direction on the positional profile, not a negative speed.

Table 9 – Data Set 30-A, Wind input conditions

Height Ref	2 m	5 m	10 m
Time Ref	[m/s]	[m/s]	[m/s]
1s [Wind_R1]	-2.35	-2.91	-3.01
4s [Wind_R4]	-1.15	-1.60	-1.98
5s [Wind_R5]	-1.31	-1.77	-2.62
6s [Wind_R6]	-1.28	-1.28	-2.18

Each of the four wind reference timeslots are interpolated using equations 3.2-16 to 3.2-21 to give a wind profile from ground [0 m] to 10 meters in height at intervals of 0.5 m. These wind profiles can be plotted onto a graph to give a visual change in wind speed vs height from the ground **[Figure 54]**.

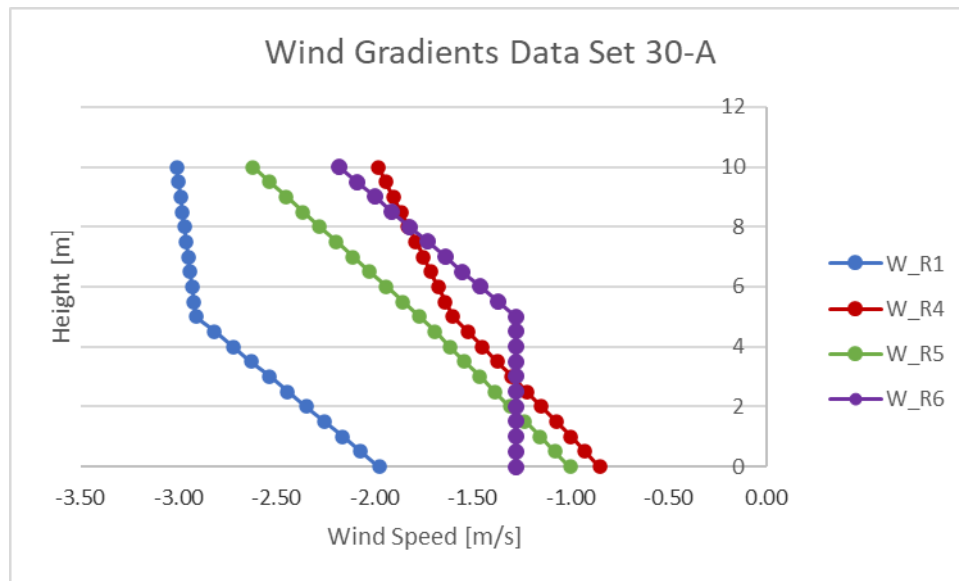


Figure 54 – Wind Speed vs Height above ground [- is R-L direction]

The output values for Data Set 30-A for **[Figure 54]** are shown in **[Table 10]** below.

Table 10 – Data Set 30-A, Wind output values

Ref Height [WH] [m]	Sec 1 [W_R1] [m/s]	Sec 4 [W_R4] [m/s]	Sec 5 [W_R5] [m/s]	Sec 6 [W_R6] [m/s]
0	-1.98	-0.85	-1.00	-1.28
0.5	-2.07	-0.93	-1.08	-1.28
1	-2.16	-1.00	-1.16	-1.28
1.5	-2.26	-1.08	-1.23	-1.28
2	-2.35	-1.15	-1.31	-1.28
2.5	-2.44	-1.23	-1.39	-1.28
3	-2.54	-1.30	-1.46	-1.28
3.5	-2.63	-1.38	-1.54	-1.28
4	-2.72	-1.45	-1.62	-1.28
4.5	-2.82	-1.53	-1.69	-1.28
5	-2.91	-1.60	-1.77	-1.28
5.5	-2.92	-1.64	-1.86	-1.37
6	-2.93	-1.68	-1.94	-1.46
6.5	-2.94	-1.71	-2.03	-1.55
7	-2.95	-1.75	-2.11	-1.64
7.5	-2.96	-1.79	-2.20	-1.73
8	-2.97	-1.83	-2.28	-1.82
8.5	-2.98	-1.87	-2.37	-1.91
9	-2.99	-1.90	-2.45	-2.00
9.5	-3.00	-1.94	-2.54	-2.09
10	-3.01	-1.98	-2.62	-2.18

Chapter 4 Method

4.1 Introduction

A modelling and simulation approach was taken for this study using real world data to simulate the projectile flight against the meteorological wind data. The approach taken to use computer based modelling compared to a full ballistic field test is a cost-effective and efficient time based assessment, which matched the intent of the aims.

A full ballistic field trial is cost prohibited in assessing modern projectiles due to the cost of ranges, rounds and the time required to conduct thousands of shots. Modelling and analysis allow for research to be completed on a cost-effective and more efficient scale of assessment. With initial ballistic data and established methods and algorithms, multiple repeatable tests can be completed quickly using a computer model.

The modelling and simulation were conducted in two parts; firstly the assessment and modelling of the wind data collected from Reading University; secondly the ballistic assessment of the wind data influence on the projectile flight performance during the engagement period.

The wind data was provided from Reading University (Reading University, 2020) through their website database. The data required initial sorting and formatting into useable data sets that could be imported into the MATLAB model. The data also required expanding using interpolation to give the correct depth and height to the data set.

Once completed the wind data sets were imported into the Point Mass Ballistic Model **[Appendix B]** which was programmed into MATLAB R2019a to R2022a edition (The MathWorks Inc, 2019). MATLAB was used as the base programme as it can provide quick and usable modelling of complex data sets. The programme also enabled multiple actions to be completed simultaneously, including the creation of graphs and tables. To verify the Point Mass Ballistic Model equations the results were compared to an EXCEL based model provided

by Cranfield University as part of attending the Fundamental Ballistic Course (Cranfield University, 2019).

The data from the Point Mass MATLAB model was programmed to output into EXCEL data files and supporting graph images. The key results from the model were also collected into a single table to provide comparison between the data sets compared to the coincidence requirements.

4.2 Meteorological Data

The meteorological wind data was kindly provided by Reading University – Department of Meteorology (Reading University, 2020) from their onsite weather station. This set of data was selected due to the access rights of the data and the key factor in that the data reported at intervals of 1 s. This 1 s frequency output was key to input the data into the ballistic model that had a total execution time of 6 s period [Chapter 2.4.3].

The majority of the weather data sets collected to support standard weather reporting are in frequencies set for averaged time sets, normally in intervals of either 5, 15, 30 or 60 minutes. The 1 s intervals provided by Reading is unique and is at the corrected required frequency to support the ballistic analysis. The downside of this data output is the number of rows to the data set that is provided at intervals of 1 s.

The Meteorological Weather data sets can be extracted from the “METFiDAS-3 data extractor” (Reading University, 2020), which is the overall database of the meteorological sensor output. The extractor is supported with an online advise set to inform the user on how to extract the correct weather data required to support research. After some experimentation on the different date sets available and variable conditions for each of the data sets the following conditions and variables were decided on.

4.2.1 METiDAS-3 Set-up

Using the website output for the METFiDAS-3, the following conditions were selected through each of the stages to define the data output. Once the first few

extractions and analysis were conducted the “fine” variable was reduced to improve the data output and post processing required.

Step 1 [Figure 55] was to select the interval frequency of the output data, the uniqueness of the Reading data is that it was sorted at real time, “instantaneous” 1 s intervals.

Step 1 - select the type of (AWS) data

- ☒ 1-sec "instantaneous" logger output
- ☐ 5-min averaged logger output
- ☐ 5-min max/min logger output (up to 14 March 2017 only)
- ☐ 5-min WMO-standard processed output
- ☐ 5-min max/min processed output
- ☐ 1-hour WMO-standard processed output
- ☐ 1-hour max/min processed output
- ☐ 0900 UTC METFiDAS climat observation - no data thrown back
- ☐ 0.1-sec sonic licor output
- ☐ Vertical profiles of wind and temperature
- ☐ Eddy covariances - 30-min averages
- ☐ Cloud base averages at 5 minute intervals
- ☐ Cloud base averages at 1 minute intervals

Click here to [continue](#)

Figure 55 – Step 1, frequency of data output

The second and third steps [Figure 56] were to select the date and time range for the output, a selection of dates were chosen to provide different wind conditions into the model. The time period was initially selected from 0600 to 2100 hours, and then reduced to 0800 to 1800 hours, to reduce the data output, which consisted of 54,062 lines at 1 s interval.

Step 2 - select the start time (y,m,d,hm) of the data

2022 ▾ Apr ▾ 01 ▾ 0800 ▾

Step 3 - select the end time (y, m, d, hm) of the data

2022 ▾ Apr ▾ 01 ▾ 1800 ▾

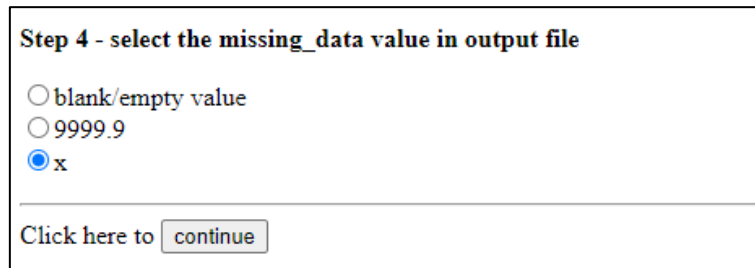
Click here to [continue](#)

Figure 56 – Step 2, Date range selection

The following date windows were selected to give a variety of different seasonal changes across the crosswind conditions. Matching the real world conditions that would change between each season to enable a year average to be produced, similar to the A.R.D.E assessment (Armament Research and Development Establishment (A.R.D.E), 1967). The three wind sets taken from spring [April], summer [June] and winter [December] were used to show any differences in the effect of the seasons on the wind profile.

- 1st to 30th April 2022
- 1st to 30th April 2021
- 1st to 30th June 2022
- 1st to 30th June 2021
- 1st to 31st December 2021

Each day was extracted and saved as an individual file in a collected monthly folder. Step 4 **[Figure 57]**, was used to select the missing data value to be inputted into the data extract, “X” was selected as the chosen form.



Step 4 - select the missing_data value in output file

☐ blank/empty value

☐ 9999.9

☒ x

Click here to [continue](#)

Figure 57 – Step 4, missing data assignment

Step 5 **[Figure 58]**, required the user to select the overall general requirements around the extract for each of the top level meteorological data. For this study only Temperature, Wind and Pressure outputs were selected.

Step 5 - select the general variables types of interest

Note that your exact choice will be refined in the next step.
You can keep all these boxes unticked and click "continue" if you wish.

☒ Temperature
☐ Rainfall
☐ Sun/radiation
☒ Wind
☒ Pressure

Click here to

Figure 58 – Step 5, General variable selection

Click “continue” the system then highlight the fine variable for each of the general variable in the data extraction [Figure 59]. Initially all the variable section was left selected in the default list, as shown below, which provided a large selection of data to be post-processed.

List of variables available for the chosen data type last updated 31.Jul.2015

Step 6 - select the variables to be extracted

If the data you expect to find are not shown below, please contact Roger Brugge

☒ Relative humidity	☐ 1sec sunshine	☒ Dry bulb temperature	☒ Concrete temperature
☒ Grass temperature	☒ Bare soil temperature	☒ 5cm soil temperature	☒ 10cm soil temperature
☒ 20cm soil temperature	☒ 30cm soil temperature	☒ 50cm soil temperature	☒ 100cm soil temperature
☐ Direct beam solar radiation	☒ Measured wet bulb temperature	☐ Channel 28	☐ Net radiative heat flux
☐ Global solar radiation	☐ Diffuse solar radiation	☐ Channel 32	☐ Channel 33
☐ Ground heat flux	☐ Potential gradient	☐ R38	☐ Corrugated plate current
☐ Flat plate current	☒ 5m wind direction	☒ 2m wind speed	☒ 5m wind speed
☐ 1sec rainfall	☒ Station pressure	☒ 10m wind direction	☒ 10m wind speed
☐ Shortwave-down	☐ Shortwave-up	☐ Longwave-down(uncorrected)	☐ Longwave-up(uncorrected)
☐ CNR4 radiometer temp	☐ Sb(csd3)	☐ PointDischarge	☒ 0.56m wind
☒ 0.8m wind	☒ 1.12m wind	☒ 1.6m wind	☒ 2.24m wind
☒ 3.2m wind	☒ 4.48m wind	☒ 6.4m wind	☒ 0.56m temperature
☒ 1.12m temperature	☒ 2.24m temperature	☒ 4.48m temperature	☒ Propeller U
☒ Propellor V	☒ Propellor W		

Click here to

Figure 59 – Step 6, default fine variable selection.

Once an initial set of test data had been extracted from the data base, the selection of fine variables was reduced to a selection that was actually used.

Step 6 - select the variables to be extracted

If the data you expect to find are not shown below, please contact Roger Brugge

☒ Relative humidity	☐ 1sec sunshine	☒ Dry bulb temperature	☐ Concrete temperature
☐ Grass temperature	☐ Bare soil temperature	☐ 5cm soil temperature	☐ 10cm soil temperature
☐ 20cm soil temperature	☐ 30cm soil temperature	☐ 50cm soil temperature	☐ 100cm soil temperature
☐ Direct beam solar radiation	☒ Measured wet bulb temperature	☐ Channel 28	☐ Net radiative heat flux
☐ Global solar radiation	☐ Diffuse solar radiation	☐ Channel 32	☐ Channel 33
☐ Ground heat flux	☐ Potential gradient	☐ R38	☐ Corrugated plate current
☐ Flat plate current	☒ 5m wind direction	☒ 2m wind speed	☒ 5m wind speed
☐ 1sec rainfall	☒ Station pressure	☒ 10m wind direction	☒ 10m wind speed
☐ Shortwave-down	☐ Shortwave-up	☐ Longwave-down(uncorrected)	☐ Longwave-up(uncorrected)
☐ CNR4 radiometer temp	☐ Sb(csd3)	☐ PointDischarge	☒ 0.56m wind
☒ 0.8m wind	☒ 1.12m wind	☒ 1.6m wind	☒ 2.24m wind
☒ 3.2m wind	☒ 4.48m wind	☒ 6.4m wind	☐ 0.56m temperature
☐ 1.12m temperature	☐ 2.24m temperature	☐ 4.48m temperature	☐ Propeller U
☐ Propellor V	☐ Propellor W		

Click here to

Figure 60 – Step 6, Improved fine variable selection.

A summary page was then displayed once all steps had been completed displaying the selected variables and conditions for the extract. The data extract was then completed and displayed in the internet page as an initial .csv list [Figure 61]. The provided an initial check on the data output, the data set could then be downloaded and saved as a .csv file.

Perform the data extraction...

processing file 2022-SMP1-091.csv

Your output can now be downloaded from [here](#).

If right mouse click fails when downloading these data, use the left mouse button and assume datafile is safe

=====A copy of the contents of your data file=====

```
TimeStamp ,RH ,Td ,Tw ,Dirn5 ,U2 ,U5 ,P ,Dirn10 ,U10 ,U0.56 ,U0.8 ,U1.12 ,U1.6 ,U2.24 ,U3.2 ,U4.48 ,U6.4
UTC ,% ,degC ,degC , ,m/s ,m/s ,hPa ,degC ,m/s ,m/s ,m/s ,m/s ,m/s ,m/s ,m/s ,m/s ,m/s
01/04/2022 08:00:00 ,77.5 ,2.56 ,1.23 ,x ,2.0 ,2.5 ,1009.04 ,355 ,2.4 ,1.7 ,1.9 ,1.8 ,2.0 ,2.9 ,3.7 ,4.3 ,4.1
01/04/2022 08:00:01 ,77.7 ,2.55 ,1.25 ,x ,2.6 ,2.0 ,1009.04 ,262 ,2.4 ,1.3 ,1.7 ,1.7 ,1.7 ,2.7 ,3.2 ,3.6 ,4.2
01/04/2022 08:00:02 ,77.4 ,2.54 ,1.24 ,x ,2.4 ,1.8 ,1009.04 ,322 ,2.3 ,1.2 ,1.4 ,1.8 ,2.1 ,2.1 ,2.3 ,2.6 ,3.4
01/04/2022 08:00:03 ,77.5 ,2.53 ,1.19 ,x ,2.2 ,1.7 ,1009.02 ,282 ,2.1 ,1.4 ,1.7 ,1.9 ,2.4 ,2.2 ,2.7 ,3.1 ,3.1
01/04/2022 08:00:04 ,77.6 ,2.58 ,1.19 ,x ,1.9 ,1.6 ,1009.02 ,287 ,2.2 ,1.7 ,2.1 ,2.3 ,2.5 ,2.3 ,3.3 ,2.9 ,2.7
01/04/2022 08:00:05 ,77.4 ,2.57 ,1.22 ,x ,1.5 ,1.7 ,1009.01 ,292 ,2.0 ,1.9 ,2.1 ,2.4 ,2.6 ,2.3 ,2.6 ,2.6 ,2.5
01/04/2022 08:00:06 ,77.5 ,2.53 ,1.20 ,x ,1.2 ,1.6 ,1009.01 ,355 ,2.1 ,1.8 ,1.9 ,2.0 ,2.1 ,1.9 ,2.0 ,2.4 ,2.6
01/04/2022 08:00:07 ,77.5 ,2.50 ,1.19 ,x ,1.4 ,1.5 ,1009.01 ,288 ,1.7 ,1.5 ,1.8 ,1.9 ,1.8 ,1.7 ,1.8 ,2.1 ,2.2
01/04/2022 08:00:08 ,77.7 ,2.57 ,1.19 ,x ,1.8 ,2.1 ,1009.02 ,294 ,1.4 ,1.5 ,1.7 ,1.9 ,1.8 ,1.9 ,2.0 ,2.4 ,2.4
01/04/2022 08:00:09 ,77.4 ,2.53 ,1.24 ,x ,2.0 ,2.1 ,1009.02 ,305 ,1.1 ,1.4 ,1.6 ,1.9 ,2.4 ,2.7 ,2.5 ,2.7 ,2.6
01/04/2022 08:00:10 ,77.4 ,2.53 ,1.17 ,x ,1.8 ,2.8 ,1009.02 ,352 ,1.1 ,1.6 ,2.9 ,3.3 ,3.8 ,3.4 ,2.6 ,2.7 ,2.6
```

Figure 61 – Web, data set extract page

4.2.2 Post Processing & Analysis

The .csv file was saved as a standard EXCEL worksheet file, to enable post-processing assessment and correct file storage. Each of the data sets was saved with a unique identifier “2022_04_01 Wind Data 08_18 hrs 1_sec int”.

For the post-processing the data was initially updated to a modern file format and organised into a number of EXCEL tabs covering the following:

- Tab 1 – Raw data, titled as “RAW 22_04_01”.
- Tab 2 – Post-processed, titled as “Analysed”.
- Tab 3 – Graphic displayed data, titled as “Data Set 1”.
- Tab 4 – Transformed Data, sometimes used.

Each of the data sets tabs was updated to match the chosen ID for each data set. The inbuilt EXCEL “Analysed Data” function was used on some of the data sets to extract graphics and tables from the large selection of outputted data. This function add in additional tabs covering the “Transformed Data” and graphic display that could be edited.

	A	Q	R	S	T	U	V	W	X
1	TimeStamp	P	Dirn10	U10	U0.56	U0.8	U1.12	U1.6	U2.24
2	UTC	hPa	degs	m/s	m/s	m/s	m/s	m/s	m/s
3	01/04/2022 06:00	1007.89	18	2.7	1.4	1.4	1.4	1.9	2.2
4	01/04/2022 06:00	1007.9	349	3.1	1.9	2.2	2.6	2.8	3.1
5	01/04/2022 06:00	1007.91	39	2.4	1.8	2.5	3	2.7	2.6
6	01/04/2022 06:00	1007.9	353	1.9	1.6	2.3	2.4	2.5	1.9
7	01/04/2022 06:00	1007.89	316	2.1	1.9	2.4	2.3	2.9	2.2
8	01/04/2022 06:00	1007.91	311	2	2.3	3.3	3.2	3	2.7
9	01/04/2022 06:00	1007.93	2	2.6	2.8	3.3	3	2.7	2.7

Figure 62 – Raw data output format.

Mostly manual post-processing was completed without the support of the inbuilt EXCEL functions other than display graph. The RAW data table [Figure 62] was left in the format provided by the extract METFiDAS-3 software, and the analysis tab data was an initial re-formatting of the data. The data that was initially output with all the variables and the time period of 0600 to 2100 hrs was left in the raw

state and then reduced in the analysed state to 0800 to 1800 hrs and a number of variables removed **[Figure 63]**.

	A	B	C	D	E	F	G
1	TimeStamp UTC	U0.56 m/s	U0.8 m/s	U1.12 m/s	U1.6 m/s	U2.24 m/s	U3.2 m/s
2	08:00:00	1.7	1.9	1.8	2	2.9	3.7
3	08:00:01	1.3	1.7	1.7	1.7	2.7	3.2
4	08:00:02	1.2	1.4	1.8	2.1	2.1	2.3
5	08:00:03	1.4	1.7	1.9	2.4	2.2	2.7
6	08:00:04	1.7	2.1	2.3	2.5	2.3	3.3
7	08:00:05	1.9	2.1	2.4	2.6	2.3	2.6

Figure 63 – Analysed Data format.

The format of the analysis data enables a clearer assessment of the data to be conducted and in a simplified formatting approach. All the number outputs were formatted to a single decimal point. The data was then copied into the 'Data Set' tab **[Figure 63]** in the Excel workbook so graphs could be extracted. Each processing action on the data was conducted on a separate tab to enable different action to be completed in the future.

TimeStamp UTC	U2 m/s	U5 m/s	U10 m/s	Dirn10 degs	Compass
09:00:00	4	5.2	6.4	347	NNW
09:00:01	4.8	5.5	6.4	38	NNE
09:00:02	6.5	6.9	5.1	13	N
09:00:03	4.8	5.9	5.8	343	NNW
09:00:04	3.4	4.4	6.4	345	NNW
09:00:05	2.9	3.6	6	12	N
09:00:06	3	3.2	5.2	4	N
09:00:07	3.6	4.8	4.7	349	NNW
09:00:08	3.2	5.7	5.2	334	NW
09:00:09	3.2	4.4	5.5	11	N
09:00:10	4	3.5	4.6	29	NNE

Figure 64 – Data Set, reduced formatting example.

The initial data sets focused on the following variables, wind speed at 2, 5 and 10 m and wind direction at 10 m. The wind direction which was in compass degrees was formatted into compass points **[Figure 64]** for simplification, this was completed using the following equation.

= LOOKUP(MOD(O4,360),{0,22.5,45,67.5,90,112.5,135,157.5,180, (4.2-1)
 202.5,225,247.5,270,292.5,315,337.5},{ "N", "NNE",
 NE,ENE,E,ESE,SE,SSE,S,SSW,SW,
 "WSW", "W", "WNW", "NW", "NNW"}))

The data sets could then be formatted into 10s sets to produce wind profiles to fit into the ballistic model. The selection of the 10s sets was kept simple by extracting the first 10 s of each hour to be compared.

4.2.3 Example - Data Set 01

Taking sample data from Data Set 01 [DS 01] – ‘2022_04_01 Wind Data 08_18 hrs 1_sec int AN’, 10 s sample profiles can be extracted from the main dataset. The data is stored in hour tables totalling 3600 lines of data for each of the data points [Table 11], these can then be extracted into graphs to display the wind speed variation across the different sensors [Figure 65].

Table 11 – Data Set 01 – 0900 hrs sample.

Timestamp [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Dirn10 [degs]	Compass
09:00:00	4	5.2	6.4	347	NNW
09:00:01	4.8	5.5	6.4	38	NNE
09:00:02	6.5	6.9	5.1	13	N
09:00:03	4.8	5.9	5.8	343	NNW
09:00:04	3.4	4.4	6.4	345	NNW
09:00:05	2.9	3.6	6	12	N
09:00:06	3	3.2	5.2	4	N
09:00:07	3.6	4.8	4.7	349	NNW
09:00:08	3.2	5.7	5.2	334	NW
09:00:09	3.2	4.4	5.5	11	N

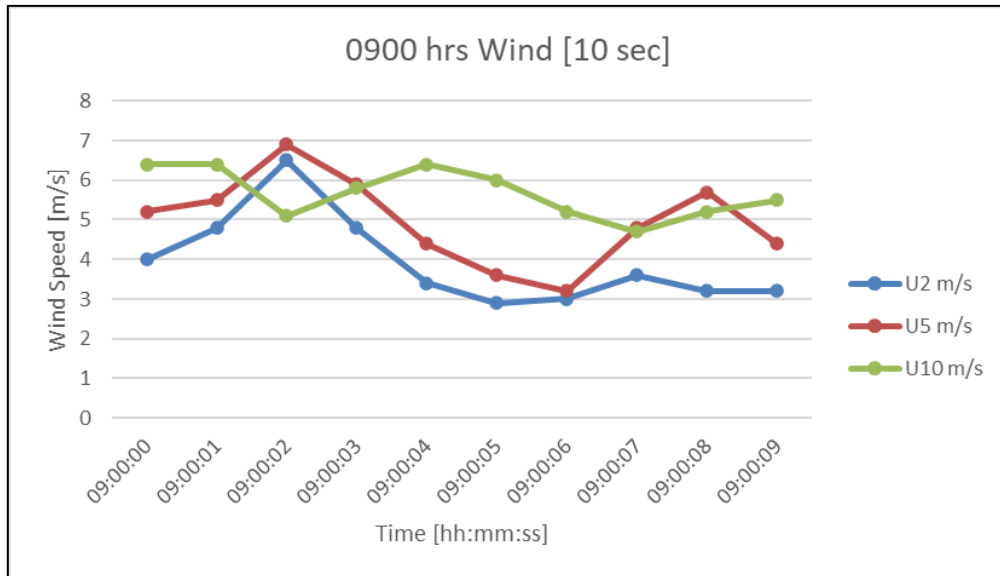


Figure 65 – Example, 10s Wind Profile, DS 01, 0900 hrs.

From the data analysed into the EXCEL tables, different wind profiles can be extracted from across the full day's range of wind speeds. To standardise the testing the first 10 s from each hour was used for the test samples but using longer sections of the day period can show other aspects of the wind variation. As can be seen from the figure below [Figure 66], a 1 minute profile can show large changes to the wind speed.

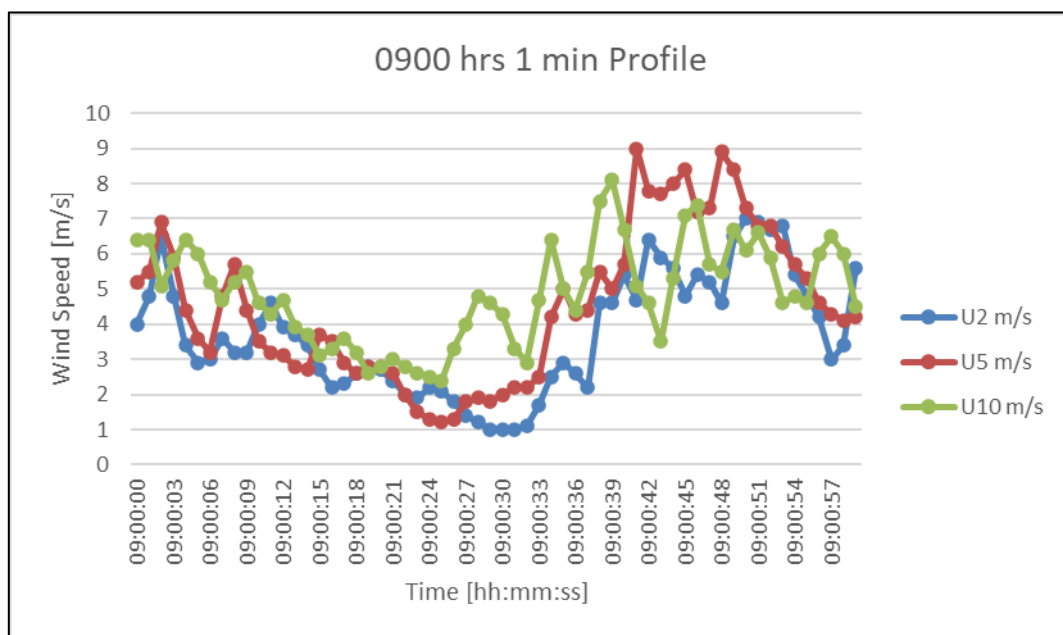


Figure 66 – Example, 1 min Wind Profile, DS 01, 0900 hrs.

Additional 10 s sample wind profiles from DS 01, for 1000 hrs [Figure 67] & 1100 hrs [Figure 68].

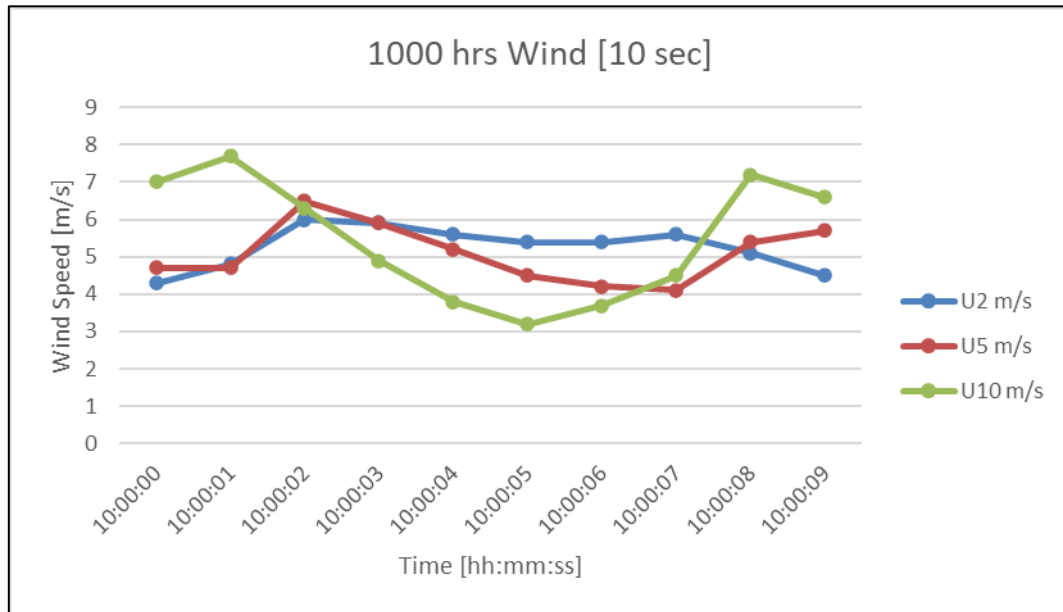


Figure 67 – Example, 10s Wind Profile, DS 01, 1000 hrs.

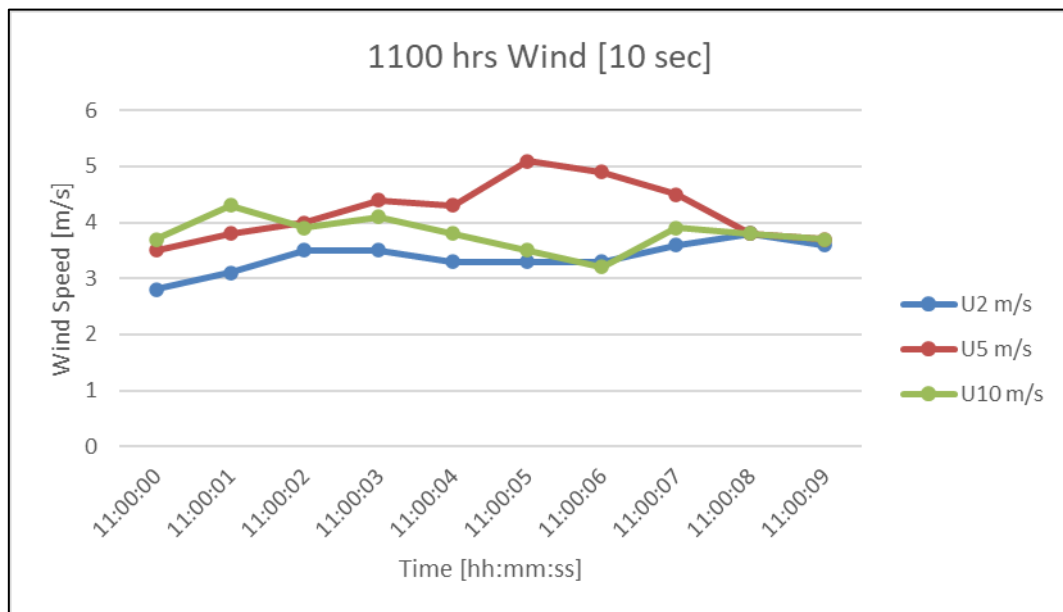


Figure 68 – Example, 10s Wind Profile, DS 01, 1100 hrs

4.3 Point Mass Ballistic Model

4.3.1 Summary

The primary model used to test the ballistics effects was the Point Mass Model programme was created from Modern Exterior Ballistics by McCoy (McCoy, 2012); STANAG 4355 (NATO Standardization Agency, 2009) and Fundamental of Ballistics Course Notes, (Cranfield University, 2019).

The equations are shown in Chapter 3 Theory, detailing the equations used in building the Point Mass model in MATLAB. As an established model and process of assessing ballistics it was simple to re-create the model into the software. The MATLAB model was checked against examples in McCoy (McCoy, 2012) and the Point Mass EXCEL model provide by Cranfield University (Cranfield University, 2019) as part of the Fundamentals of Ballistics Course.

Once the model had been tested and proofed using a number of examples, it was used to create the first set of test data. The model was then developed as different outputs were added into the overall main programme **[Appendix B]**. The final model used is at version 06, all other models have been saved for iteration reference. Changes across the interactions includes wind equations; the graphs and tables; hit and coincidence equations.

The data from the MATLAB model was exported into either EXCEL [.xls] format and graphs in [.jpg] format. Each of the test files also had a standard naming convention including the date and data set being tested, example; [Model_A_V6_WTI_01_Oct_22_DS30-A1].

4.3.2 Point Mass Model

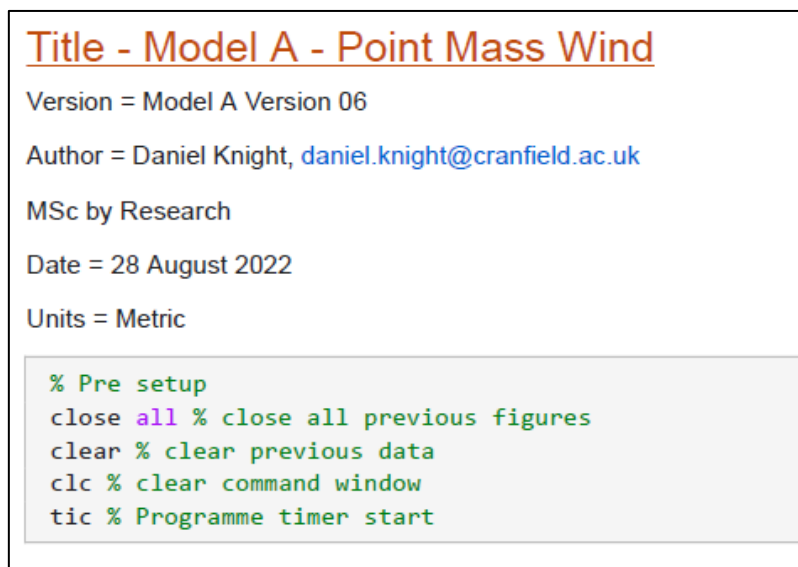
The Point Mass Model was created as a MATLAB script, this allowed multiple functions to be completed within a single programme and allow for developmental work to be conducted. The final programme is located in **[Appendix B]**, which will allow the reader to import it into MATLAB [edition - R2022b or higher], to conduct their own tests.

The programme was laid out in several sections within the programme to enable easier management and following of the programme design. The programme is in the following sections, along with a front introduction.

1. Initial Conditions
2. Initial Math Conditions
3. Table Settings
4. Wind Settings Input
5. Trajectory calculations
6. Cross wind velocity (m/s) – reference positions
7. Tables
8. Plots
9. Ballistic Output Calculation
10. Data Saving

4.3.2.1 Initial Conditions

The first part of the model is the initial introduction and admin notes, as the model was created as a Live Script, notes [Figure 69] can be more easily added into the programme than a normal MATLAB script. This included author information and pre MATLAB starting conditions [in grey box].



```
Title - Model A - Point Mass Wind
Version = Model A Version 06
Author = Daniel Knight, daniel.knight@cranfield.ac.uk
MSc by Research
Date = 28 August 2022
Units = Metric

% Pre setup
close all % close all previous figures
clear % clear previous data
clc % clear command window
tic % Programme timer start
```

Figure 69 – Programme introduction

A tic / toc function was used to produce the end elapsed time from running the programme. The next sections in the programme contained the input conditions for the projectile and the ballistic model, the projectile variables [Table 12] were detailed here. The projectile used was a 40 mm Target Practice Trace [TP-T], with variables taken from the projectile information sheet [Appendix A]. The Drag Coefficient for the projectile is classified and not reported on the information sheet, so an estimated nominal value was used.

Table 12 – Projectile Input Variables

Name	ID	Units	Value
Muzzle Velocity	MV	m/s	1000
Calibre	Cal	mm	40
Mass	m	kg	.98
Drag Coefficient	DC		0.4
Air Density	Air	kg/m ³	1.23
Cross-sectional area	A	m ²	0.0013
Gravity	G	m/s	9.81

4.3.2.2 Table Parameters

The next section detailed the table input conditions [Figure 70] for each of the ballistic and wind tables used to output and collect the results. For MATLAB programmes the tables are required to be setup via a number of initial conditions to create a blank collection pot. Each of these table pots are then filled when the programme is run through the mathematic iterations. The table conditions are as follows.

- 'Sz' – table size, first number rows and second columns.
- 'vartypes' – variable setting, MATLAB condition, the programme used double strings.
- 'varnames' – variable names, names for each column title.
- 'data' – table function to generate table.

Each table was setup as [0] rows as the initial conditions, using a condition later in the programme [data2(end+1,:)] adds a new row at each iteration of the

programme. This enables each run through of the programme to save data as a new line, in a continuous table.

3. Table Settings

```

19 % Table 1 - Wind Input Table
20 sz1 = [0 5];
21 vartypes1 = {'double','double','double','double','double'}; % variable settings
22 varnames1 = {'WH','W_R1','W_R4','W_R5','W_R6'}; % variable name, column headers
23 data1 = table('Size',sz1,'VariableTypes',vartypes1,'VariableNames',varnames1); % table set up
24 % Table 2 - Ballistic Table 1
25 sz2 = [0 12];
26 vartypes2 = {'double','double','double','double','double','double','double','double','double','double','double','double'}; % variable settings
27 varnames2 = {'time','Vel','angle','Drag','Fx','Fz','Acc_x','Acc_y','Vel_x','Vel_y','Dis_x','Dis_y'}; % variable names
28 data2 = table('Size',sz2,'VariableTypes',vartypes2,'VariableNames',varnames2); % table set up
29 % Table 3 - Ballistic Table 2
30 sz3 = [0 7]; % table size
31 vartypes3 = {'double','double','double','double','double','double','double'}; % variable settings
32 varnames3 = {'Time_sec','Range_m','Hieght_m','Wind_1_m/s','Drift_Lase_m','Wind_2_m/s','Drift_Fir'}; % variable names
33 data3 = table('Size',sz3,'VariableTypes',vartypes3,'VariableNames',varnames3); % table set up
34 % Table 4 - Wind Data Table
35 sz4 = [0 8]; % table size
36 vartypes4 = {'double','double','double','double','double','double','double','double'}; % variable settings
37 varnames4 = {'Wind_1','CWDf1','CWD1','Disz1','Wind_2','CWDf2','CWD2','Disz2'}; % variable names
38 data4 = table('Size',sz4,'VariableTypes',vartypes4,'VariableNames',varnames4); % table set up
39 % Table 5 - Variables Saving
40 sz5 = [0 16]; % table size
41 vartypes5 = {'double','double','double','double','double','double','double','double','double','double','double','double','double','double','double','double'}; % variable settings
42 varnames5 = {'Muzzle_Vel','Calibre_rd','Mass_rd','Cross_Sec_Area_rd','Drag_Coeff','Elev_deg','Elev_ang','Wind_1','Wind_2','Wind_3','Wind_4','Wind_5','Wind_6','Wind_7','Wind_8'}; % variable names
43 data5 = table('Size',sz5,'VariableTypes',vartypes5,'VariableNames',varnames5); % table set up

```

Figure 70 – Section 3, Ballistic table settings

A table was created for each of the following requirements.

- Table 1 – Wind Input Table
 - Collected the wind input conditions, outputted from the interpolation equations.
- Table 2 – Ballistic Table 1
 - Standard range table collected all ballistic output data.
- Table 3 – Ballistic Table 2
 - Focus range table collecting the drift data only.
- Table 4 – Wind Data Table
 - Collected the wind output data from the ballistic model.
- Table 5 – Variables Saving
 - Summary table collecting all input variables and calculated variable conditions entered into the programme.

Each of the tables was saved as an EXCEL .xls file, with a corresponding name.

4.3.2.3 Wind Profile Calculation

The next section in the model was a sub-programme producing wind input conditions. The code covered the interpolation equations as detailed in [section 3.4]; this produced the input wind gradient profile for each of the seconds in the wind profile [Figure 71].

```

44      % Wind Input Arguments
45      Height_Ref = [2 5 10]; % Wind Sensor Heights
46      Wind_R1 = [-1.15 -1.60 -1.98]; % Wind at +1 Sec (lase)
47      Wind_R4 = [-1.15 -1.60 -1.98]; % Wind at +4 Sec (Fire)
48      Wind_R5 = [-1.31 -1.77 -2.62]; % Wind at +5 Sec (Fire +1 Sec)
49      Wind_R6 = [-1.28 -1.28 -2.18]; % Wind at +6 Sec (Fire +2 Sec)
50      % Calculating Frozen Wind Turbulance
51      xq = 0:0.5:10; % Interploation new Height range
52      wq1 = interp1(Height_Ref,Wind_R1,xq,'linear','extrap');
53      wq4 = interp1(Height_Ref,Wind_R4,xq,'linear','extrap');
54      wq5 = interp1(Height_Ref,Wind_R5,xq,'linear','extrap');
55      wq6 = interp1(Height_Ref,Wind_R6,xq,'linear','extrap');
56      % Re-shaping ouputs
57      WH = reshape(xq,[21,1]);
58      W_R1 = reshape(wq1,[21,1]);
59      W_R4 = reshape(wq4,[21,1]);
60      W_R5 = reshape(wq5,[21,1]);
61      W_R6 = reshape(wq6,[21,1]);
62      % Wind data into a table
63      data1 = table(WH,W_R1,W_R4,W_R5,W_R6);

```

Figure 71 – Wind interpolation sub-programme

This section required manual input into lines 46 to 49 of the code to add in the wind speed conditions for each of the wind profiles. The wind speed for each sensor for their corresponding second interval was added. The data output was then saved as data 1, which collected the output wind profile data as per [Table 10].

4.3.2.4 Point Mass Trajectory calculations.

The next section was the main part of the overall programme detailing the Point Mass model equations [Figure 72]. The equation produced the ballistic trajectory data for the round in flight, a [for loop] was used to iterate the equation in relation to time of flight. For each 0.05 s of flight time the model outputted the ballistic values which were captured in the ballistic tables [data 2, 3, 4] [4.3.2.2].

5. Trajectory calculations

```

64   for t = 0.05:0.05:3.00
65       Vel_r = sqrt(Vx^2+Vy^2); % calculate the velocity magatude|
66       F_ag = atan(Vy/Vx); % calculate the angle of flight
67       Dg_F = 0.5*Air*Vel_r^2*CS_rd*DC; % calculate the drag force
68       Fx = -Dg_F*cos(F_ag); % force in x axis
69       Fy = -Dg_F*sin(F_ag)-M_rd*g; % force in y axis
70       Accx = Fx/M_rd; % acceleration in x axis
71       Accy = Fy/M_rd; % acceleration in y axis
72       Vx = Vx+Accx*0.05; % velocity in x axis
73       Vy = Vy+Accy*0.05; % velocity in y axis
74       Disp_x = Disp_x+0.5*(Vx+Vx)*0.05; % displacement in x axis range
75       Disp_y = Disp_y+0.5*(Vy+Vy)*0.05; % displacement in y axis hieght

```

Figure 72 – Point Mass Model Equations

For the wind drift calculations [Figure 73], a set of [if loops], were used to match the correct conditions to the iteration loop of the main ballistic equations in the [for loop]. The issue was matching the longitudinal process [time of flight] with the change of height of the projectile in flight and the correct second interval of the wind profile.

6. Cross wind velocity(m/s) - refereñce postions

Inputing a Negative Wind Value '-' is for a Right to Left drift across the firing line whilst facing the Target. (I.e. Target is "South", an West to East Cross Wind is '-' input)

Inputing a Positive Wind Value '+' if for a Left to Right drift across the firing line whilst facing the Target. (I.e. Target is "South", and East to West Cross Wind is '+' input)

```

if t > 0.00 && t < 1.00
    if Disp_y > -1 && Disp_y < 1
        Vw1 = data1{1,"W_R1"}; % m/s = Laser
        Vw2 = data1{1,"W_R4"}; % m/s = fire
    elseif Disp_y > 1 && Disp_y < 2
        Vw1 = data1{3,"W_R1"}; % m/s = Laser
        Vw2 = data1{3,"W_R4"}; % m/s = fire
    elseif Disp_y > 2 && Disp_y < 3
        Vw1 = data1{5,"W_R1"}; % m/s = Laser
        Vw2 = data1{5,"W_R4"}; % m/s = fire
    elseif Disp_y > 3 && Disp_y < 4
        Vw1 = data1{7,"W_R1"}; % m/s = Laser
        Vw2 = data1{7,"W_R4"}; % m/s = fire

```

Figure 73 – Wind Drift Equations

A set of changing if conditions were used to make sure the correct wind speed condition at the correct height and time of flight was used. This condition set took a few iterations of the overall programme model to get correct. As the wind

condition were output earlier in the model into the first table an extraction function [= data1 {1,"w_R1"}] was used. This along with the if function was able to extract the correct wind speed value, in relation to both the time of flight and the height of the projectile.

Bands of 1 meter across the total height of 10 m were used for the modelling to keep the overall data output to a simple minimum. The programme could be improved to a tighter band set of either 0.5 m or 0.1 m, but this would increase the overall output data and processing time.

The data at this point in the model was extracted and saved into two different formats, a set of tables and two graphs. The ballistic data was saved into two different range tables, as detailed in section 4.3.2.2, and a wind table covering the output wind data only.

Additional two graphs were produced, one a standard trajectory plot covering range vs height and the second a projectile drift vs range **[Figure 74]**.

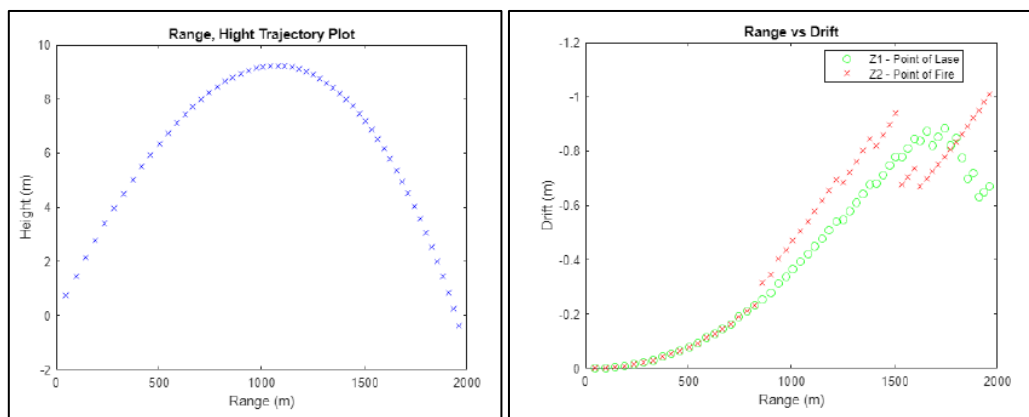


Figure 74 – Example, Trajectory Plots

The output data at this point in the programme could be matched to the EXCEL Point Mass model **[Figure 75]** from Cranfield University (Cranfield University, 2019). This was used to verify the accuracy of the MATLAB model functionality compared to an EXCEL based model.

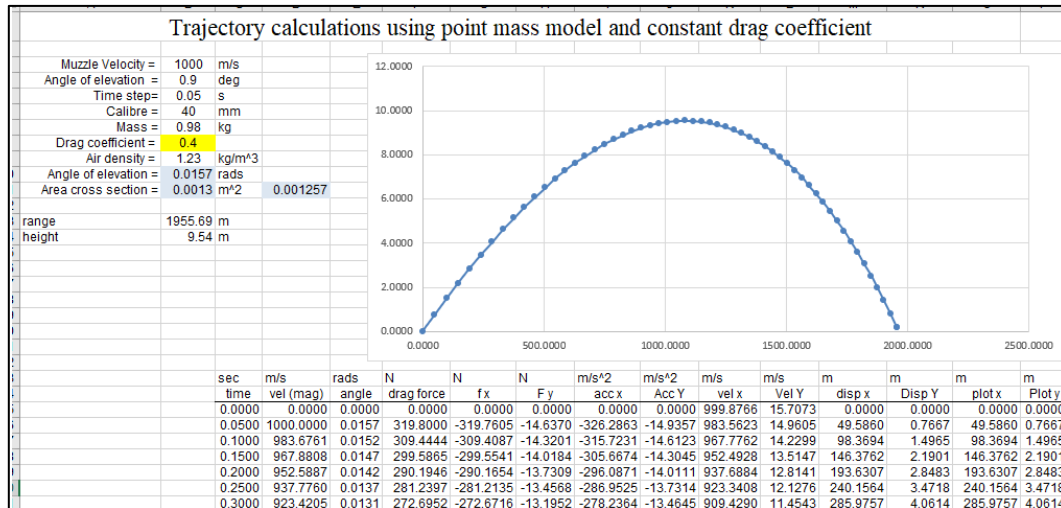


Figure 75 – Cranfield EXCEL Point Mass Model, (Cranfield University, 2019)

4.3.2.5 Coincidence Equations

The final section of the programme is the ballistic hit and coincidence equations to find the hit performance of the projectile in flight. The equations for this section are from **[Section 3.3]** and covered the formatting of the ballistic results into the main coincidence equation **[Figure 76]**.

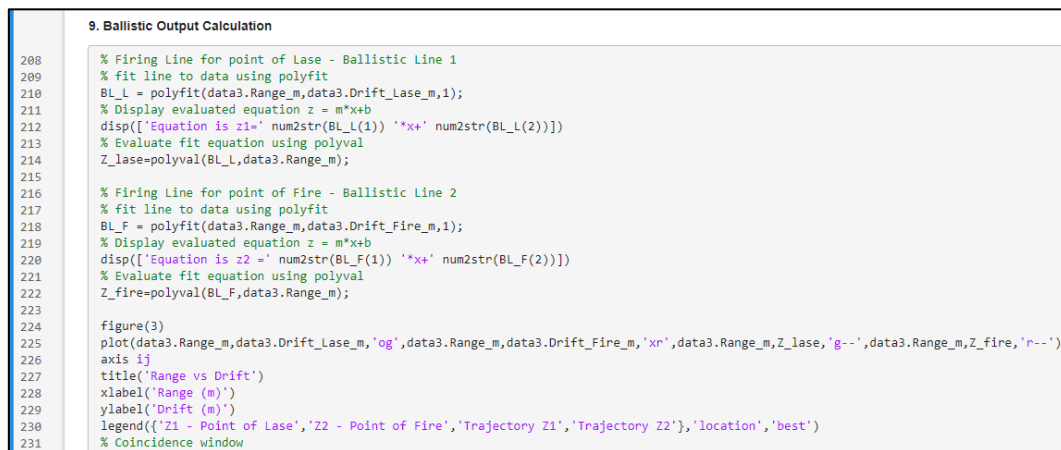


Figure 76 – Coincidence equations.

The coincidence results were displayed by MATLAB as single values and saved in the final variable table. The line of best fit used to calculate the final hit location and the coincidence value was then overlaid onto a new drift vs range graph **[Figure 77]**.

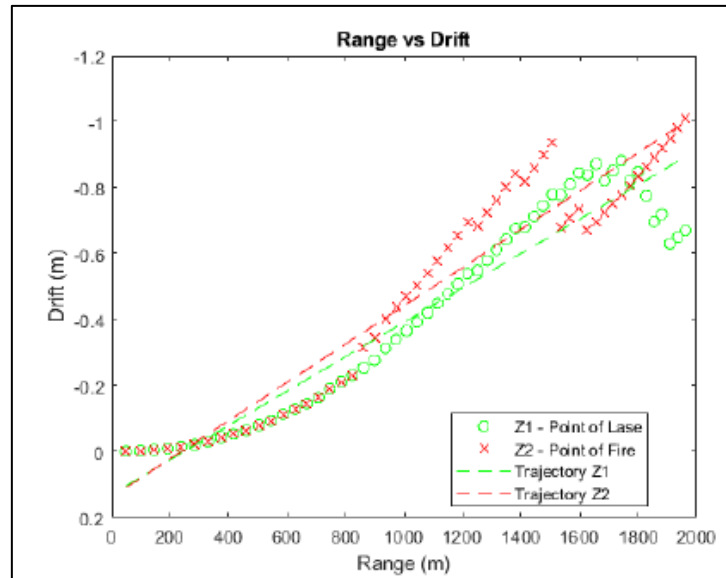


Figure 77 – Example, Drift and Coincidence drift graph.

Once all data had been produced the final section of the programme, completed two different functions. Firstly, all variables were saved into a table input all initial inputs and created named variables within the programme. Secondly, each of the tables and graphs were saved to a common folder and file name designation [Figure 78].

```

10. Data Saving

250 data5(1,:) = {MV,Cal,M_rd,CS_rd,DC,Ele_d,Ele_r,Air,g,Hit_L1,Hit_L2,Hit_L,Hit_F1,Hit_F2,Hit_F,Coin}; % step data
251
252 writetable(data1,'Model_A_V6_WTI_01_Oct_22_DS30-A1.xls'); % Wind Table Input (WTI)
253 writetable(data2,'Model_A_V6_BT1_01_Oct_22_DS30-A1.xls'); % Ballistic Table 1 (BT1)
254 writetable(data3,'Model_A_V6_BT2_01_Oct_22_DS30-A1.xls'); % Ballistic Table 2 (BT2)
255 writetable(data4,'Model_A_V6_WT_01_Oct_22_DS30-A1.xls'); % Wind Table (WT)
256 writetable(data5,'Model_A_V6_VL_01_Oct_22_DS30-A1.xls'); % variables list (VL)
257 saveas(ffigure(1),'Model_A_V6_Figure1_01_Oct_22_DS30-A1.jpg'); % figure 1 save
258 saveas(ffigure(2),'Model_A_V6_Figure2_01_Oct_22_DS30-A1.jpg'); % figure 2 save
259 saveas(ffigure(3),'Model_A_V6_Figure3_01_Oct_22_DS30-A1.jpg'); % figure 3 save
260 toc % programme time end, output elapsed time in sec's.

End

```

Figure 78 – Table and Graph saving functions.

The last output of the programme was the toc closing function, which displayed the overall elapsed time of running taken from each activation of the programme.

4.4 Conclusion

The method chosen for this thesis focused on the established Point Mass Model which could be easily recreated into the format required by MATLAB. The use of MATLAB as the main analytical software used is due to the simplicity of the software and the different functions and options available. The Point Mass Model was compared to the EXCEL based model to ensure the programme was functioning correctly and producing correct outcomes.

The use of an analytical modelling and simulation approach enabled multiple iterations of the model and concepts around the wind drift to be experimented with in a short duration and cost-effective way, as conducting full ballistic trials is extremely expensive and time consuming task.

The limited selection of wind data used in this study was due to the limitations of time for the study and the fact that a large amount of data was available. A whole year at 1 s wind intervals would have provided over 31 million data points to be assessed. The date periods assessed provided different wind conditions from the points in the year the data was taken from spring, summer, and winter.

Additionally reducing the wind data to the fire control period of 10 s of data, on each hour removed some of the assessments required on finding the 'right' wind conditions.

Chapter 5 Results

5.1 Introduction

This chapter will detail a selection of the results from the modelling and simulation of the Point Mass Ballistic Model and the Meteorological assessment. Each of the Data Sets that were tested produced a number of different exported results including graphs and tables. These results are presented in a digital format to accompany the thesis due the number of results produced, around 4,000 files.

The key data from these tests on each Data Set is collected into the Appendix's at the back of this thesis, along with the full MATLAB code which can be used to repeat the tests conducted. The full MATLAB code is shown in **[Appendix B]**, this MATLAB code was used to conduct all the tests and is the final iteration of the code. Appendix C to E contain the full results of the testing conducted in summary form for each Data Set.

Appendix C: Meteorological Data Sets

[Appendix C] contains the inputted meteorological wind data for each of the Data Sets used in the testing, as shown in **[Table 13]**. The wind data is shown in the sample sets taken on each hour, comprising of the 6s ballistic window used for the simulation. The full meteorological raw samples are located in the supporting digital format.

Table 13 – Meteorological Data Set

Month & Year	Days	Data Sets	Sub Samples
April 2022	1 st – 10 th	1 – 10	0800, 0900, 1000, 1100, 1200
June 2022	1 st – 10 th	1 – 10	0800, 0900, 1000, 1100, 1200
December 2021	1 st – 10 th	1 – 10	0800, 0900, 1000, 1100, 1200

Appendix D: Ballistic Test Summary

[Appendix D], Ballistic Test Summary comprises of a full table of the test results from each of the ballistic tests conducted in the Point Mass Ballistic Model. The results are in order of the Data Sets and the test samples conducted. Each of the sub sample of the wind data are named A to E for hours 0800 to 1200 hrs.

Each of the sub sample sets were tested against a different set of ballistic tests to compare the results of the ballistic model and prediction of the coincidence and hit locations. **[Table 14]**, details the list of each of the tests conducted for most of the samples. For each of the Data Sets a selection of tests were conducted in no particular order covering the following comparisons of wind data:

Table 14 – Ballistic Tests Conducted

ID	Test Title	Test Description	Initial Lase	Fired Wind
0	Dynamic wind response	Dynamic wind data 1 s	1 s	4-6 s
1	Current Fire Control	2.5 m 1 s fixed	1 s [2.5 m]	4-6 s
2	-2 s delay test	Dynamic wind data 2 s	2 s	4-6 s
3	-1 s delay test	Dynamic wind data 3 s	3 s	4-6 s
4	Coincidence FC	Dynamic wind data 4 s	4 s	4-6 s
5	Fixed wind response	2.5 m 3 s fixed	3 s [2.5 m]	4-6 s
6	Fixed wind response	2.5 m 4 s fixed	4 s [2.5 m]	4-6 s
7	Fixed wind response	All 2.5 m fixed	1 s [2.5 m]	4-6 s [2.5 m]
8	Fixed wind response	2.5 m 2 s fixed	2 s [2.5 m]	4-6 s

Not all of the tests were completed on each sample as the initial first set of tests would show the wind data was within the coincidence window, so no further experimentation was required.

The file convention for each of the tests is detailed as the following layout, the file name “29_Aug_22_DS1-A”, the first part covers the file date “29_Aug_22” and the Data Set in question summarised as “DS#”. Next is the data set number “1”.

Appendix E: Target Hit Silhouettes

[Appendix E] Target Hit Silhouettes, contains the full summary tables for each of the Data Sets. The silhouettes are of the reference target H-1 T-72 Head-on silhouette, scaled to 1:20 for a reference range of 2000 m **[Figure 79]**. The images have been frozen and can be scaled up to the correct size.

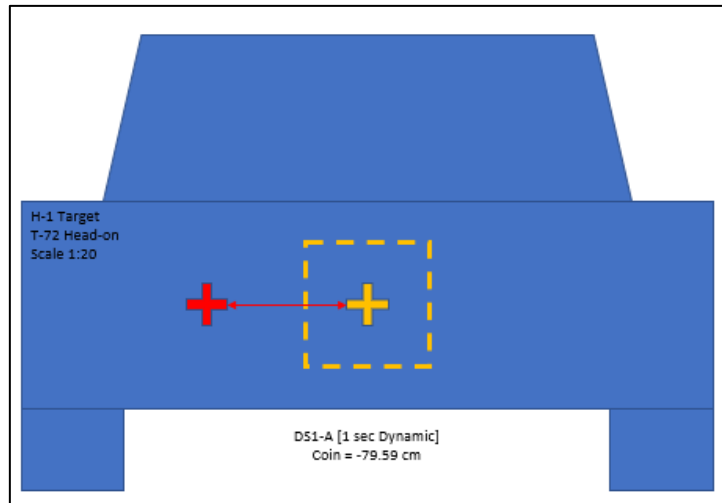


Figure 79 – Example silhouette.

5.2 Meteorological Results

5.2.1 Summary

As detailed in the method, the initial meteorological wind data was extracted from the METFiDAS-3 database (Reading University, 2020), and simplified to be used and assessed. A total of 5 different months across 2021 & 2022 were extracted to assessed [Table 15]. This provided a selection of different meteorological conditions as the samples were taken from different points in the year.

Table 15 – Meteorological Wind Data Sets

Day / Month / Year	Days assessed	Data Set	Sub-sets	Total
1-30 April 2022	1-10	1-10	10	100
1-30 April 2021	1-10	11-20	10	100
1-30 June 2022	1-10	21-30	10	100
1-30 June 2021	1-10	31-40	10	100
1-30 December 2021	1-10	41-50	10	100
Total	50		500	

As a large volume of data was extracted, the focus was on first ten days of each month. For each of these days, the initial wind data was moved into a new tab for assessment, this was then focus down into a set of 6 s sections at the start of each hour. A total of five samples A to E were created for each of the Data Sets from the wind data, this enables easy extraction and comparison at the hourly

intervals. Around 500 sample sets were created for each of the wind profiles, these were later reduced to half the number to ease the overall assessment process.

The following data sets will be detailed in the results chapter as they present a wide sample of the different resulting themes, which are Data Sets 01, 06, 24, 28, 48 and 50. The remaining data sets are collected in **[Appendix C]**.

5.2.2 Normal Wind vs Real wind

In the literature review **[Chapter 2]** there were a number of ‘normal’ reference wind speeds given, that are used primarily in mathematical science ballistics experiments. The reference wind speed of 10 mph [4.47 m/s] crosswind is primarily used during research and laboratory experimental ballistic analysis (McCoy, 2012; Litz, 2015).

Additionally as described in the literature review there was an analysis conducted by A.R.D.E in the 1950’s into assessing the statistical standard deviation of North West Europe wind conditions into an average crosswind value (Shepard and Beach, 1958; Armament Research and Development Establishment (A.R.D.E), 1967). This gave two standard values of 1.49 & 1.82 m/s as crosswind speed, to be used as reference as crosswind and gustiness. Using these three reference wind speed as the normal wind which should be experienced during an engagement, the wind gradient for these wind speed conditions can be produced **[Figure 80]**.

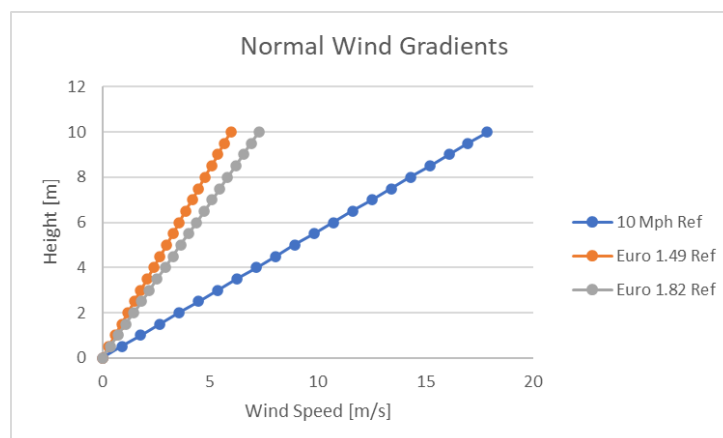


Figure 80 – Normal Wind Gradients

The reference wind conditions have been set at a height of 2.5 m which is the average height of a MBT meteorological sensor. The wind speed has then been interpolated to give a wind gradient across the reference height range of 0 to 10 m [Table 16].

Table 16 – Normal Wind Gradient Values

Height [m]	10 Mph Ref	Euro 1.49 Ref	Euro 1.82 Ref
0	0	0	0
0.5	0.894	0.298	0.364
1	1.788	0.596	0.728
1.5	2.682	0.894	1.092
2	3.576	1.192	1.456
2.5	4.47	1.49	1.82
3	5.364	1.788	2.184
3.5	6.258	2.086	2.548
4	7.152	2.384	2.912
4.5	8.046	2.682	3.276
5	8.94	2.98	3.64
5.5	9.834	3.278	4.004
6	10.728	3.576	4.368
6.5	11.622	3.874	4.732
7	12.516	4.172	5.096
7.5	13.41	4.47	5.46
8	14.304	4.768	5.824
8.5	15.198	5.066	6.188
9	16.092	5.364	6.552
9.5	16.986	5.662	6.916
10	17.88	5.96	7.28

Creating data sets for the wind gradient for each of the mathematical reference samples, allows for further comparison to the real crosswind gradients collected. The overall statical values for each month of real crosswind will be compared to the mathematical reference [10 mph] and the Northwest Europe statistical wind references [1.49 & 1.82 m/s]. To compare the Data Sets to the statistical references wind speed values that have been used in other studies, the wind data was set into three average values.

The initial wind sample across the first three seconds was collected into a single wind average and the second average from the last three seconds. The third values were an overall wind speed average across the full 6 s timeline, these have been collected in **[Table 17]** and **[Appendix C31-33]**.

The sample overall average [All Av] crosswind velocity was compared to the three reference velocities, to understand how close the statistics values were to real values. A value of 100% is an exact match of sample average to the statistical target, over 100% is exceeding and less than 100% is an average less than target. Noting that '+' is Left to Right and '-' is Right to Left wind across the line of fire, not related to wind velocity.

Taking Data Set 1, Sample A, has an All Average crosswind speed of [-]1.65 m/s heading right to left across the line of fire. Compared to the three statistical values the crosswind velocity is less than the 10 mph ref and close to the two Northern European values at 11% over and 9% under target.

Table 17 – Wind Data Sets compared to reference wind.

Data Set		Wind Speed [m/s]			10mph ref	NW Euro Stand Dev	
		1-3 Av	4-6 Av	All Av	Tgt - 4.47 m/s	Tgt - 1.49 m/s	Tgt - 1.82 m/s
1	A	-1.49	-1.81	-1.65	-37%	-111%	-91%
	B	1.31	-0.60	0.35	8%	24%	19%
	C	0.16	3.63	1.89	42%	127%	104%
	D	1.42	1.66	1.54	34%	103%	85%
	E	-0.94	-0.38	-0.66	-15%	-44%	-36%
28	A	-3.65	-2.761	-3.21	-72%	-215%	-176%
	B	-0.185	-0.298	-0.24	-5%	-16%	-13%
	C	-3.257	-2.996	-3.13	-70%	-210%	-172%
	D	-1.799	-1.645	-1.72	-39%	-116%	-95%
	E	-5.198	-3.846	-4.52	-101%	-303%	-248%
50	A	-1.701	-3.294	-2.5	-56%	-168%	-137%
	B	-4.016	-3.873	-3.94	-88%	-265%	-217%
	C	-2.257	-1.773	-2.02	-45%	-135%	-111%
	D	-1.545	-2.009	-1.78	-40%	-119%	-98%
	E	0.215	-1.015	-0.4	-9%	-27%	-22%

5.2.3 Data Set 01 – Meteorological Wind Data

Data Set 1 is for the 1st of April 2022, samples A and B for hour periods of 0800 and 0900 hours [Table 18], the remaining data is in [Table C-1]. The raw wind data across the six second period is provided by the wind sensors [U2, U5, U10] this provided raw wind speed in m/s. The number on these sensors indicates the height of the wind sensor, that was then used to extract and interpolate across the missing values.

Table 18 – Data Set 1 – Ballistic Wind Sample A and B

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2	2.5	2.4	NNW [-0.17]	-0.34	-0.43	-0.41	1.00
08:00:01	2.6	2	2.4	WSW [-1]	-2.60	-2.00	-2.40	2.00
08:00:02	2.4	1.8	2.3	NW [-0.64]	-1.54	-1.15	-1.47	3.00
08:00:03	2.2	1.7	2.1	W [-0.98]	-2.16	-1.67	-2.06	4.00
08:00:04	1.9	1.6	2.2	W [-0.98]	-1.86	-1.57	-2.16	5.00
08:00:05	1.5	1.7	2	W [-0.94]	-1.41	-1.60	-1.88	6.00
09:00:00	4	5.2	6.4	NNW [-0.34]	-1.36	-1.77	-2.18	1.00
09:00:01	4.8	5.5	6.4	NNE [0.64]	3.07	3.52	4.10	2.00
09:00:02	6.5	6.9	5.1	N [0.34]	2.21	2.35	1.73	3.00
09:00:03	4.8	5.9	5.8	NNW [-0.34]	-1.63	-2.01	-1.97	4.00
09:00:04	3.4	4.4	6.4	NNW [-0.34]	-1.16	-1.50	-2.18	5.00
09:00:05	2.9	3.6	6	N [0.34]	0.99	1.22	2.04	6.00

The crosswind factor is the relationship between the compass direct given by the meteorological sensors and the weight crosswind value that can be used to produce the crosswind and headwind values from the raw true wind.

The crosswind weight value is given in the square brackets next to the compass value "[##]". This value changes the real wind speed to a direct crosswind and headwind value as detailed in the Theory [Table 8] and shown in the [CW] columns. A negative "-" value is a Right to Left crosswind and a positive "+" a Left to Right crosswind across the line of fire, not a relation to the strength of the wind speed.

Using the three reference point in the MATLAB interpolated code, the wind gradient can be produced for each sample. This is saved as an excel file titled Wind Table Input [WTI], example “Model_A_V6_WTI_29_Aug_22_DS1-A”.

For Data Set 1, the wind gradients were extract using the MATLAB interpolation code to produce a full wind template from 0 to 10 m in height. The data is located in the supporting digital format, and from the tables can produces the following graphs.

[Figure 81], shows the wind gradient for Data Set 01, sample A [0800 hrs]. The wind gradient is shown for the initial lase at 1 s and the inflight of the projectile at 4-6 s.

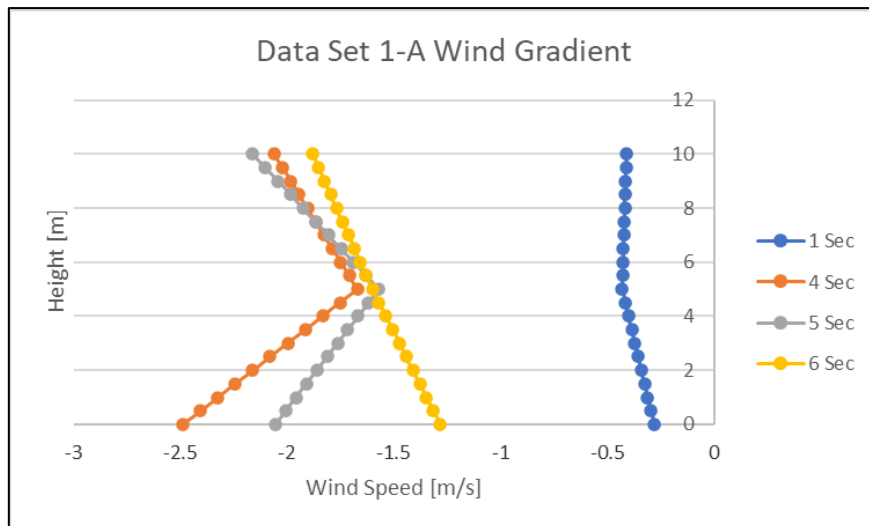


Figure 81 – Data Set 01-A Wind Gradient

This sample shows that the wind profile that the round experiences in flight after being fired [4 s], is different to the data used by the FCC to calculate the offset [1 s]. The average across the time of flight of the round, the wind speed is nearly 2 m/s higher than the wind speed at point of FCC calculation. Additionally it can be seen that the wind speed is decreasing between 4 to 6 s of the profile, in the lower part of the height domain. The wind speed is still showing a higher wind speed at the top part of the height domain, were typically the projectile is at its lowest velocity in its arc of flight.

The wind gradient profile for Data Set 01-B [0900 hrs], is shown in **[Figure 82]**. The interesting part of this wind gradient profile is that there is not much change in the wind profile between 1 to 5 s, and a complete change at 6 s.

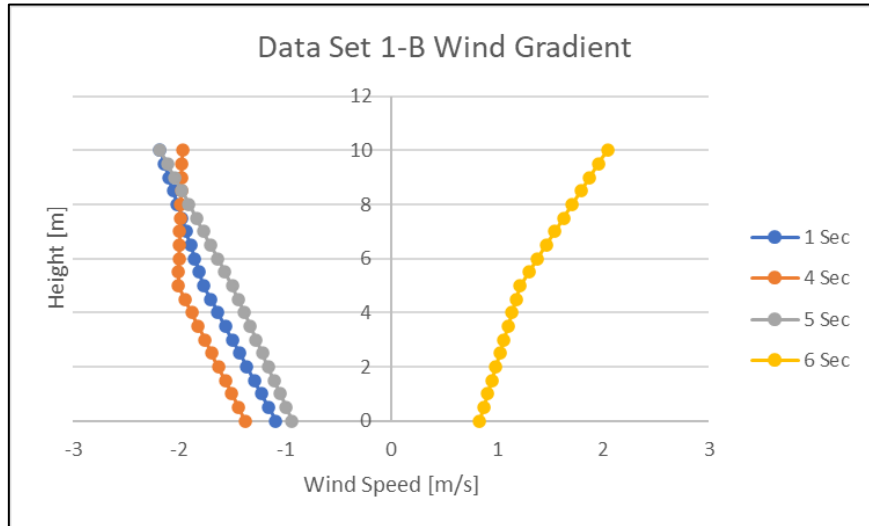


Figure 82 – Data Set 01-B Wind Gradient

At 6 s in the wind profile the wind speed completely changes direction from negative to positive. So as detailed earlier, positive value on the wind speed is a crosswind from Left to Right across the line of fire. As shown in the table below **[Table 19]**, the crosswind factor has changed from “-“ to “+” due to the direction of the real wind.

The real wind in this sample is approaching from the North quadrant, at 5 s the wind is at NNW which is the left side of the line of fire and at 6 s is now at the right side of the line of fire **[Table 19]**.

Table 19 – Data Set 01, sample B 0900 hrs, for 5 s & 6 s

Time [UTC]	Compass [Degrees]	Compass Bearing	Crosswind Factor	Seconds
09:00:04	345	NNW	-0.34	5.00
09:00:05	12	N	0.34	6.00

This shows that a small change in the wind direction can cause a large change to the ballistic flight of the projectile. As in pure crosswind and headwind terms the wind is now approaching from the opposite direction.

Data Set 1-D [1100 hrs] wind gradient profile is shown in the **[Figure 83]**. This wind profile is now all approaching from the positive direction [L-R]. The interesting factor about this set of wind gradients is the initial flight of the projectile at 4 s and later at 6 s is subject to higher speed wind than the initial calculation of the FCC at 1 s.

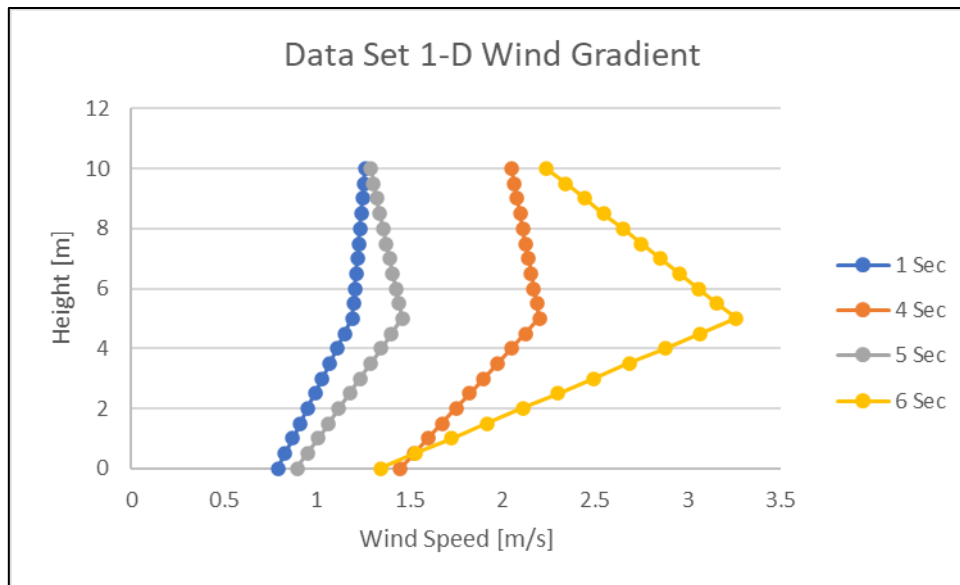


Figure 83 – Data Set 01-D Wind Gradient

The FCC data calculation based on the 1 s, is close to the middle of the flight period at 5 s, in the wind profile. The wind on the final part of the flight [6 s], shows a sharp arrow in the gradient profile. The wind speed dramatically changes across the three reference sensors, showing a higher speed wind in the middle of height profile.

5.2.4 Data Set 06 – Meteorological Wind Data

Data Set 06 covers the 06th of April 2022, with the full raw real wind data located in the supporting digital format. The sample wind profiles for this Data Set are located in **[Appendix C.6]**. **[Figure 84]**, shows the wind speed of sample 06-A, at 0800 hrs. The crosswind values are shown for the three sensors used as the input reference prior to the interpolation. The data shows a constant steady wind profile across the reference timeline.

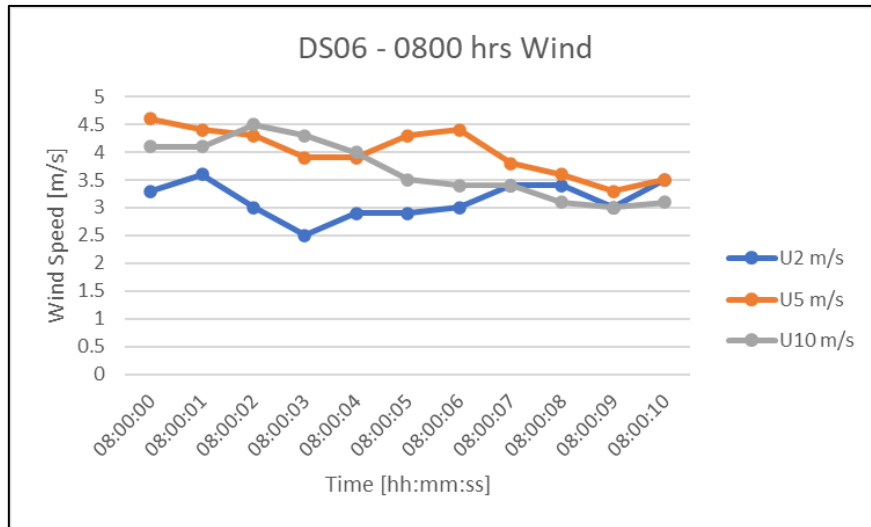


Figure 84 – Data Set 06-A, 0800 hrs wind profile

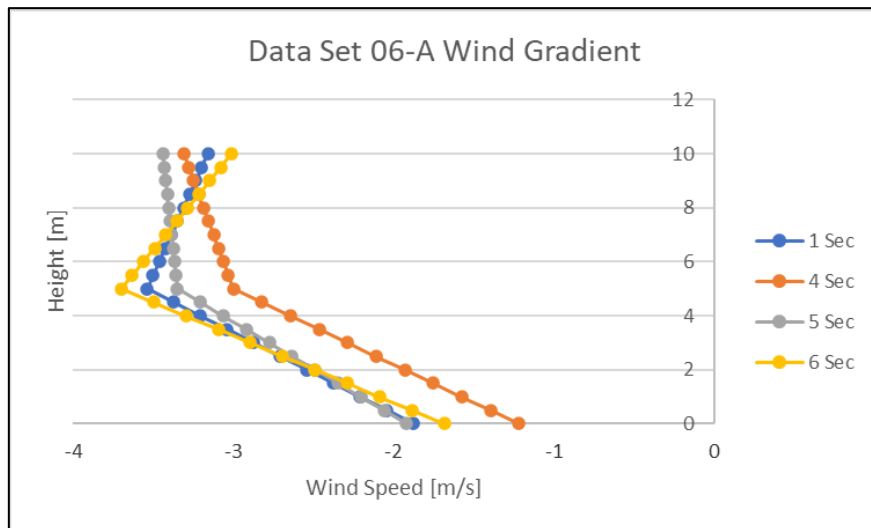


Figure 85 – Data Set 06-A Wind Gradient

The initial sample data for sample 06-A, was then converted to produce the wind gradient for the sample set. The wind gradient profile is shown in **[Figure 85]**, for the initial FCC calculation at 1 s. Also, the time of flight across 4 to 6 s. As seen in the wind gradient and the initial raw data in **[Figure 84]** each of the wind sensor report a similar steady wind profile.

Data Set 06-B [0900 hrs] wind gradient is shown in **[Figure 86]**, this sample shows a different shape to the wind gradient. The wind is constant in the scaling

of the wind speed compared to height, different to the “z” shaped profiles seen in other samples.

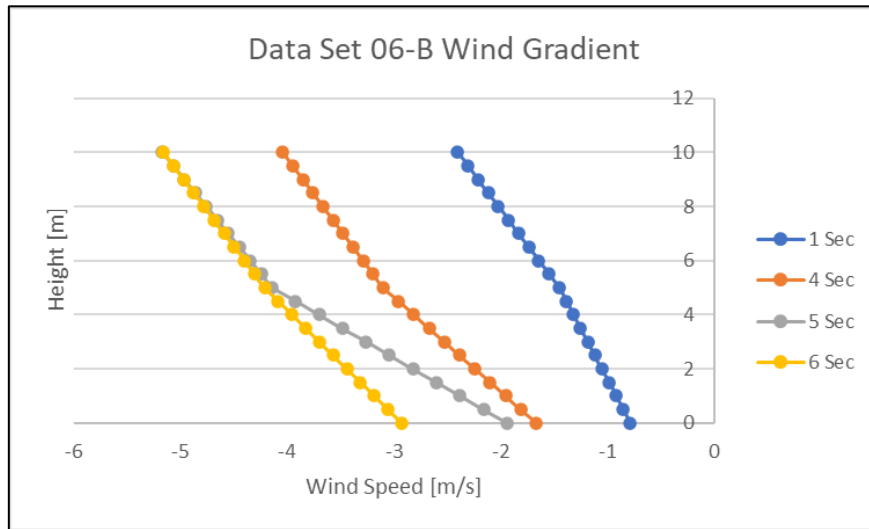


Figure 86 – Data Set 06-B Wind Gradient

The wind speed has increased from the initial wind taken at 1 s, the wind speed is constantly increasing through 4 to 6 s.

Data Set 06-C [1000 hrs] wind gradient is shown in **[Figure 87]**, this sample shows a return to the sharp “Z” shaped profile of the wind speed compared to height. The projectile flight period [4-6 s] is still a higher wind speed compared to the initial FCC sample at [1 s].

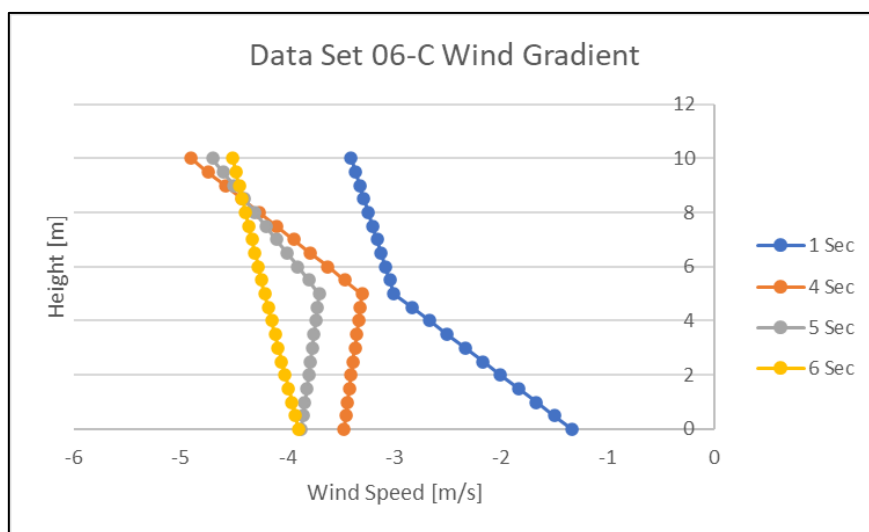


Figure 87 – Data Set 06-C Wind Gradient

5.2.5 Data Set 24 – Meteorological Wind Data

Data Set 24 is from the 4th of June 2022, the input data samples are located in [Appendix C.14] for each of the sample's A to E. [Figure 88] shows the wind gradient for sample A [0800 hrs] for the initial FCC calculation at 1 s, and the projectile flight 4 to 6 s.

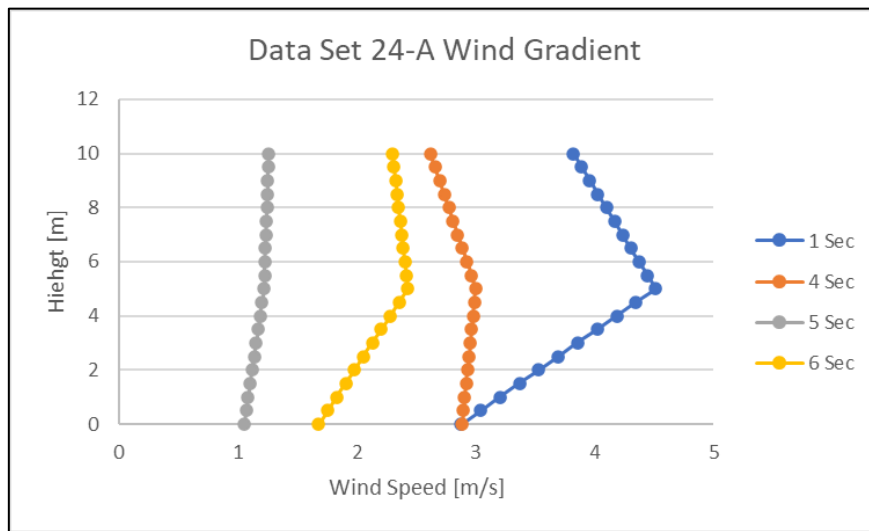


Figure 88 – Data Set 24-A Wind Gradient

The wind gradient for the initial wind speed collected at 1 s, shows the unique “Z” profile of the wind speed changing in height compared to the straighter wind profiles for 4 to 6 s.

[Figure 89] is for sample E [1200 hrs] for the ballistic wind gradient profile. The wind gradients overlap each other in the wind speed from low to higher height of the sensors. All the wind gradient profiles in this sample, start as low speed at ground level and move to high speed crosswind at the 10 m mark.

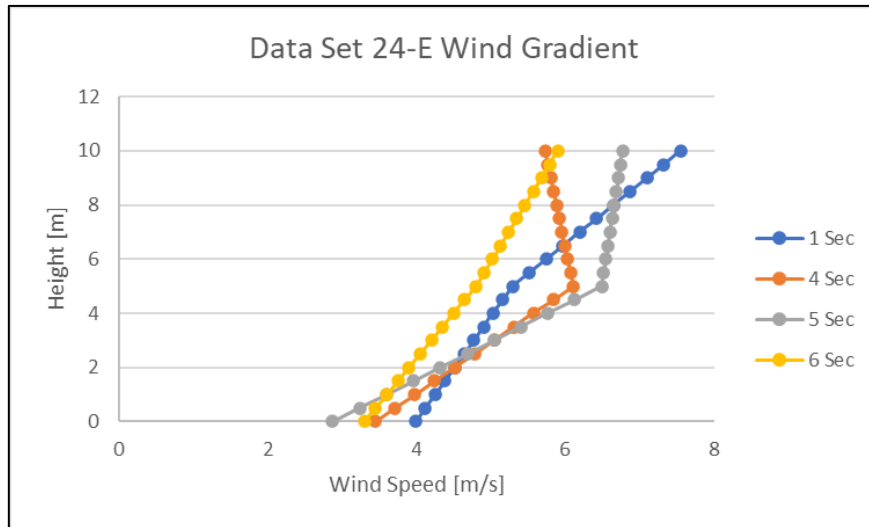


Figure 89 – Data Set 24-E Wind Gradient

This has the crosswind speed approaching 8 m/s which is nearly 50% higher than the overall average of this sample. This sample is also similar in its average crosswind speed to the scientific average of 10 mph [4.47 m/s] used in most mathematical experiments.

5.2.6 Data Set 28 – Meteorological Wind Data

Data Set 28 is data from 08th of June 2022, is meteorological wind data is from the summer of 2022. The ballistic wind profiles for the five samples are located in **[Appendix C.18]**.

Sample E [1200 hrs] in **[Figure 90]** below, the wind gradient profiles show a difference in the initial FCC wind reference [1 s] and the remaining crosswind. The wind gradient for the FCC reference [1 s], is reducing in speed across the height window compared to the inflight crosswind values.

The crosswind during the projectile flight [4-6 s], are of a similar profile shape and direction compared to the initial wind sample [1 s], but are increasing in wind speed from the ground to the top of the ballistic height window at 10 m.

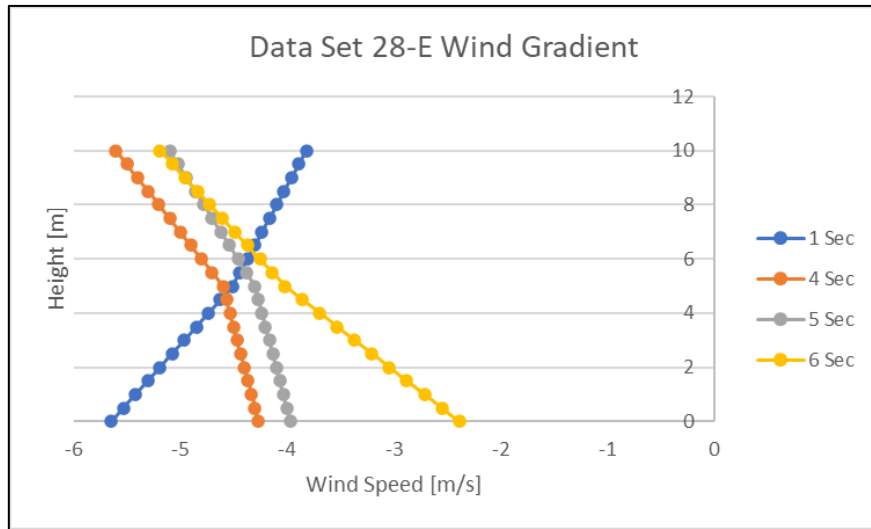


Figure 90 – Data Set 28-E Wind Gradient

This would cause a large drift in the projectile due to the projectile being at its lowest velocity at the top of its ballistic arc. The crosswind in the inflight stage [4-6 s] is showing a maximum crosswind at the top of the ballistic height window.

Data Set sample A [0800 hrs] wind gradient profile is presented in **[Figure 91]**. This sets of wind gradients show the unique “Z” shaped profile to the wind gradient, in that the mid-height of the wind gradient is at a higher wind speed than the rest of the profile.

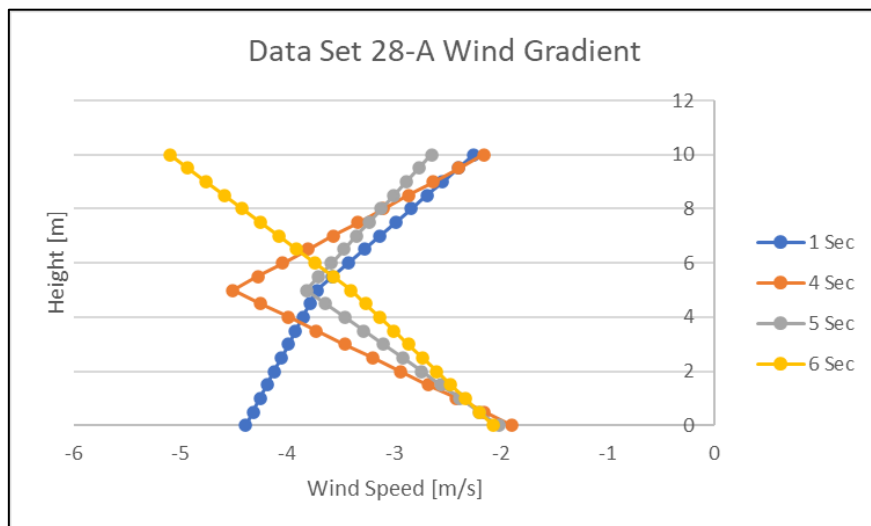


Figure 91 – Data Set 28-A Wind Gradient

The wind at the 4 s has a very sharp “Z” profile to the wind gradient, which demonstrates an extreme change in the wind speed across the ballistic height profile in this sample. The projectile in its ballistic arc will experience an over 100% change in the wind speed as the wind transitions from 2 m/s to over 5 m/s.

In comparison the wind profile for 6 s, is a steady line from a low speed of 2 m/s to a height of over 5 m/s. The wind used for the initial reference at 1 s is in the opposite direction trending from a low height of 4.5 m/s down to nearly 2 m/s at the height of 10 m.

5.2.7 Data Set 48 – Meteorological Wind Data

Data Set 48 is from the 08th of December 2021, and the ballistic wind profiles are located in **[Appendix C.28]**. The first of the sample shown in this section is sample D [1100 hrs] **[Figure 92]**, the wind gradient profile are again different to the other sample sets shown so far.

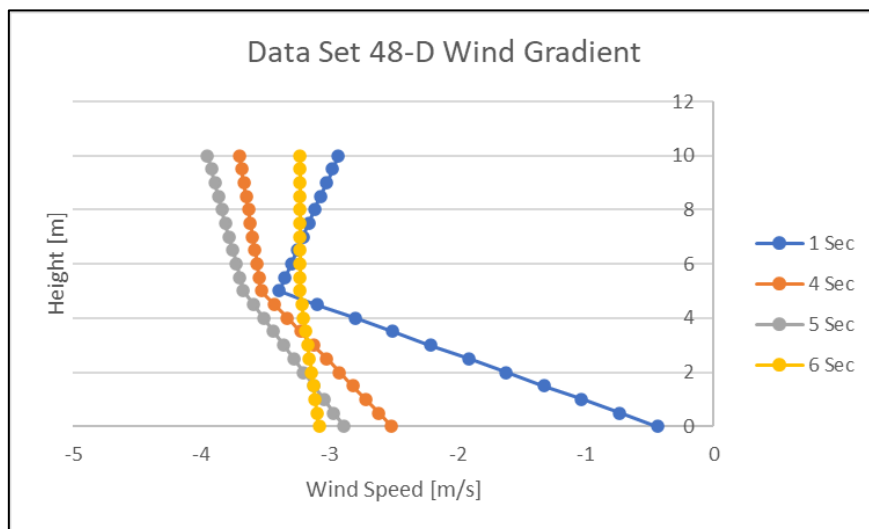


Figure 92 – Data Set 48-D Wind Gradient

The initial wind used by the FCC for the ballistic offset calculation at 1 s has a unique profile that trends from nearly 0 m/s wind speed at ground level to 3 m/s at 10 m. In comparison the three seconds of the projectile flight [4-6 s] have relatively flat and straight profiles, that do not change as dramatically between ground level and 10 m.

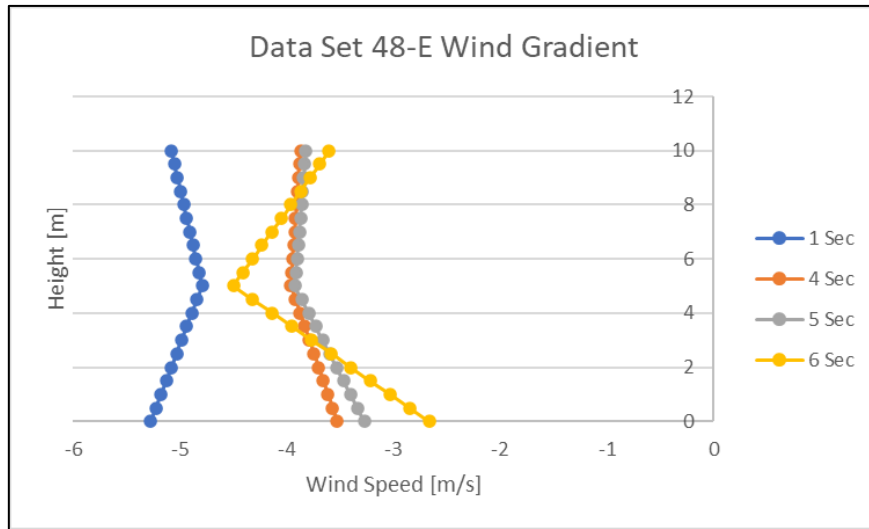


Figure 93 – Data Set 48-E Wind Gradient

Data Set 48 sample E [1200 hrs] **[Figure 93]**, wind gradient profile shows that the wind speed of the 4-6 s period is of a collectively slower speed than the FCC reference at 1 s. The average across the wind during projectile flight [4-6 s] is 3.5 m/s, compared to the average 5 m/s for the FCC reference.

5.2.8 Data Set 50 – Meteorological Wind Data

Data Set 50 is from the 10th of December 2021, with the ballistic reference profiles shown in **[Appendix C.30]**. The first of the samples in detail is sample B [0900 hrs] **[Figure 94]**, which has the following wind gradient profile for the ballistic wind window.

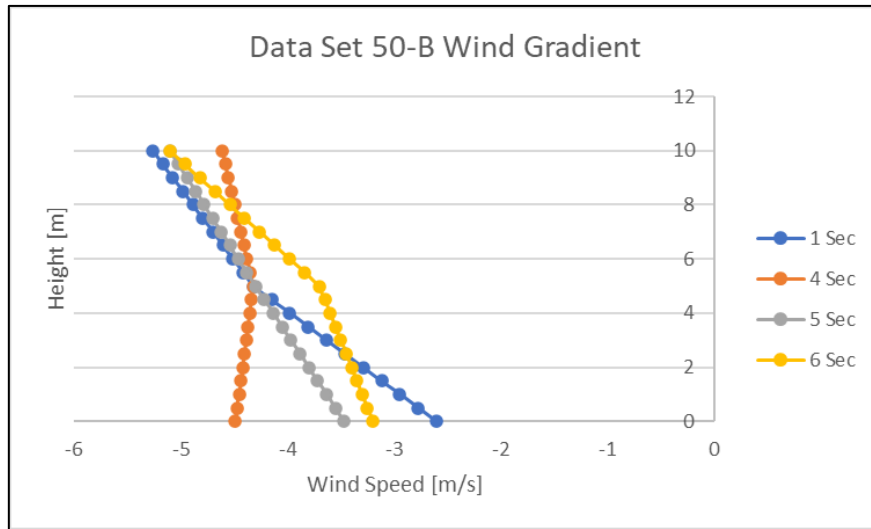


Figure 94 – Data Set 50-B Wind Gradient

For sample 50-E [1200 hrs] additional test sets from **[Table 14]** were conducted to attempt to reach the coincidence window tolerance. **[Figure 95]** shows the initial wind gradients for 1 s & 4-6 s, and **[Figure 96]** shows all 6 s of the ballistic profile wind gradient profile shapes.

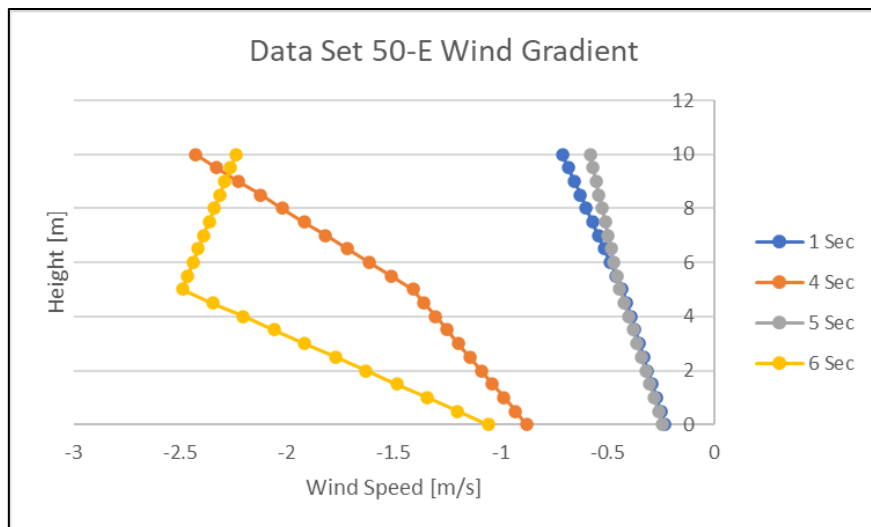


Figure 95 – Data Set 50-E Wind Gradient

Sample E wind gradient data was then expanded to cover all 6 s of the ballistic window used during testing. The Figure below **[Figure 96]** shows all wind gradients across the full sample. As can be seen in the sample the wind direction and speed massively change across the 6 s of the profile.

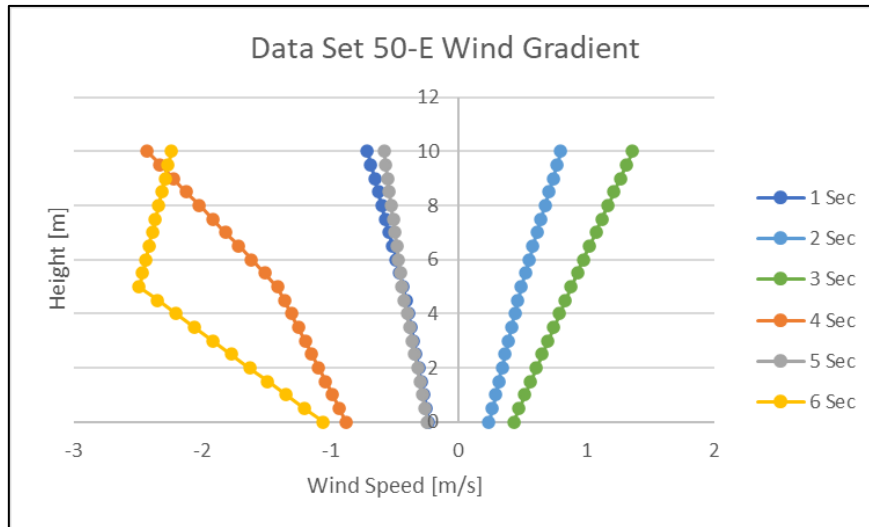


Figure 96 – Data Set 50-E Wind Gradient, full profile

Some of this period is less important as during 2 s & 3 s the wind changes direction into the “+” positive Left to Right direction. From the Chieftain engagement timelines these seconds are in the waiting period prior to the projectile being fired. These would only produce an incorrect ballistic offset from the FCC, if the offset calculation was re-calculated during these seconds.

5.2.9 Summary

The common themes that can be seen from the analysis of the meteorological wind data samples is that the wind conditions cannot be summarised into a single reference speed. Firstly, the crosswind is subject to change in wind speed and direction both due to time and height of the projectile in reference to the wind gradient.

Using a single vehicle metrological sensor at 2.5 m as a single fixed crosswind value can show the wind speed but does not consider the wind gradient or changes in relation to this. The gustiness and variation of the wind gradient can influence the projectile in flight at its most influence state, at the top of the ballistic arc.

Secondly, the time drift in the wind speed and direction is not considered in most cases but can be seen to provide a large influence on the gustiness and variation

in the crosswind speed. The crosswind is a multiple part variable, in the ballistic calculation were only one of the many parts of the variable is only considered.

Using the Chieftain MBT engagement timeline demonstrates this in the crosswind samples taken, the wind is sometimes considerably changing across the 6 s period of the engagement. The gustiness and variation of the crosswind is not considered in most cases and will influence the hit probability to maintain the coincidence window.

5.3 Ballistic Results

5.3.1 Summary

The ballistic results section details the same data sets as analysed in the meteorological result section. The remaining ballistic result data for all data sets are shown in **[Appendix D]** Ballistic Test Summary and **[Appendix E]** Target Hit Silhouettes.

The ballistic analysis of each meteorological wind data set was comprised of a number of different ballistic test conditions, test cases, which are detailed below. Using the Point Mass Ballistic Model **[Appendix B]** in MATLAB each of the data sets were tested in the following sequence **[Table 20]**.

Table 20 – Ballistic Tests Conducted

ID	Test Case Title	Test Description	Initial Lase	Fired Wind
0	Dynamic wind response	Dynamic wind data 1 s	1 s	4-6 s
1	Current Fire Control	2.5 m 1 s fixed	1 s [2.5 m]	4-6 s
2	-2 s delay test	Dynamic wind data 2 s	2 s	4-6 s
3	-1 s delay test	Dynamic wind data 3 s	3 s	4-6 s
4	Coincidence FC	Dynamic wind data 4 s	4 s	4-6 s
5	Fixed wind response	2.5 m 3 s fixed	3 s [2.5 m]	4-6 s
6	Fixed wind response	2.5 m 4 s fixed	4 s [2.5 m]	4-6 s
7	Fixed wind response	All 2.5 m fixed	1 s [2.5 m]	4-6 s [2.5 m]
8	Fixed wind response	2.5 m 2 s fixed	2 s [2.5 m]	4-6 s

The test sequence tested each Data Set against conditions that would cause the shot to fall outside of the coincidence window conditions, and cycled through the tests until the window was reached. Test ID 0, 1 and 4 were the main test cases conducted on most samples, the other tests were experiments on the results, to find changes in the coincidence conditions.

Test Case Conditions

Test Case, ID 1 is the Chieftain IFCS engagement timeline profile, which is the current system assumption, using the single 'fixed' crosswind sensor reading at

2.5 m. The 'fixed' crosswind reading does not change in height or time in relation to the wind gradient curve.

Test ID 4 is the modern assumed process using the coincidence check process, using a crosswind reading just prior to firing at 4 s mark. This test also uses the 'dynamic' approach of a multiple crosswind reading to generate a crosswind gradient curve.

Test ID 2 & 3 used different points in the engagement timeline, at intervals of 2 s & 3 s, to understand if the effects of a reduced delay in the crosswind data improve the hit probability, for -2 s & -1 s prior to firing. To see if these points in the engagement timeline are different to the test ID 1 assumption.

Tests ID 5 to 8 used the fixed 2.5 m constant crosswind sample data in relation of a standard MBT metrological sensor position **[Figure 7]**. Each test case compared the single 2.5 m sensor crosswind data to their matching 'dynamic' test case [ID 2, 3, 4]. The flight profile of the projectile [Fired Wind] with the projectile in flight across 4-6 s period used a dynamic crosswind gradient, changing in both height and time, from the multiple sensors.

Test ID 7 used a fixed projectile flight profile to understand the differences between a constant fixed 2.5 m crosswind and a dynamic variable crosswind using multiple sensors in the model.

Due to the amount of data produced during the research; only a selection of the data will be shown in this section. Each MATLAB programme produced around six tables & graphs each, with about 450 tests sets completed this totalled around 2,700 tables and graphs to display in the thesis.

As with the meteorological results only Data Sets 01, 06, 24, 28, 48 and 50 are shown in detail here.

For the readers awareness the following conventions will be used when discussing the impact locations. The FCC tested correction will be the centre yellow marker, with the NATO coincidence window around it [dashed square] and

the real impact of the projectile in flight will be the red/green marker/s **[Figure 97]**.

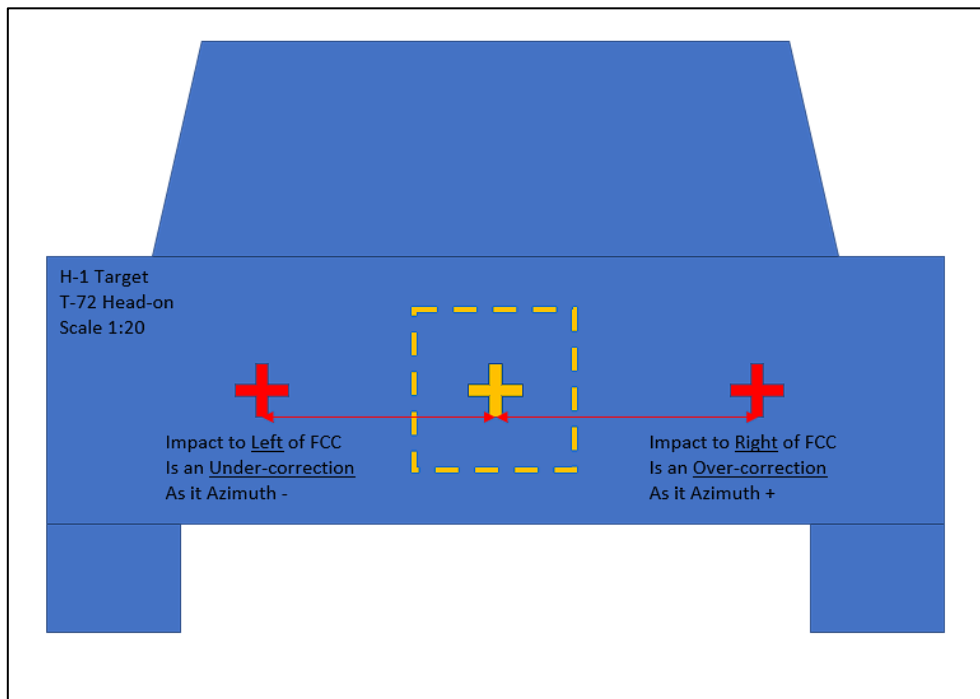


Figure 97 – Correction Conventions

If the real impact is to the LEFT of the FCC prediction, this will be an under correction. If the real impact is to the RIGHT of the FCC prediction, then this will be an over correction, which is aligned to the overall plus and minus axis in the azimuth [Z axis].

5.3.2 Data Set 01 – Ballistic Results

For Data Set 01, each of the five samples were tested through the first five test conditions in the sequence **[Table 20]**. **[Figure 98]**, shows the ballistic flight of the projectile in the Y Axis of range vs height. This trajectory profile matches the profile from the Cranfield Point Mass Model **[Figure 75]** (Cranfield University, 2019). This graph was extracted on all the ballistic tests conducted to ensure the Point Mass Model was behaving as predicted, and no random errors were being introduced.

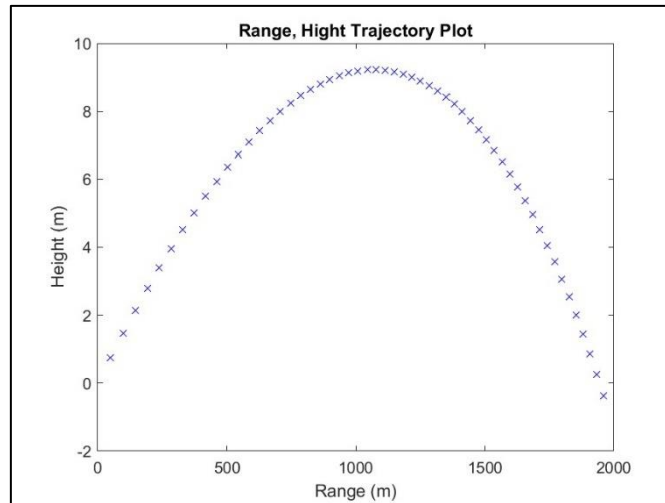


Figure 98 – Data Set 01, Ballistic Flight profile

Only this graph **[Figure 98]** will be displayed in the thesis, as all the 300 tests conducted produced the exact same graph and profile. The two sample sets that will be focused on are DS01-A and DS01-D in the ballistic results section as they have the most interesting results.

[Figure 99], displays the impact locations for all the ballistic tests conducted on sample DS01-A. The graph shows real impact location for the projectile in relation to the FCC prediction located at [0,0] centre target mass. The drift is only shown in the longitudinal azimuth, Y axis of the graph direction only, as the projectile is only subjected to crosswind.

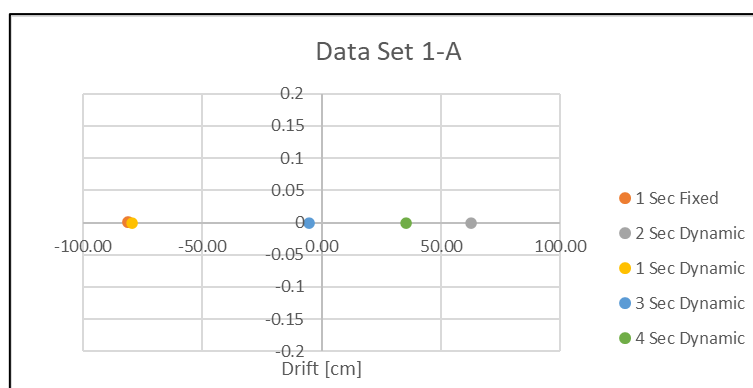


Figure 99 – Data Set 01-A, Impact Points

The collective data shows that three shots would land left of the FCC prediction of centre mass, as the FCC is under correcting for the crosswind. The current FC

method using 1 s data crosswind only [orange marker] has the largest drift error of -80 cm. Compared to a re-calculated coincidence FC, at the point prior to firing at 4 s into the timeline, has an impact over corrected to the right [green marker] [Figure 99].

The projectile hit location from the crosswind experience during flight, the uncalculated gustiness at [4 s] in the ballistic timeline, would offset the projectile impact to the right, and past the coincidence window on the other side of centre mass [35.17 cm]. This comparison is shown in [Figure 100], against the H-1 silhouette.

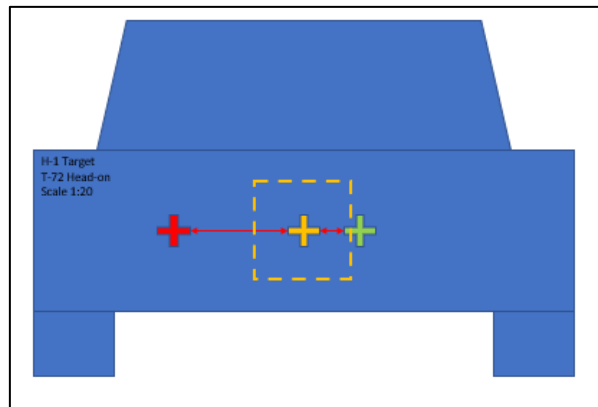


Figure 100 – DS1-A1 (red), Coin = -80.66 cm, DS1-A4 (green), Coin = 35.17 cm

The projectile flight drift profiles from MATLAB for these impact points are shown in the figures below. Each of the drift vs range plots shown the FCC initial correction in “green” and the crosswind inflight exposed drift profile in “red”. The estimated trajectory of the projectile is shown via the linear line of best fit, for each calculation.

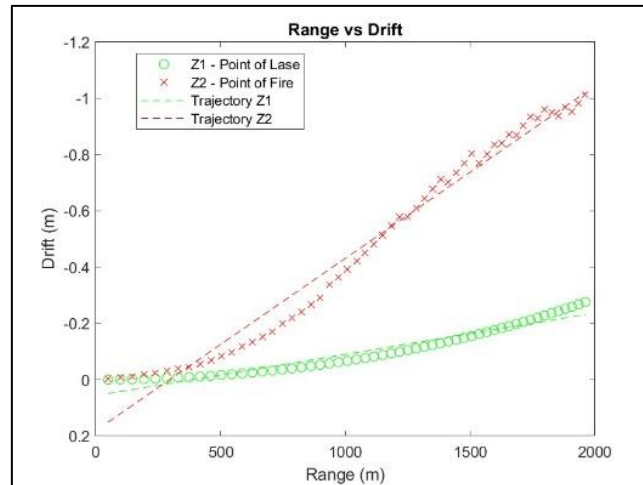


Figure 101 – Data Set 01-A1, Projectile Drift

The linear line of best fit is used as the wind drift offset does not produce a clean trajectory line as the wind drift is influenced by both the wind speed in time and height gradient of the wind profile. **[Figure 101]**, shows the projectile drift from data set 01-A1 and **[Figure 102]** for Data Set 01-A4, which are the red and green crosses in **[Figure 100]** respectively.

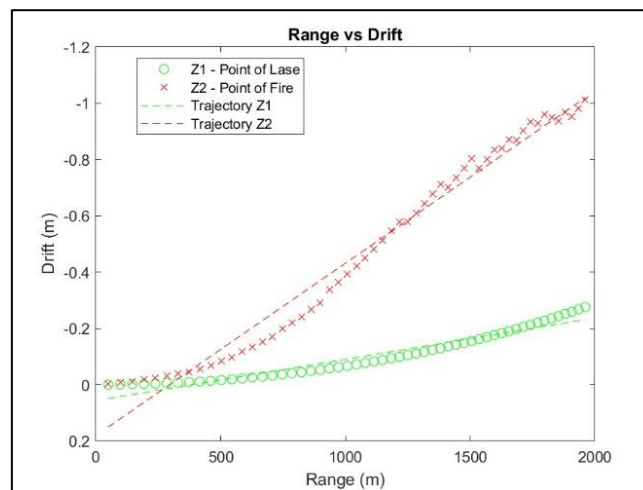


Figure 102 – Data Set 01-A4, Projectile Drift

Data Set 01 sample D impact markers in **[Figure 103]**, the FCC prediction at the 1 s into the timeline, the real crosswind exposed projectile would land right at 71.57 cm [red cross]. A re-calculation at the 4 s, intime with firing would yield an improved result compared to real drift by 11.92 cm [green cross].

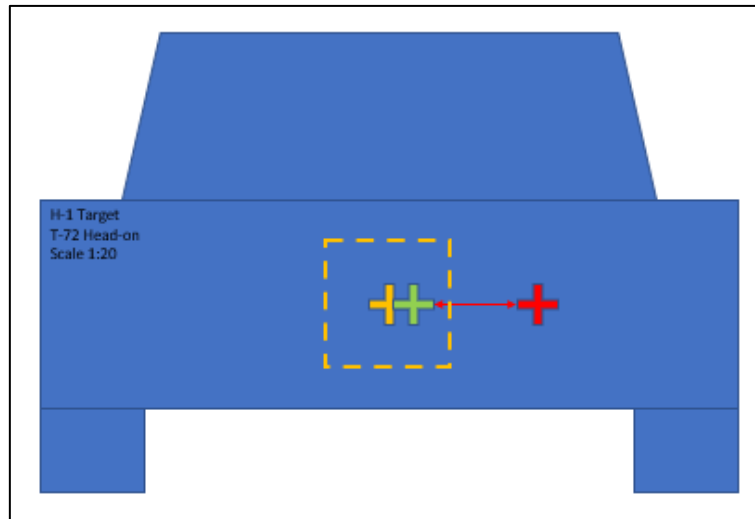


Figure 103 – DS1-D1 (Red), Coin = 71.57 cm, DS1-D4 (green), Coin = 11.92 cm

The initial FCC prediction compared to the real impact [red cross] is over corrected outside even the maximum coincidence drift window [60 cm]. Compared to the Chieftain engagement timeline and FCS process, holding that ballistic calculation for all 6 s prior to impact would breach coincidence, reducing P-Hit success.

[Figure 104] shows the drift vs range graph from the MATLAB data, the unique aspect of this data is the jumps seen in the [Z2 red] projectile in flight drift data. Firstly, the projectile crosswind drift jumps at the split between each of the three second coding slots in the flight profile. Secondary, the projectile drift scatters across a large area in the third second of the flight profile.

The jumps between each of the three second intervals of the drift in flight are due to large gaps being present between the interpolated wind data. The programme selects new wind data related to the wind gradients at each second interval in the timeline to conduct the calculations with. The larger the difference in wind speed between each second in the timeline the gaps between the data increase, as the interpolation is only conducted in the height domain.

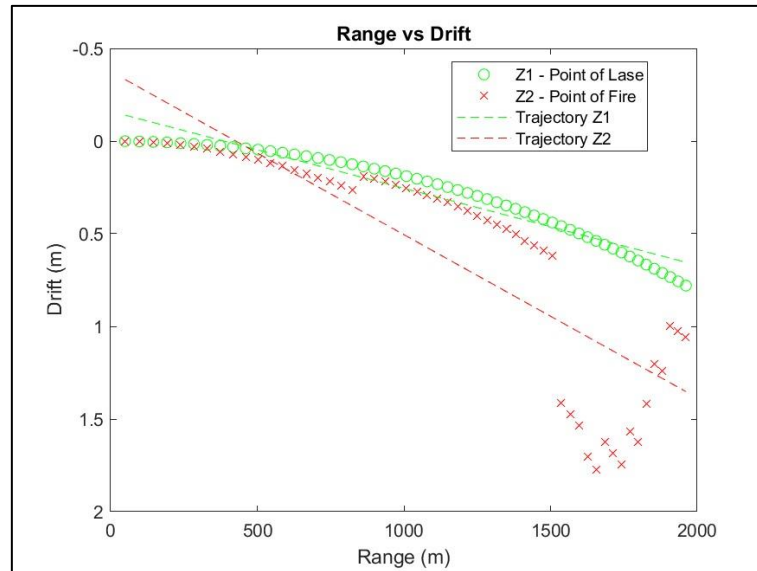


Figure 104 – Data Set 01-D4, Projectile Drift

The projectile data scatters across a large window in the final second of flight [1500-2000 m], is due to the much sharper wind gradient seen at the final second [6 s, yellow] of the sample compared to the rest of the sample [Figure 105]. The sharper curve compared to the more linear curves [4 & 5 s], has been seen on multiple samples, causing scattering of the ballistic results.

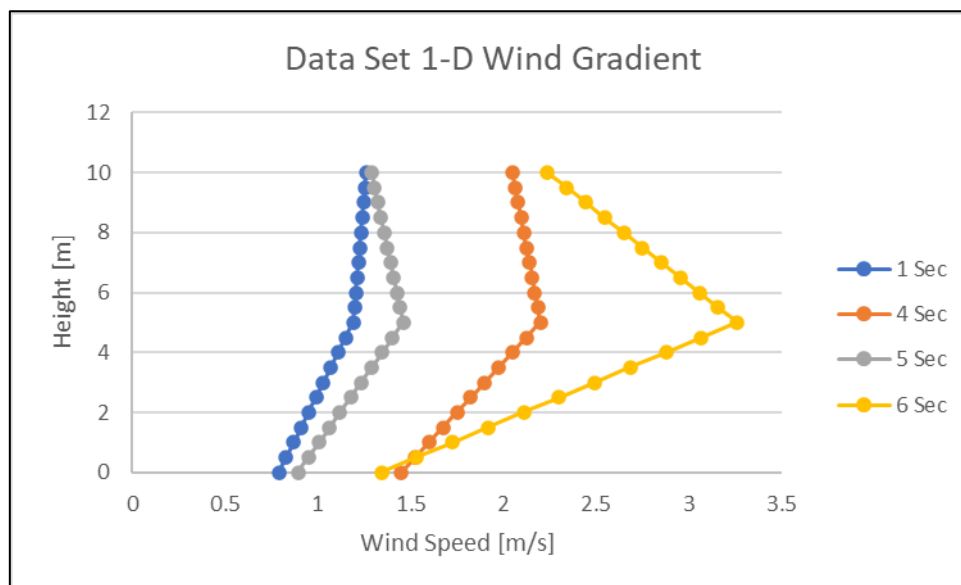


Figure 105 – Data Set 01-D Wind Gradient

The trajectory line of best fit enables a smooth trajectory to be calculated for the purpose of the coincidence conditions, removing the wind gradient scatter effect.

5.3.3 Data Set 06 – Ballistic Results

Data Set 06 ballistic results are shown for set DS06-B and DS06-C as they match with the wind gradients shown in the previous section. The first set of results is from DS06-B, both the 1 s single sensor [B1] and the 4 s prior to firing [B4] conditions will be compared. **[Figure 106]** shows the real wind impact locations compared to the FCC centre mass prediction, the 1 s single sensor condition [red cross], produces an under correction to the left compared to the FCC location. This is compared to an improved real impact point compared to the FCC prediction at the 4 s of -79.99 cm [green cross].

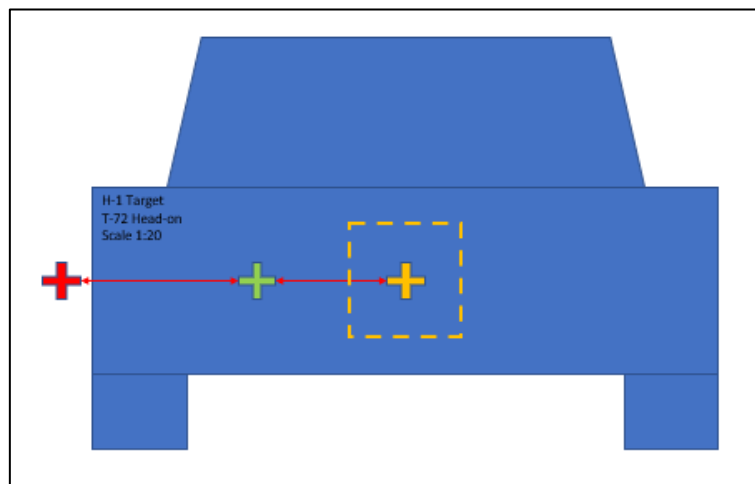


Figure 106 – DS6-B1 (red), Coin = -184.40 cm, DS6-B4 (green), Coin = -79.99 cm

Both real impact points are out of coincidence at -184.40 and -79.99 cm respectively compared to the FCC predictions. This scenario shows that even with a re-calculation prior to firing at the 4 s, the real crosswind experienced in flight would move the impact out of the FCC coincidence window. The re-calculation shows an improvement but would probably cause less damage than a centre mass hit, a M-kill compared to a K-kill.

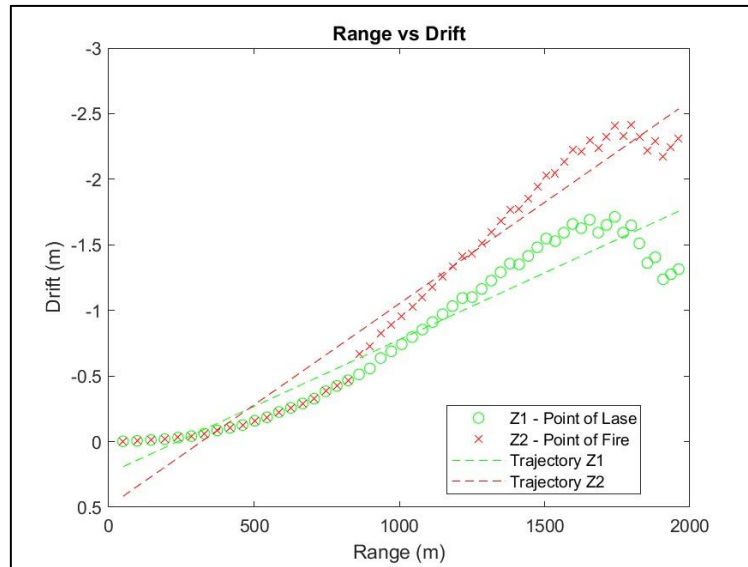


Figure 107 – Data Set 06-B4, Projectile Drift

The ballistic drift graph **[Figure 107]** of the projectile in flight shows a much smoother wind drift calculation compared to sample 01-D4 **[Figure 104]**. The wind gradient from sample DS-06 have a much smoother wind gradient profile **[Figure 86]**, more similar to the statistical normal wind gradient conditions **[Figure 80]**.

DS06-C conditions are different to the previous two samples, but similar to DS06-B the crosswind in flight is moving the projectile offset to the left. The crosswind conditions for this sample are much lower and have caused less of an offset compared to the FCC prediction. The real impact location compared to the 1 s fixed crosswind [red] is still under corrected to the left at -132.07 cm, but the 4 s firing [green] is much closer **[Figure 108]**.

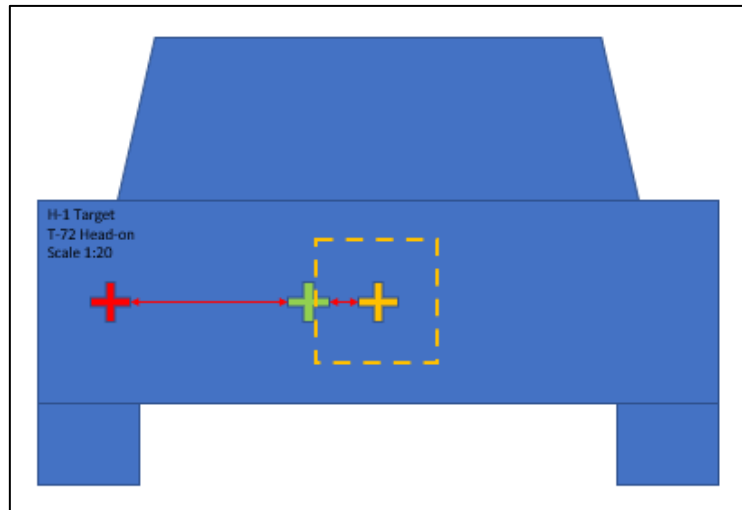


Figure 108 – DS6-C1 (red) -132.07 cm, DS6-C4 (green) -34.59 cm

The calculation at the 4 s prior to firing reduces the drift gap between the FCC and the real impact point, to just outside the coincidence window. The impact is with the top tolerance of 0.30 mrad [60 cm] and just over required tolerance of 0.15 mrad [30 cm] but would still cause a re-calculation as it outside the requirement.

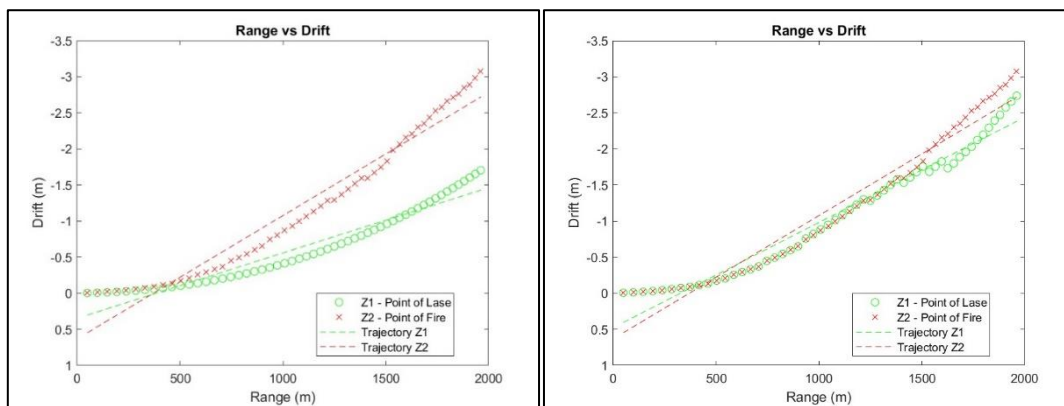


Figure 109 – DS 06-C1 [left] & DS 06-C4 [right], projectile drift comparison.

[Figure 109] shows the MATLAB export of the two projectile profile tests, in the second test for C4 the re-calculation at the 4s maintains a near identical profile between the FCC prediction and the real flight. It is only in the last second of the profile that the two paths diverge, this shows that there is some effect from the downrange crosswind influencing the flight of the projectile.

5.3.4 Data Set 24 – Ballistic Results

Data Set 24 is from the June summer period of wind conditions that was assessed in this thesis. As shown in the meteorological results section the change in time period between April and June has an effect on the ballistics. The ballistic results will be shown for samples DS24-A and DS24-E, the remaining data sets are in the Appendix's.

DS24-A sample has shown the following impact assessment from the crosswind conditions. The first test that was conducted was against the standard single fixed crosswind value for 2.5 m, DS24-A1 showed a predicted FCC drift to real impact point to the left of -123.91 cm **[Figure 110]**.

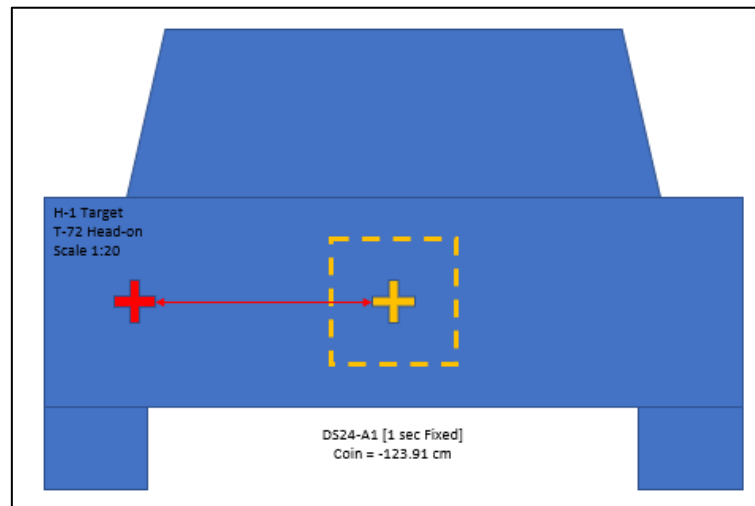


Figure 110 – DS24-A1, Target Hit Result

The downrange crosswind experienced by the projectile has move the impact location outside of the FCC coincidence window by over twice the requirement. A re-calculation at the 4 s in the timeline does reduce the drift between the real impact at the FCC prediction down to -70.47 cm **[Figure 111]**, but still exceeding the maximum coincidence specification.

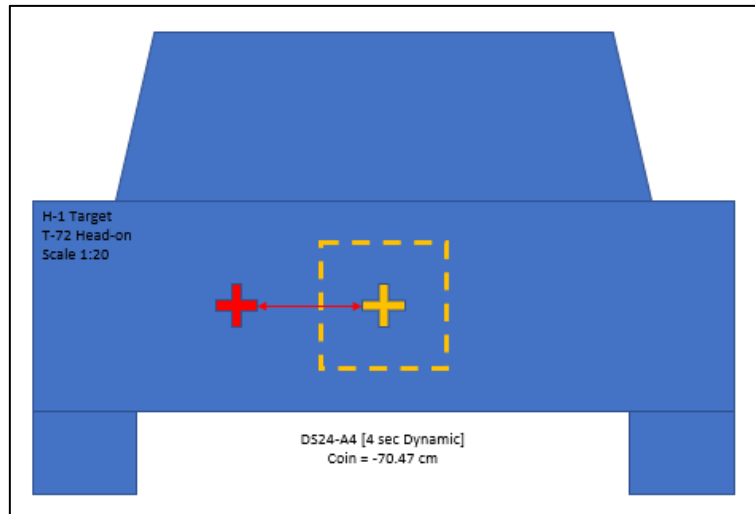


Figure 111 – DS24-A4, Target Hit Result.

Further comparison on this sample was conducted by running another test to compare how a dynamic wind profile compared to a fixed wind profile yields a different result from the FCC. The dynamic wind profile uses the interpolated wind gradient profile for the crosswind measurements, which change in relation to height. The fixed crosswind profile only uses the crosswind value at the 2.5 m mark for all points of the calculation.

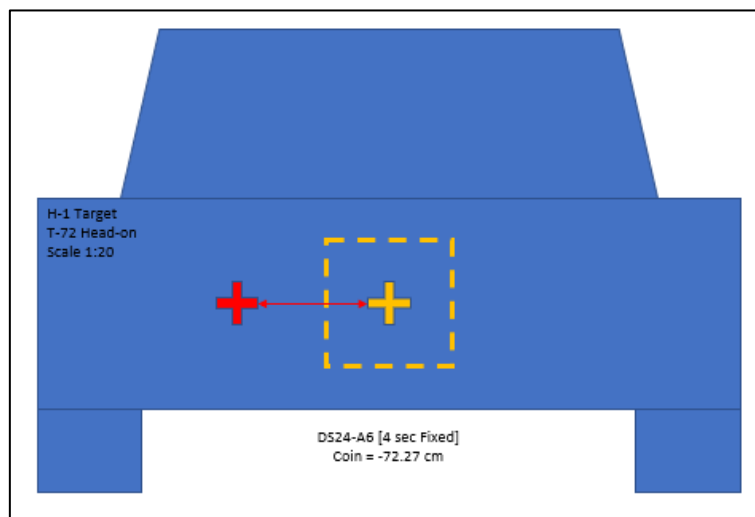


Figure 112 – DS24-A6, Target Hit Result

Comparing the two test results has yielded some interesting results, there is only a minor difference between the two set of impact for the FCC and real impact locations. The dynamic wind profile **[Figure 111]** and fixed wind profile **[Figure**

112] only separate between -70.47 and -72.27 cm respectively. Using a dynamic profile reduces the drift by only ~2 cm in this example, which shows that there is only a small error due to using a single point reference system.

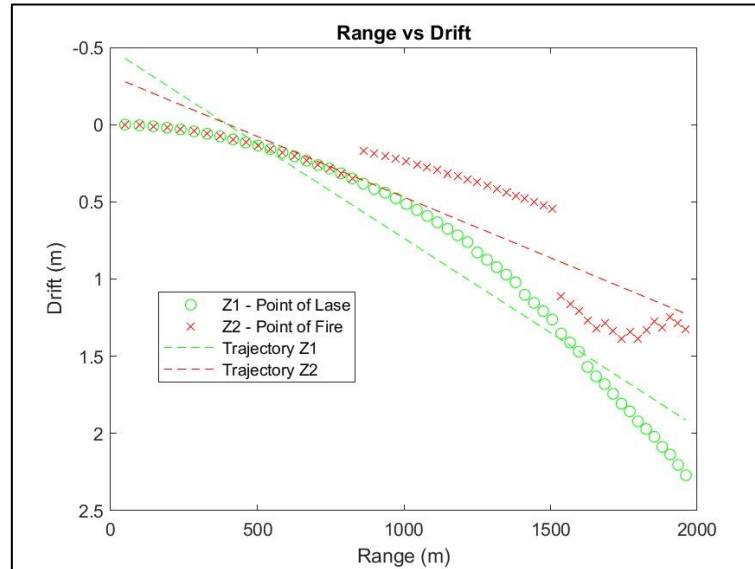


Figure 113 – Data Set 24-A4, Projectile Drift

[Figure 113] show the MATLAB projectile drift for sample DS24-A4, which against shows the split and drift in the dynamic crosswind profile. The dynamic profile which changes every second in the engagement and flight timeline, is variable due to the change in the crosswind speed in relation to the wind gradient **[Figure 88]**. The wind gradient for this profile again has more angled curves to the interpolation compared to the straighter statistical wind profile.

The next sample tested was the DS24-E set, this again was compared between the two main tests of 1 s fixed to 4 s dynamic. The results in this sample show that in both test conditions the real impact compared to the FCC prediction is within the coincidence window. **[Figure 114]** the real impact point is within -2.59 cm of the FCC prediction from the single crosswind reference point.

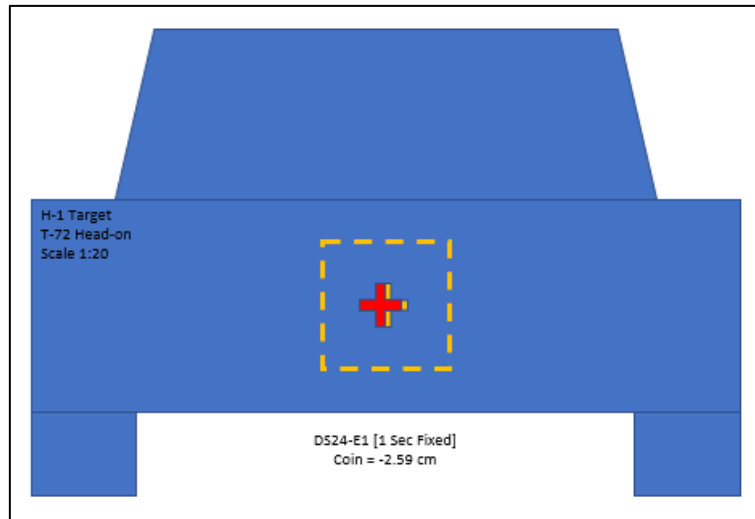


Figure 114 – DS24-E1 Target Hit Result

Compared to the 4 s prior to firing re-calculation test, the FCC prediction from the newer data actual caused a larger drift error to occur. [Figure 115] shows the real impact location compared to the 'second before firing' FCC ballistic estimate. The drift from this test is larger -24.47 cm compared to -2.59 cm using the 1 s crosswind data in the engagement timeline.

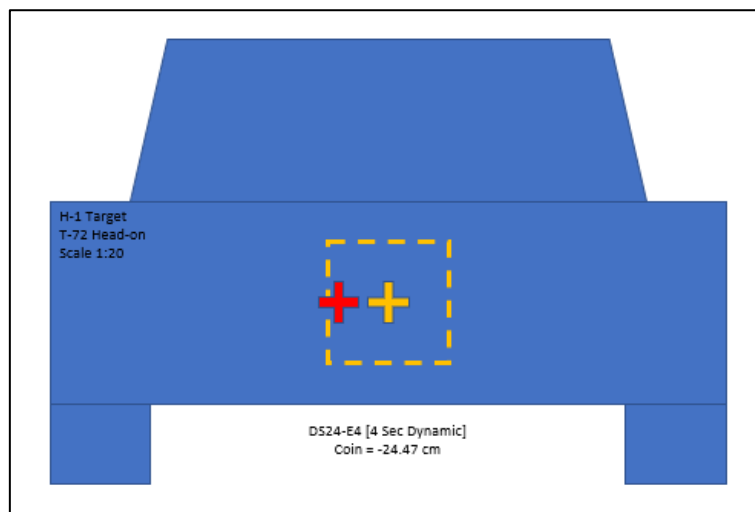


Figure 115 – DS24-E4 Target Hit Result

This set of results shows that there is a good chance that the crosswind maintains a constant profile during the engagement timeline. Both test results are within the required coincidence window of 0.15 mrad [30 cm] and would not cause a stop to the engagement timeline.

5.3.5 Data Set 28 – Ballistic Results

DS28 is also from the June summer wind set of conditions, two sets of samples will be detailed, DS28-E and DS28-A. DS28-E presents some interesting results in that the full test sequence does not produce a result within coincidence. The FCC predictions at each test are still far off the real impact location and producing large overcorrections [Table 21].

Table 21 – DS28-E Ballistic Results

Data Set	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	Coin	Correction
DS28-E	1 Sec Dynamic	-330.77	-239.31	91.45	0.457	Out	over corrected
DS28-E1	1 Sec Fixed	-344.10	-239.31	104.78	0.524	Out	over corrected
DS28-E2	2 Sec Dynamic	-357.20	-239.31	117.88	0.589	Out	over corrected
DS28-E3	3 Sec Dynamic	-325.45	-239.31	86.13	0.431	Out	over corrected
DS28-E4	4 Sec Dynamic	-312.56	-239.31	73.24	0.366	Out	over corrected

The in the summary table above it can be seen that the coincidence error window between FCC and real impact from crosswind in flight is not achieved. The drift error is between 117 and 73 cm for the difference tests conducted, twice the required 30 cm [0.15 mrad] error window. While the result show that the FCC and projectile in flight would be out of coincidence the impact point is still located onto the target face. [Figure 116] shows the impact from test using the fixed 1s crosswind data compared to the 4 s dynamic data [Figure 117].

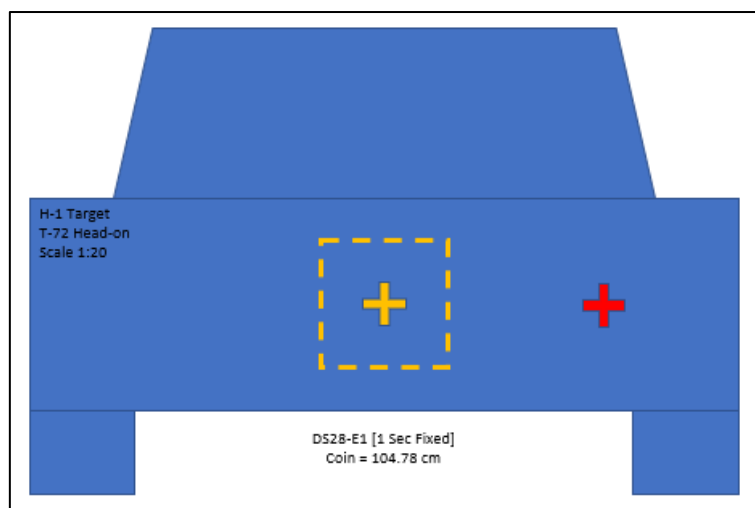


Figure 116 – DS28-E1, Target Hit Result

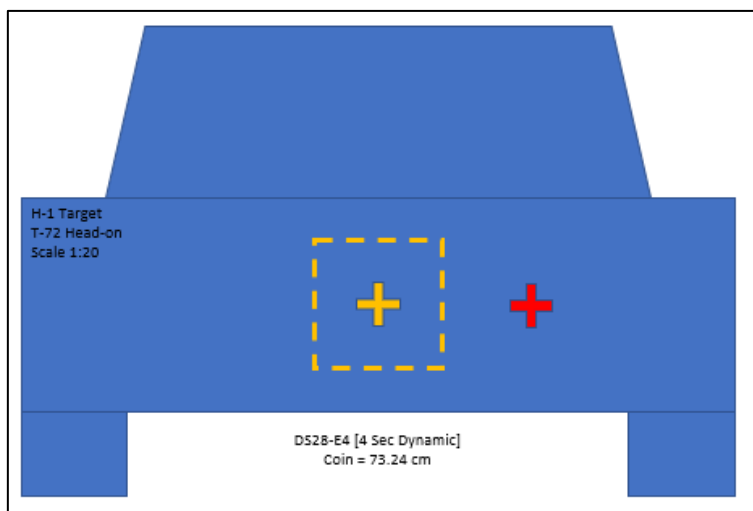


Figure 117 – DS28-E4, Target Hit Result

The initial 1 s FCC prediction to the real impact point drift was at 104.78 cm compared to a drift of 73.24 cm using the 4 s data.

The next sample is DS28-A, this sample set in comparison was able to achieve coincidence in 2 out of the 5 tests. The initial test using the crosswind at the 1 s in the engagement timeline resulted in an out of coincidence result. But using later data closer to the firing window, the 4s in the engagement timeline enabled a coincidence result.

This sample shows that the engagement timeline used by Chieftain and maintaining the FCC ballistic result would have resulted in worse performance of the system [Table 22]. Additionally, the crosswind calculation using the 2 s crosswind data was within the coincidence window compared to the 1 s.

Table 22 – DS28-A Ballistic Results

Data Set	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	Coin	Correction
DS28-A	1 Sec Dynamic	-256.60	-191.67	64.92	0.325	Out	over corrected
DS28-A1	1 Sec Fixed	-274.73	-191.67	83.05	0.415	Out	over corrected
DS28-A2	2 Sec Dynamic	-204.10	-191.67	12.42	0.062	In	over corrected
DS28-A3	3 Sec Dynamic	-246.56	-191.67	54.88	0.274	Out	over corrected
DS28-A4	4 Sec Dynamic	-210.74	-191.67	19.06	0.095	In	over corrected

The crosswind data closer to the point of firing achieved improved results compared to the crosswind drift exposed to in flight. [Figure 118] shows the initial

FCC prediction compared to real impact location for DS28-A1, with a coincidence of 83.05 cm.

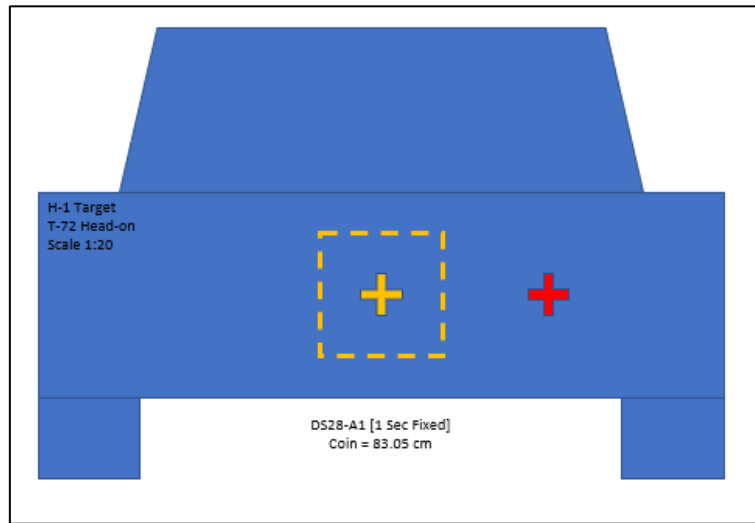


Figure 118 – DS28-A1, Target Hit Result

DS28-A4 achieved a coincidence between FCC prediction and real impact point of 19.06 cm **[Figure 119]** which is within the coincidence window. The result from test DS28-A2 using the crosswind at the 2 s resulted in further improvement of a coincidence down to 12.42 cm.

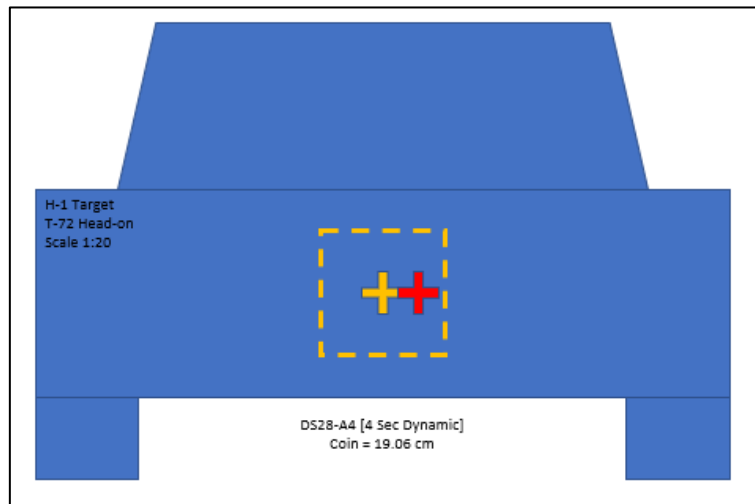


Figure 119 – DS28-A4, Target Hit Result

5.3.6 Data Set 48 – Ballistic Results

Data set 48 and 50 are both from the December collected set of meteorological wind data. The winter weather has again provide a different overall set of conditions and profiles as shown in the previous section. The result for sample DS48-D and DS48-E will be shown in this section, with the remain results in the appendix. The summary of all the ballistic results for DS48-D are shown in **[Table 23]**, this table details all the tests that were conducted.

Table 23 – DS48-D Ballistic Results

Data Set	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	Coin	Correction
DS48-D	1 Sec Dynamic	-143.73	-223.73	-80.00	-0.400	Out	under corrected
DS48-D1	1 Sec Fixed	-129.44	-223.73	-94.29	-0.471	Out	under corrected
DS48-D2	2 Sec Dynamic	-144.14	-223.73	-79.59	-0.398	Out	under corrected
DS48-D3	3 Sec Dynamic	-182.58	-223.73	-41.15	-0.206	Out	under corrected
DS48-D4	4 Sec Dynamic	-212.87	-223.73	-10.86	-0.054	In	under corrected
DS48-D5	4 Sec Fixed	-171.50	-223.73	-52.23	-0.261	Out	under corrected
DS48-D6	3 Sec Fixed	-204.76	-223.73	-18.97	-0.095	In	under corrected

From the test results for the sample, it can be seen that again the initial crosswind data at the 1st in the engagement timeline yield an out of coincidence result. The coincidence is only achieved using data later in the engagement timeline. **[Figure 120]** displays the target hit results for DS48-D1, between the FCC prediction and the real impact point. The FCC to real impact achieved a coincidence drift of - 94.29 cm outside of coincidence.

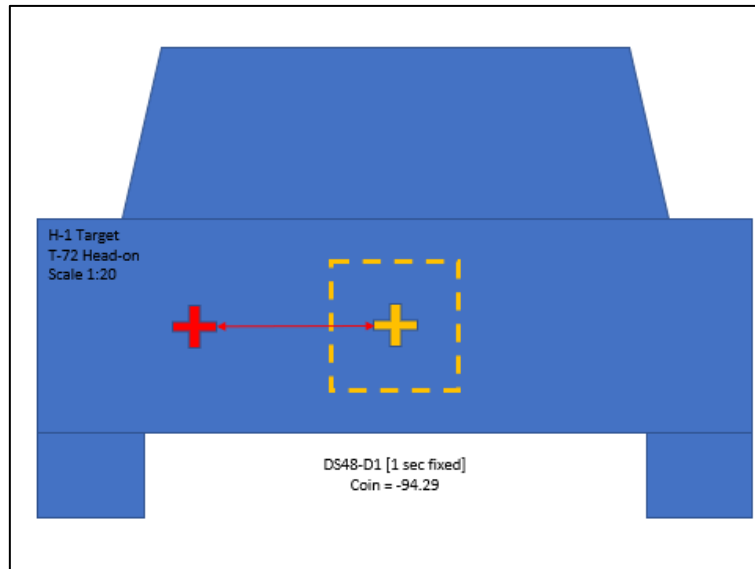


Figure 120 – DS48-D1, Target Hit Result

Comparing to a re-calculation at the 4 s prior **[Figure 121]** to firing for test DS48-D6, a fixed crosswind data set achieved an FCC to real impact drift of -18.97 cm, within coincidence.

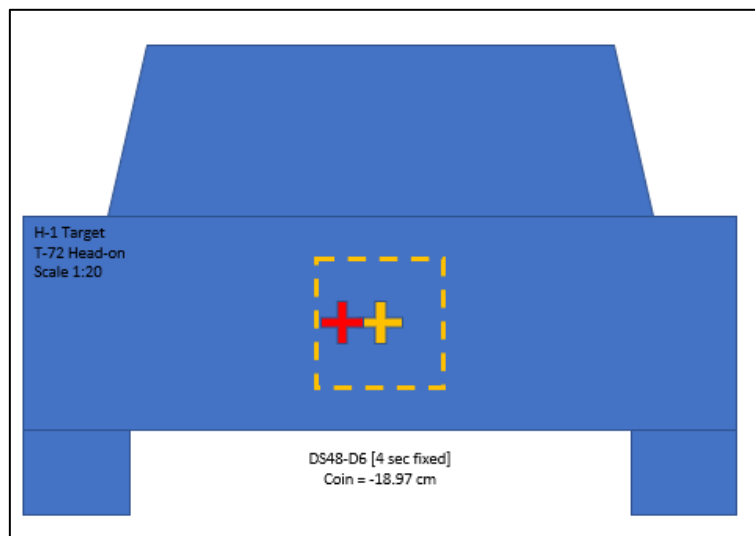


Figure 121 – DS48-D6, Target Hit Result

Further assessment of the difference in the engagement timeline can be found by assessing multiple points in the timeline. Comparing the initial laser and FCC calculation at the 1 s to recalculations at the 3 s and 4 s in the timeline. These

two points are interesting as they represent the -1 s to firing and the instant of firing [4 s] in the timeline **[Table 24]**.

Table 24 – Vehicle Sensor Fixed wind comparison.

Test	Predicted Drift at point of lased [cm]	Drift at second Fired [4s] [cm]	Coin [mrad]
1sec - Fixed 2.5m crosswind, [DS48-D1]	-129.44 	-223.73 	-0.47
3sec – Fixed 2.5m crosswind, [DS48-D5]	-171.50 	-223.73 	-0.26
4sec – Fixed 2.5m crosswind, [DS48-D6]	-204.76 	-223.73 	-0.09

Comparing each of the predicted FCC impact marks, the yellow cross, to each of the impacts from the crosswind effected flight of the projectile **[Figure 122]**. The drift from the gustiness and crosswind in flight not being corrected for by the FCC moves the impact markers to the left of the centre.

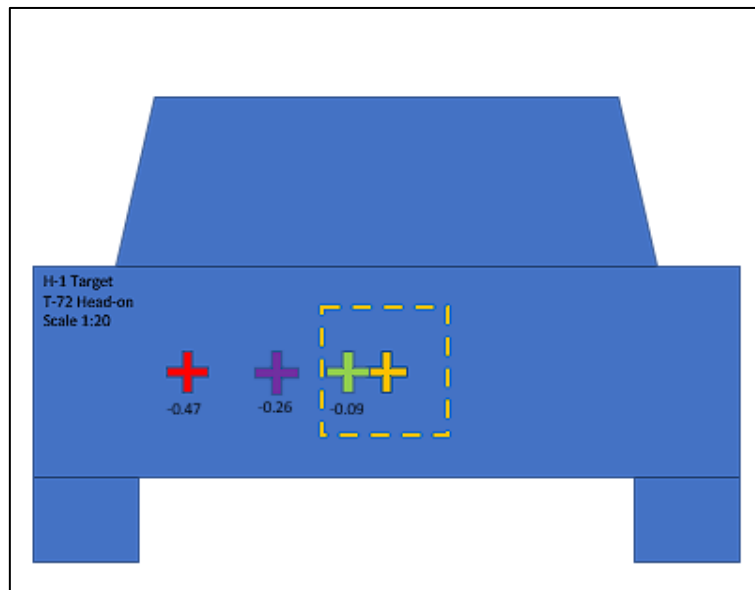


Figure 122 – Comparing the three fixed wind impacts

Only the re-calculation by a modern FCC at the instant prior to firing, the 4 s, would enable the FCC to achieve a coincidence shot. The remaining shots falling outside of the coincidence requirement window. All the shots would impact the reference target face of the H-1 T-72 target but would cause different degrees of damage.

The next sample set is the DS48-E set, with tests of the 1 s fixed and 4 s dynamic crosswind results being shown. The sample shows that using the initial crosswind and holding the ballistic result until firing would not produce a coincidence hit results [Figure 123].

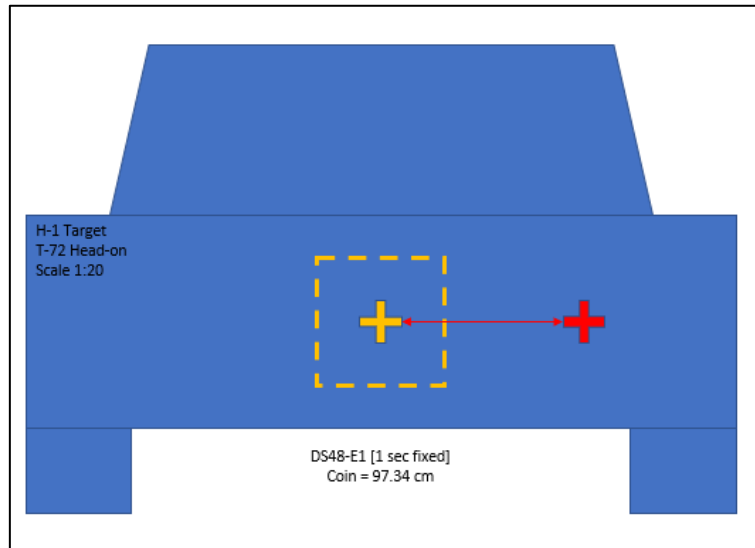


Figure 123 – DS48-E1 Target Hit Result

In this sample the coincidence results are not achieved until using the instant of firing crosswind data at the 4 s in the timeline [Table 25]. Even the 3 s mark crosswind data, does not achieve a coincidence results, which is normal seen in other samples.

Table 25 – DS48-E Ballistic Results

Data Set	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	Coin	Correction
DS48-E	1 Sec Dynamic	-341.25	-244.02	97.23	0.486	Out	over corrected
DS48-E1	1 Sec Fixed	-341.37	-244.02	97.34	0.487	Out	over corrected
DS48-E2	2 Sec Dynamic	-317.86	-244.02	73.83	0.369	Out	over corrected
DS48-E3	3 Sec Dynamic	-325.55	-244.02	81.52	0.408	Out	over corrected
DS48-E4	4 Sec Dynamic	-255.72	-244.02	11.70	0.059	In	over corrected

The meteorological data for this sample does have a rogue instance in the wind gradient data [Figure 93]. The wind gradient at the 6 s is a very different shape to the remainder of the instances in the timeline, which could be the cause to the drift values being very different. The coincidence is then only achieved using the data closes to the time of flight [Figure 124].

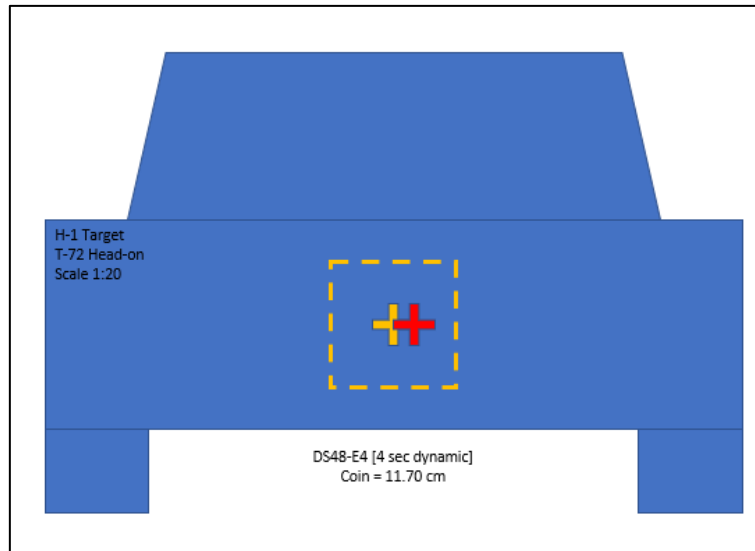


Figure 124 – DS48-E4 Target Hit Result

5.3.7 Data Set 50 – Ballistic Results

The final data set to be detailed in Data Set 50, showing sample sets B and E. Sample DS50-B of the data set shows a very relative normal wind gradient pattern **[Figure 94]**, compared to some of the other samples. The wind gradient is a smooth slope similar to the statistical normal wind gradient patterns.

Table 26 – DS50-B Ballistic Results

Data Set	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	Coin	Correction
DS50-B	1 Sec Dynamic	-254.60	-254.13	0.45	0.002	In	over corrected
DS50-B1	1 Sec Fixed	-234.65	-254.15	-19.49	-0.097	In	under corrected
DS50-B2	2 Sec Dynamic	-274.58	-254.15	20.43	0.102	In	over corrected
DS50-B3	3 Sec Dynamic	-330.31	-254.15	76.16	0.381	Out	over corrected
DS50-B4	4 Sec Dynamic	-300.52	-254.15	46.37	0.232	Out	over corrected

The ballistic results for DS50-B shows the reverse of what is normally seen with the initial crosswind producing the coincidence results and the later timeline points drift outside of the window **[Table 26]**. The initial FCC prediction using the crosswind at the 1 s in the timeline achieving the best set of coincidence error results **[Figure 125]**.

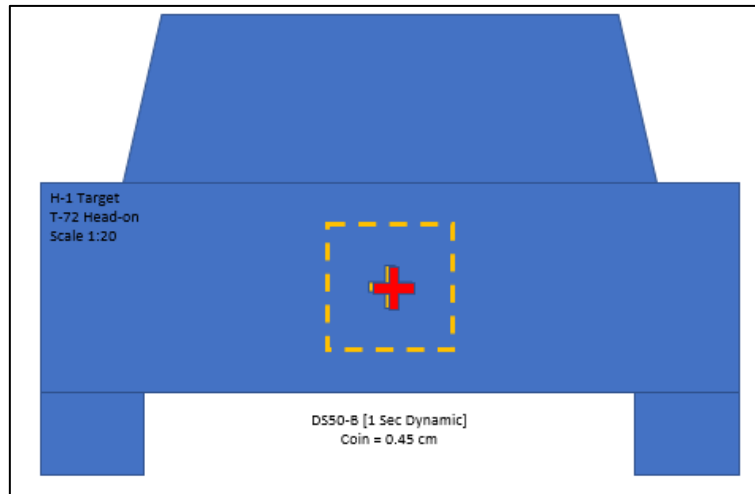


Figure 125 – DS50-B Target Hit Result

Using the dynamic crosswind data on the 1 s achieves a coincidence drift of 0.45 cm [0.002 mrad] one of the smallest errors. But in comparison to other samples the fixed crosswind results in a larger window between the fixed and dynamic crosswind calculations. The 1 s fixed crosswind the drift is -19.49 cm, compared to the dynamic at 0.45 cm **[Figure 126]**.

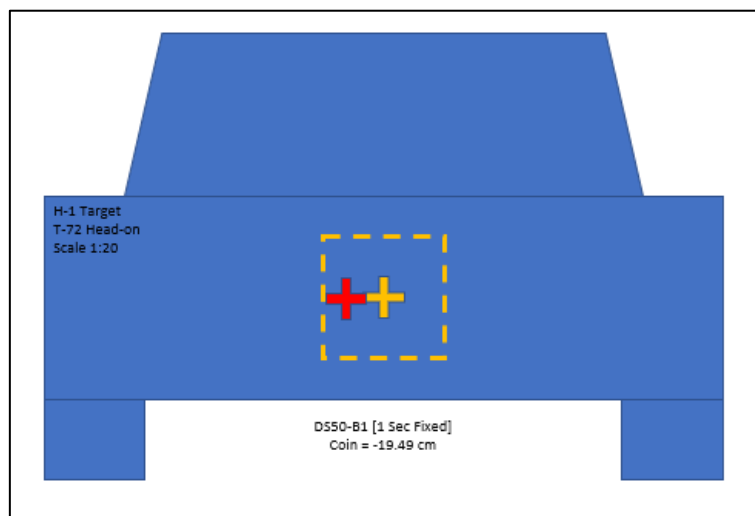


Figure 126 – DS50-B1 Target Hit Result

The drift direction also changes from a right drift to a left drift between the FCC prediction and the real impact mark **[Figure 127]**.

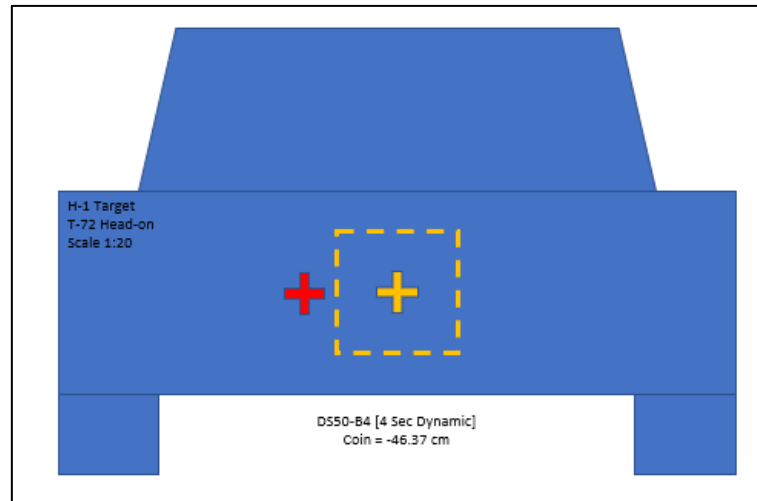


Figure 127 – DS50-B4 Target Hit Result

[Figure 127] shows the coincidence drift between the FCC prediction and real impact for using the 4s crosswind value.

The final Data Set to be discussed is DS50-E, this data set had the most tests conducted on the sample set. The data set initially presented that all the test sets would produce an out of coincidence result [Table 27]. But the 4 s result only producing an inside of coincidence result.

Table 27 – DS50-E Ballistic Results

Data Set	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	Coin	Correction
DS50-E	1 Sec Dynamic	-26.77	-99.84	-73.57	-0.368	Out	under corrected
DS50-E1	1 Sec Fixed	-22.34	-99.84	-77.50	-0.388	Out	under corrected
DS50-E2	4 Sec Dynamic	-90.59	-99.84	-9.25	-0.046	In	under corrected
DS50-E3	4 Sec Fixed	-77.23	-99.84	-22.61	-0.113	In	under corrected
DS50-E4	All Fixed (2.5 m)	-22.34	-98.97	-76.62	-0.383	Out	under corrected
DS50-E5	2 Sec Dynamic	29.22	-99.84	-129.07	-0.645	Out	under corrected
DS50-E6	3 Sec Dynamic	51.71	-99.84	-151.56	-0.758	Out	under corrected
DS50-E8	2 Sec Fixed	24.37	-99.84	-124.22	-0.621	Out	under corrected
DS50-E9	3 Sec Fixed	43.99	-99.84	-143.84	-0.719	Out	under corrected

Test set E7 was removed as this was a repeat of test E3, both the fixed and dynamic crosswind samples were tested to understand if this would influence the results. The crosswind profile for this sample influenced the resulting ballistic testing due to the dynamic profile of the wind gradient [Figure 95].

The crosswind profile in this sample change in all three variable conditions, speed, direction, and wind gradient slope **[Figure 96]**. The resulting ballistic projectile drift from the crosswind produced large scattering of the data points and separation between the intervals in the timeline **[Figure 128]**.

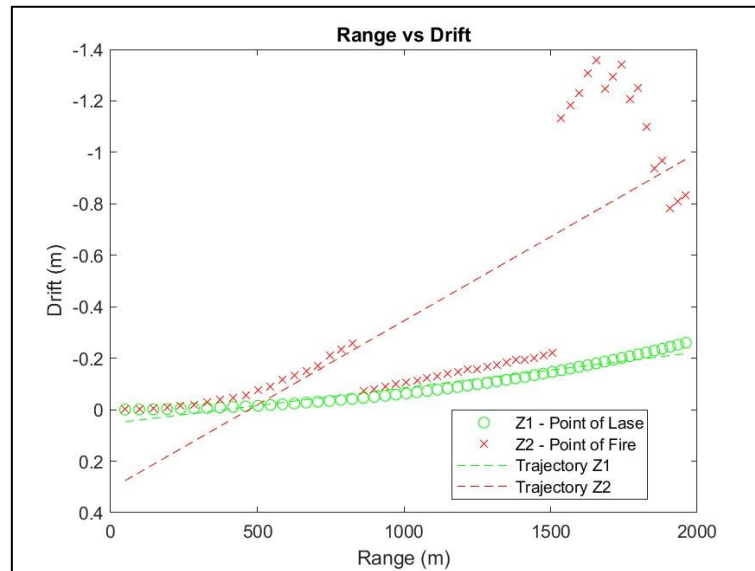


Figure 128 – DS50-E1, Projectile drift results

For the initial 1 s crosswind FCC prediction produces a steady result [green], compared to the dynamic crosswind experience during the flight [red]. This results in a large drift between the two results and out of coincidence hit result for the projectile **[Figure 129]**.

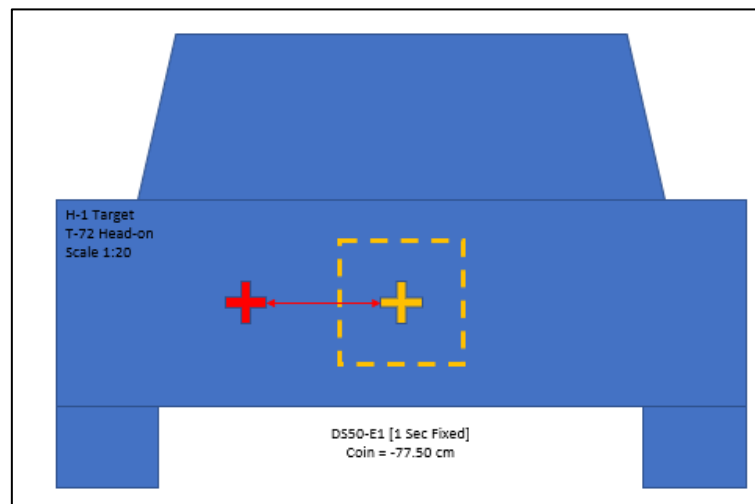


Figure 129 – DS50-E1, Target Hit Results

In comparison when using the crosswind data at the 4 s in the timeline, it produces a more in line result with the in flight data **[Figure 130]**. This sample produces a within coincidence hit result between the FCC prediction and the real flight of the projectile **[Figure 131]**.

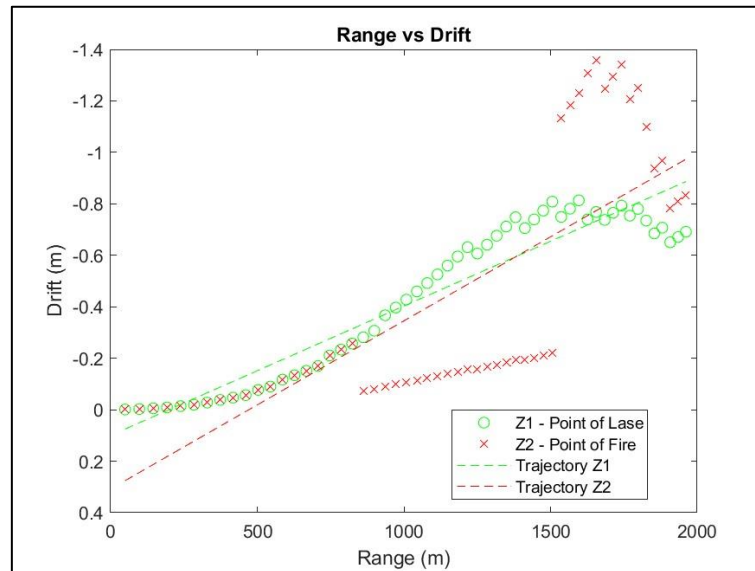


Figure 130 – DS50-E2, Projectile Drift Results

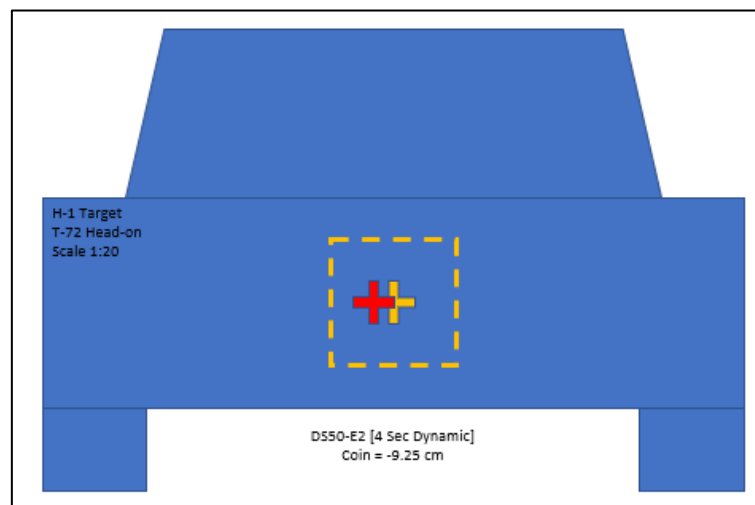


Figure 131 – DS50-E2, Target Hit Results

It can be seen in **[Figure 130]**, that the predicted result matches the line of best fit to the real flight crosswind data [green]. The scattering of the inflight crosswind drift is nullified by using the 4s data that is the closes to the inflight period of the timeline.

The last example set for DS50 is test sample set E9, which examined the crosswind at the 3 s in the timeline. The crosswind in at this point in the sample was occurring from the opposite direction using a fixed reference position of 90 degree to the line of flight. Due to this factor the FCC predicted ballistic calculation is pushed further away from the real impact **[Figure 132]**.

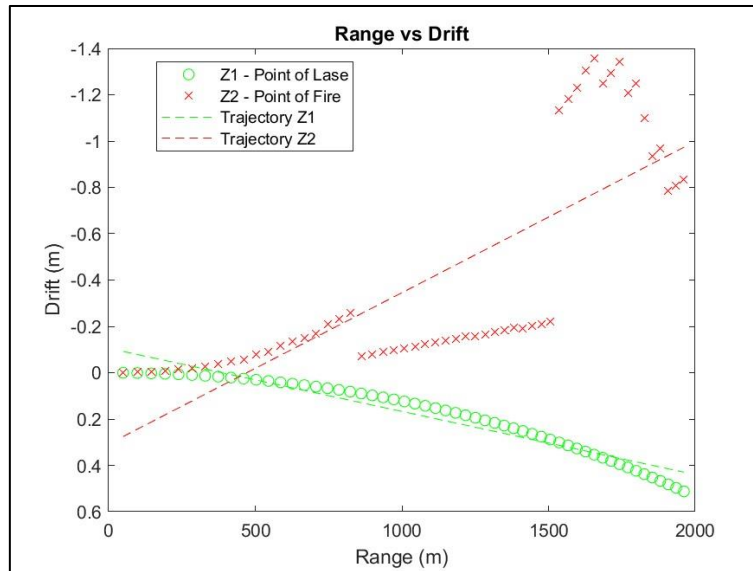


Figure 132 – DS50-E9, Projectile Drift Results

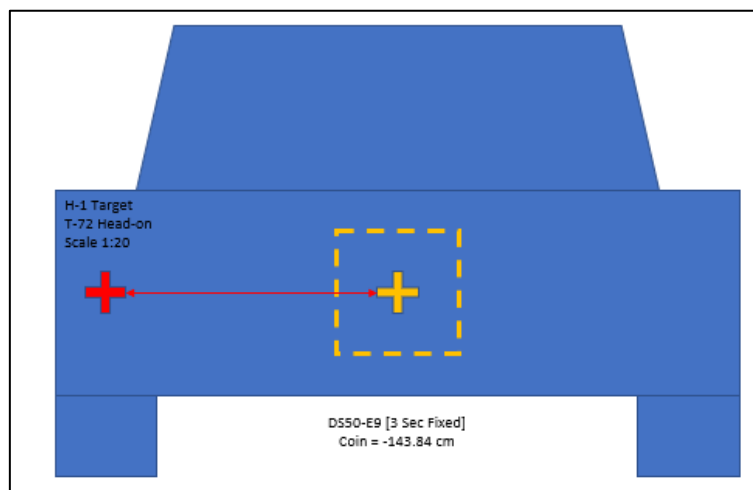


Figure 133 – DS50-E9, Target Hit Results

The real meteorological wind in this scenario switch across left and right side of the true North compass point. Reducing the wind condition specific to the pure crosswind and headwind values caused this massive change in the ballistics

results. Using a more dynamic crosswind angle calculator that the rigid set used in this thesis would enable a finer profile to be extracted.

5.3.8 Summary

Assessing the ballistic results in summary, the correction by the FCC from the inputted crosswind value, does not consider the full impact of the crosswind drift on the projectile. Despite the FCC correction for the crosswind drift, the gustiness change in the wind between the calculation and the projectile impact will move the impact outside of the coincidence window.

The time that the FCC holds onto the ballistic correction will add error into the overall hit probability Error Budget. The older the crosswind value used in the FCC ballistic correction prior to firing the higher the drift and lower hit probability.

The inflight crosswind which is not included in the FCC calculation also has an effect on the hit probability likelihood. Not taking this change in the crosswind profile risks added further error into the system. Similarly, the wind gradient changes in the height of the crosswind velocity in relation to projectile high above ground has an effect. The projectile sees further crosswind drift influence from dramatic, non-linear wind gradient transitions.

Chapter 6 Discussion

6.1 Introduction

This chapter will detail the discussion of the overall themes shown across the results and data output produced in the assessment of the ballistic model. The discussion is separated into two sections, the first looking at the themes across the meteorological wind data and the second section detailing the ballistic assessment.

The focus of the discussion will be centred around the results output compared against the four research questions proposed in the introduction.

1. Do varying crosswind conditions affect the 40CTAS projectile drift in flight to a target?
2. Does the time delay in an FCS engagement timeline (Chieftain FC) affect the coincidence window?
3. Can the varying crosswind conditions move projectile impact point outside of the NATO 0.3 mrad error window, reference to centre target mass?
4. Can the FC system conditions be improved to support an improved crosswind assumption for the ballistic solution?

6.2 Meteorological Crosswind Analysis

6.2.1 Crosswind Results vs Statistical Normal

As described in the Literature Review [Chapter 2], there are three statistical normal crosswind conditions that have been previously used during mathematical analysis. Generally the main statical normal crosswind speed condition used is the 10 mph [4.47 m/s] as described in the works by both (McCoy, 2012; Litz, 2015). The military institutes of A.R.D.E and U.S Army Aberdeen Test Center are known to use this condition in their experiments.

A.R.D.E did propose a new statistical reference set of wind conditions in the 1960's from research conducted on Northern European wind conditions (Armament Research and Development Establishment (A.R.D.E), 1967). A.R.D.E research proposed two new conditions sets of 1.49 & 1.82 m/s crosswind

speed to be used from the overall average conditions. These new conditions were proposed as the MBT in the 60's was going to fight on the cold war front in Germany. A.R.D.E proposal was to condition and design FCS to work off this as their main baseline.

Due to the cold war front in Germany never becoming a hot conflict, the research along with integrating the A.R.D.E conditions set was dropped. The development of FCS's using an improved meteorological systems in later MBT Chieftain and Challenger 1 platforms (Dunstan and Sarson, 1998), resulted in the statistical input being no longer needed.

Comparing the statistical references to the meteorological wind data sets used in this thesis shows some interesting themes. The meteorological wind data was collected from Reading University (Reading University, 2020), based in the southern part of the United Kingdom [UK]. Both the UK and Northern Europe are along the same latitude of 50-60 degrees north, which enable a good comparison between the statistical wind conditions.

The wind data sets for the period of the six seconds were collected together to produce an average crosswind result which was compared to the three statistical normal values [Table 28]. The sets were compared to see if the average crosswind speed value would be within +/- 10% or +/- 20% of the static normal reference wind speed or declared out of specification. The +/- side of the statistical result is related only to the direction of the crosswind, i.e., '+' is left to right, when looking from the gun towards the target.

Table 28 – Daily Wind Sample vs Statistical Normal sets

	Reference Targets		
	10 mph [4.47 m/s]	A.R.D.E Ref 1 1.49 m/s	A.R.D.E Ref 2 1.82 m/s
Within			
in +/-10%	5	16	16
in +/-20%	6	16	17
Out	139	118	117
Total	150	150	150

Of the 150 data sets tested from the initial raw data collected for this thesis, the majority of the average crosswind samples were out of specification compared to

the statical normal examples. For the 10 mph [4.47 m/s] sample, only a total of 11 data sets were within +/- 20% of this target value. This shows that the statistical crosswind conditions are largely out of reality compared to real wind data experienced in the field.

In comparison, the A.R.D.E statical Northern European Wind reference values of 1.49 & 1.82 m/s fared much better to the Reading University wind samples. Both reference sets have a total of 32 and 33 sample respectively, to be within the +/- 20% tolerance. This shows that the A.R.D.E reference crosswind speed were a better statical value to be used compared to the 10 mph reference.

In further comparison between the Reading data and the A.R.D.E reference set from Northern Europe, the Reading data produced a comparative average low of 1.52 m/s and high of 1.88 m/s crosswind speed. The Reading data was taken from three points in the year April, June, and December, which across the data sets shows changes in the seasonal wind conditions.

Data sets 1-10 were from April 2022, Data sets 21-30 in June 2022 and Data Sets 41-50 in December 2021. **[Table 29]** shows the statistical minimum, median, average, and maximum in the crosswind speed for the sample sets.

Table 29 – Data Sets crosswind speed statistics

Stats	Data Sets [m/s]		
	1 to 10	21 to 30	41 to 50
Minimum	0.00	0.00	0.04
Median	1.52	1.44	1.57
Average	1.87	1.52	1.88
Maximum	6.89	4.52	5.28

Comparing the average values to the A.R.D.E reference recommendation from there report of 1.49 and 1.82 m/s, the average wind speed seen across the full data range is within the same range. The June 2022 [21-30], reported the lowest average at 1.52 m/s and December 2021 [51-50] reporting the highest average of 1.88 m/s in crosswind speed.

The median crosswind values present a much lower range in speed compared to the A.R.D.E reference of 1.44 to 1.57 m/s. The range reducing by -0.05 and -0.25 m/s respectively for the low and high ends. The maximum average crosswind speed in the data sets was 6.89 m/s [15.41 mph] showing that the crosswind can far out exceed the A.R.D.E reference values.

The fact that the A.R.D.E. reference values are reached with the Reading Data shows the value of both the A.R.D.E. research and the data produced in this thesis. The A.R.D.E. team was working to the principle that an inputted statical crosswind value would be a good base to their FCS, as a meteorological sensor was not being used.

The real wind data that was collected in this thesis, has a similar statistical set of results to the tests conducted by A.R.D.E and other agencies. This support the validity of the data used and shows that the initial assumptions for crosswind are valid. The real crosswind data still hold variations that the statistical assumptions cannot reproduce, focusing on the dynamics of real wind.

6.2.2 Wind Gradient

The wind gradient sample produced from the meteorological wind data produced some interesting themes across the Reading University wind data, compared to the statical normal values. **[Figure 134]** shows the wind gradient produced by the statical normal crosswind speed when interpolated across the ballistic reference height of 0 to 10 m.

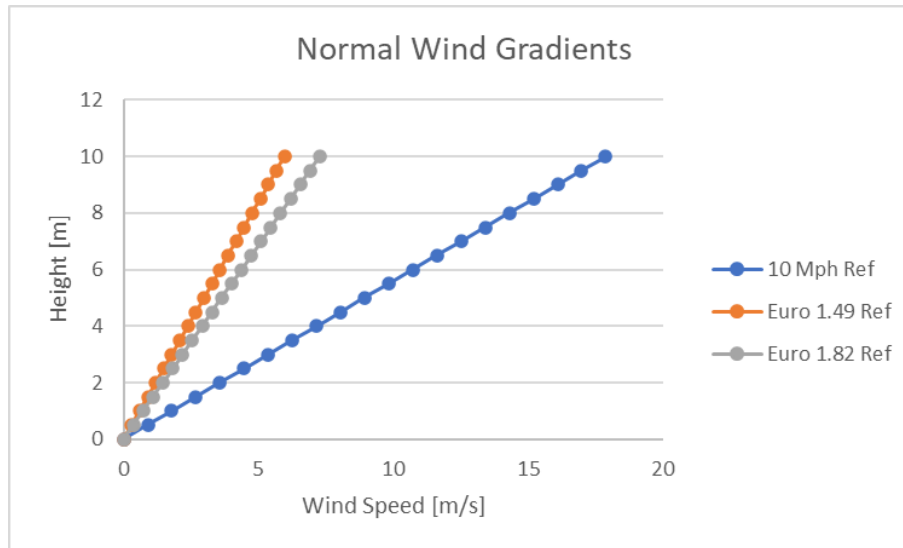


Figure 134 – Normal Wind Gradients

The normal wind gradient was produced from a single data point at the 2.5 m mark, in reference to the normal MBT meteorological sensor height. The wind gradient for each of the Reading University Data Sets were produced from three references. These references were at 2, 5 and 10 m, have the three reference points give an improved interpolation across the remaining points.

Majority of the Data Set samples from Reading did not produce a smooth and straight wind gradient line as shown in **[Figure 134]** and produce more jagged 'z' in shape **[Figure 135]**.

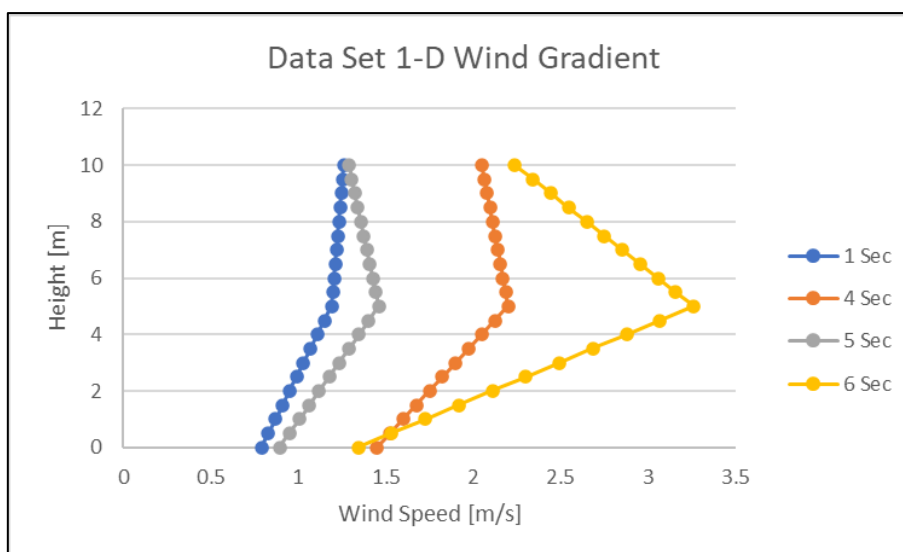


Figure 135 – Data Set 01-D Wind Gradient

The wind gradient samples across all the Data Sets, show these jagged results of the wind speed changing at the 5 m point. This can be seen in both Data Set 01 [Figure 135] and 28 [Figure 136] which come from two different points in the year.

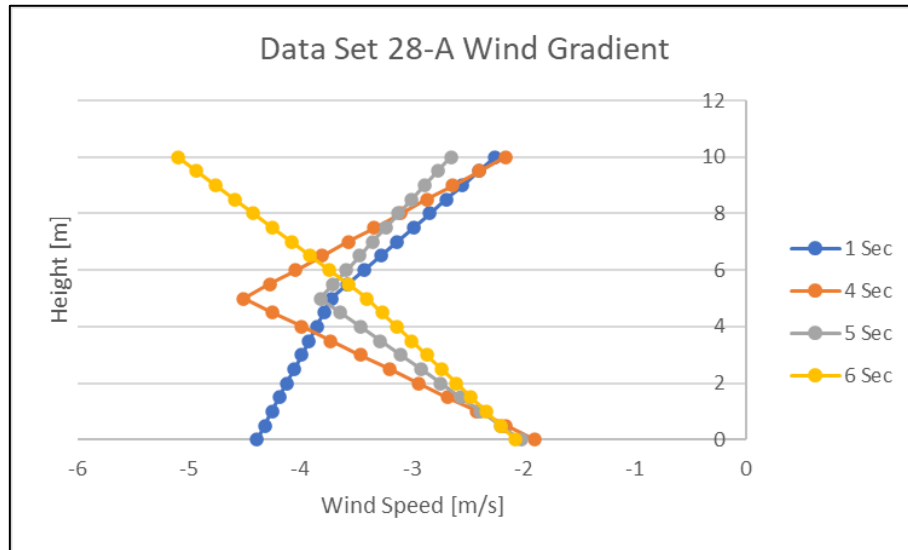


Figure 136 – Data Set 28-A Wind Gradient

This change in the wind gradient direction and shape at the 5 m mark, which matches with one of the sensor locations on the meteorological mast could be the defined reason, but this is unknown. Overall, the wind gradients in the samples do produce a steady wind gradient that increase in wind speed compared to height.

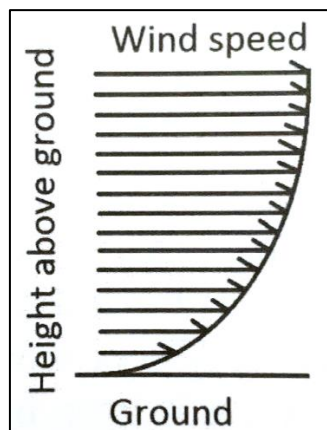


Figure 137 - Wind Gradient (Litz, 2015)

This matches with the information on the wind gradient effects discussed in the Literature Review **[Figure 137]**. The wind gradient profile is affected by local environment factors in the form of trees and buildings (Litz, 2015). Changes in the samples at the 5 m sensor, could be influenced by these conditions interacting with the wind velocity at that level.

In reality, MBT meteorological sensor will be affected by clutter around the sensor. This could be equipment on the vehicle interfering with the path of the wind to the sensor, or local terrain features causing turbulence in the wind. The crosswind gradient would also be affected along the line of fire, between the firing point and the target point from terrain factors.

6.3 Ballistic Analysis

6.3.1 Central themes

The output of the ballistic results produced several central themes around the overall ballistics data outputted from the Point Mass Model, comparing a vehicle Fire Control Computer (FCC) prediction based on the assumed vehicle constant crosswind data to the dynamic crosswind model for the projectile flight **[Figure 138]**. Comparing the two projectile impact positions, initially from the FCC predicted crosswind drift to the inflight crosswind drift, shows any changes in crosswind variation [gustiness] that leads to coincidence error.

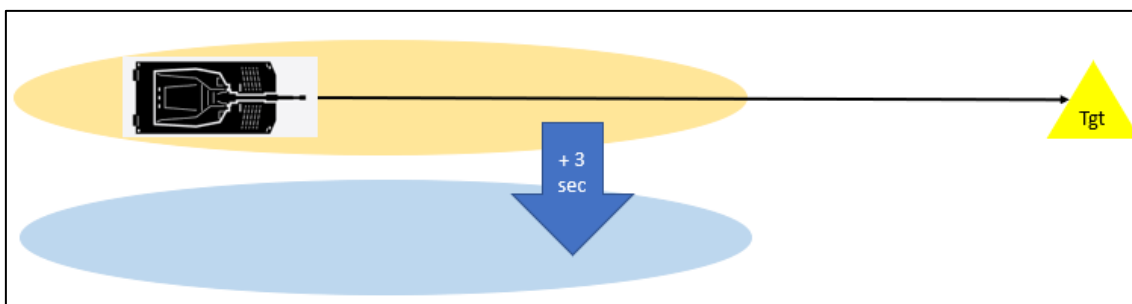


Figure 138 – Crosswind offset against the Firing line.

The FCC prediction using the Point Mass Model, calculates a correction to the azimuth split between the left and right directions **[Table 30]**. The data matches

with the split between the Data Set samples in the direction of the crosswind applied to the model.

Table 30 – FCC Calculation Over or Under Corrected

FCC Correction	Tests	%
Over Corrected	172	47.25%
Under Corrected	192	52.75%
Total	364	

Further examination of the direction split of FCC and projectile drift against the crosswind shows that, the FCC prediction has a 95% chance of achieving the correct drift direction to offset the shot between the real impact point and the fall of shot [Table 31].

Table 31 – On and Off Shot Drift Direction to Target

FCC Correction	Tests	%
On Drift	344	95%
Off Drift	20	5%
Total	364	

In 5% of the cases the FCC predicted a projectile drift direction was counter [off drift] to that of the real crosswind experienced in flight, with the results being a breach of the coincidence window. There is a low probability the direction of the crosswind will change during the projectile flight and the engagement window. The FCC will only need to make calculation for changes in the crosswind speed, not the direction of the crosswind, the crosswind direction can be assumed to be a constant, with speed changes being the main variable.

Assessing the coincidence window across the test data produces several key themes. For all 364 tests and shots analysed through the Point Mass Model there was a ~50% split between the FCC and projectile drift being within 0.15 mrad coincidence requirement [Table 32].

Table 32 – Hits within 0.15 mrad Coincidence

0.15 mrad	Tests	%
In Coincidence	181	49.73%
Out Coincidence	183	50.27%
Total	364	

This shows that there is a 50.27% chance that the FCC will be using an invalid ballistic solution to engage the target and exceed the coincidence error window of 0.15 mrad. This error caused by changing the environmental factor of the crosswind is much larger than the 15% error predicted from Brassey's example error budget **[Table 3]** (Terry *et al.*, 1991). However the overall error budget in **[Table 3]** is scaled along with the effect of the other conditions in the error budget.

A closer comparison can be seen when comparing the data to the more detailed environmental error budget **[Table 7]** (Terry *et al.*, 1991), comparing the individual environmental factors. The error percentage of 50.27%, is closer to the detailed environmental error budget, which detailed a 'Crosswind at Tank' causing an error of 50% **[Table 7]**. This shows that the ballistic model matches the example environmental error budget design presented in previous works into FCC and vehicle design.

Comparing the test shots, to the maximum coincidence range of 0.30 mrad, which applies the coincidence window in a single point to point split compared to +/- 0.15 mrad box. The following split between in and out of coincidence is produced for a single directional drift **[Table 33]**.

Table 33 – Hits within 0.30 mrad Coincidence

0.30 mrad	Tests	%
In Coincidence	263	72.25%
Out Coincidence	101	27.75%
Total	364	

At total of 72.25% of the test shots were inside the maximum coincidence window, compared to the 49% seen when looking at the requirement level of 0.15 mrad. The maximum tolerance level if used at a single directional drift would enable a further 23% of hit chances to maintain coincidence.

The remaining 27% of shots falling outside of the coincidence would be influenced by the change in crosswind between the vehicle position to the target. The example error budget **[Table 7]** taken from Brassey's Fighting Vehicle book (Terry *et al.*, 1991), details downrange gusts influence 20% of the error budget.

The model results are indicative of the book example error budget with a 27% error due to gustiness.

Expanding Table 32 and 33, into the unique test sets that were conducted against each of the meteorological data sets, different trends start to appear. Each test case detailed in [Table 20] compared a different point in the engagement timeline to the reference flight period of 4 s to 6 s. The two highlight critical tests were 1 s fixed constant crosswind and 4 s dynamic crosswind test cases [Table 34].

The table compares the **IN** and **OUT** of coincidence against the 0.15 mrad NATO coincidence window (US Army Aberdeen Test Center, 2009b) around the centre vehicle aiming mark [Figure 52].

Table 34 – Coincidence Window Hit Probability [0.15 mrad]

Tests			In		Out	
Dynamic wind response	1 s Dynamic	150	79	52.67%	71	47.33%
Current Fire Control	1 s Fixed	73	33	45.21%	40	54.79%
-2 s delay test	2 s Dynamic	30	14	46.67%	16	53.33%
Fixed wind response	2 s Fixed	1	0	0.00%	1	100.00%
-1 s delay test	3 s Dynamic	30	12	40.00%	18	60.00%
Fixed wind response	3 s Fixed	3	1	33.33%	2	66.67%
Coincidence FC	4 s Dynamic	73	41	56.16%	32	43.84%
Fixed wind response	4 s Fixed	3	1	33.33%	2	66.67%
Fixed wind response	All Fixed (2.5 m)	1	0	0.00%	1	100.00%
Total		364				

Comparing the individual test sets against the coincidence requirement, shows that using early crosswind value and holding a ballistic solution reduces the possibility of maintaining the coincidence window. The lowest possibility of achieving coincidence is using the crosswind data from that is -1 s prior to firing at the 3 s mark in the engagement timeline, with a 40% success rate.

The best possibility of achieving the coincidence window is at the 4 s mark, with a success rate of 56.16%, inside the coincidence window. The Chieftain IFCS process using the crosswind data at the 1 s mark, achieved a IN coincidence success rate of 45.21%, for the fixed constant crosswind data.

Table 35 – Key Timeline Points Hit Probability [0.15 mrad]

Tests		In		Out	
1 s Dynamic	150	79	52.67%	71	47.33%
1 s Fixed	73	33	45.21%	40	54.79%
2 s Dynamic	30	14	46.67%	16	53.33%
3 s Dynamic	30	12	40.00%	18	60.00%
4 s Dynamic	73	41	56.16%	32	43.84%

The difference between the 1 s and 4 s ballistic solutions is an improvement of 10.95% in probability of maintaining a coincidence solution **[Table 35]**. Using crosswind data that is as close to the firing window as possible will improve the overall chance of hitting a target on the first attempt.

The data also shows that the gustiness and dynamic movement of crosswind in the ballistic solution has a large effect on the accuracy of a weapon system. Gustiness and downrange meteorological crosswind are required to be factored into an improved ballistic solution.

6.3.2 Statistical Hit Coincidence

The data was assessed to understand if the statistical average fixed crosswind solutions as proposed by A.R.D.E (Armament Research and Development Establishment (A.R.D.E), 1967) would achieve a preferred result. The A.R.D.E Northern European average crosswind condition of 1.82 m/s was compared to newer averages produced by the meteorological data from the data sets **[Table 29]**. The new reference value of 1.88 m/s was used as the average from the data sets used in this thesis.

The performance of a statistical reference for crosswind exposed to the vehicle was compared to the A.R.D.E value, and the new average from the data, whilst comparing to the current performance **[Table 36]**.

Table 36 – Coincidence Performance

Test Sets			In		Out	
Tests	1s Fixed	73	33	45.21%	40	54.79%
	4s Dynamic	73	41	56.16%	32	43.84%
New Av [1.88 m/s]	1s Fixed	73	15	20.55%	58	79.45%
	4s Dynamic	73	16	21.92%	58	78.08%
A.R.D.E [1.82 m/s]	1s Fixed	73	19	26.03%	54	73.97%
	4s Dynamic	73	19	26.03%	54	73.97%

The data shows the active meteorological station achieves the highest coincidence hits percentage compared to the two statistical average crosswind values. Both the statistical crosswind values only achieve 20% and 26% for the new and A.R.D.E references respectively. Interestingly the A.R.D.E. Northern European crosswind had a higher inside coincidence hit rate than the average of the data sets used in the thesis.

This shows that having a live meteorological crosswind sensor is important factor in the ballistic solution. This sensor is a key factor in both the vehicle design and the function of the FCS and should not be replaced by an averaged solution in the FCC ballistic calculation.

6.3.3 Time delay [Chieftain MBT Model]

Assessing the engagement timeline model used by Chieftain IFCS [Figure 139] and modern MBT's, several factors can be seen from the resulting analysis. The engagement timeline length influences the resulting accuracy of the ballistic solution generated by the FCC. The FCC holding onto a ballistic solution across the engagement timeline adds further errors into the overall error budget and hit performance.

						
Title	Target – Left SABOT	ON	Tracking	Aim off Injection	Ready to Fire	Target
Timeline	- 6.5 Sec	0 sec	+ 0.2 sec	+ 2.2 sec	+ 3.2 sec	+6.2 sec
Gunner action	Target Sighted and tracked	MBS centred on Target	Gnr, Fires Laser	Checks results	Gunner, fires gun once ellipse corrects.	
Fire Control System (FCS)			Ballistic Aim Mark projected (ellipse), Ballistic correction calculated	Ballistic correction applied, ellipse moves with correction aim-off results	Gun and sights re-locate to inside the ellipse window	
Met Data			Wind data collected			
Lase			Fired, distance reported			

Figure 139 – Chieftain MBT Engagement Timeline

The six second engagement timeline does not leave a long period of time for an error to generate into the systems performance. But the constant changing meteorological crosswind conditions will induce a drift into the ballistic solution accuracy. The accuracy of the FCS can be improved and reduce the resulting error from the crosswind conditions by taking the gustiness and dynamic nature of the crosswind conditions into account.

The Chieftain IFCS engagement timeline can be improved by conducting an additional ballistic calculation prior to firing of the weapon system. Modern MBTs with advanced FCS conduct this check when the firing trigger is pressed. The FCS induces a millisecond delay into the system to conduct a re-calculation of the ballistic solution and compare it against the coincidence window (Taylor, 2018).

Modern FCS as part of the coincidence check prior to firing of the system, will not allow a target to be engaged until coincidence has been achieved. In relation to the findings [Table 36], 54.79% of 1 s and 43.84% 4 s FCS predictions would fail this test. Depending on the design of the safety checks in the FCS, the firing of the system would be inhibited until a coincidence result is achieved.

In a combat scenario having half your engagement be either delayed or not initiated due to the FCS trying to achieve a coincidence result could be problematic.

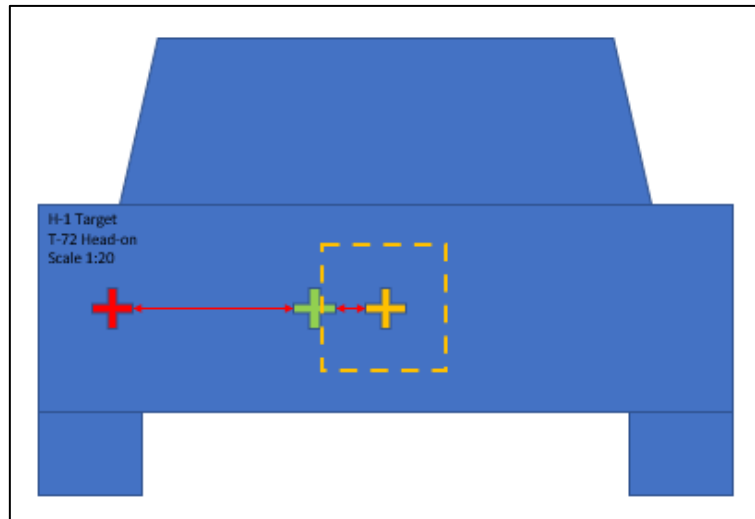


Figure 140 – 1s (red), 4s (green) Hit Difference

As demonstrated by the Point Mass Model **[Figure 140]** and assessment in this thesis a re-calculation prior to firing of the weapon system has a 10.95% increase in the performance. This increase in the accuracy of the ballistic solution would increase the overall performance of the weapons system in a combat scenario.

Increasing the Hit Performance of the system would increase the probability of achieving a critical kill [K-Kill], compared to a Mobility kill in relation to a vehicle target. The coincidence window at of ± 30 cm [± 0.15 mrad] (US Army Aberdeen Test Center, 2009b), as a range of 2 km, whilst small in relation to the overall vehicle size is still important.

The importance of this size factor is useful when considering new defensive systems being installed on modern vehicles. Modern combat vehicles are fitted with Explosive Reactive Armour [ERA] or Active Protection Systems [APS], which provide additional protection to vehicle. A projectile impact point moving outside of the coincidence window of 30 cm would make a difference when engaging these types of systems **[Figure 141]**.

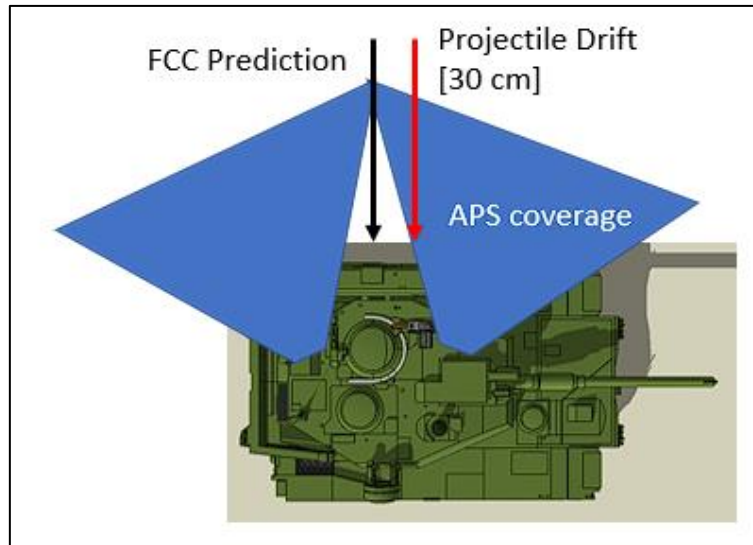


Figure 141 – Example of Vehicle APS vs Meteorological Wind Drift Error

(Dedoimedo, 2011)

The small change in the impact point would change the effectiveness of the APS or ERA system in responding to the threat. Not all APS and ERA system provide a full 360 degree coverage, so there is the possibility of the projectile finding the sweet spot in the coverage gap. The unaccounted for crosswind drift in the FCS ballistic solution would then shift the projectile impact point away from this spot.

Comparing vehicle tactical and FCS system design between the 1980's when coincidence firing was first introduced, to modern scenarios the unaccounted for gustiness and crosswind play a factor in the critical hit performance. An FCS without this coincidence check would lose out on a performance increase of 10.95% in their chances of a successful engagement.

Chapter 7 Conclusion

7.1 Final comments

In final comments for this thesis, the key objectives will be assessed against the research and analysis conducted.

1. Do varying crosswind conditions affect the 40CTAS projectile drift in flight to a target?

The meteorological crosswind conditions collected show that varying crosswind conditions affect the flight of the 40CTAS projectile. The effect of both the wind gradient and time delay in crosswind conditions have demonstrated an impact to the flight of the projectile. Taking only a single fixed crosswind reading to calculate a ballistic solution, adds a disadvantage into the overall system performance. The gustiness of the crosswind between the firing point and target should be considered to reduce the ballistic error.

Additionally, wind characteristics should be considered in the ballistic equations, as the crosswind influence varies due to both height and crosswind velocity. The wind gradient samples showed a non-linear shape compared to the statistical normal wind values used in mathematical approaches. The wind gradient changes have a turbulent effect on the projectile flight in reality, which is not consider if only recording off a single sensor position.

2. Does the time delay in an FCS engagement timeline (Chieftain FC) affect the coincidence window?

The length of the engagement timeline and the length of time that an FCS ballistic solution is held by the system can result in additional error being included. Conducting a coincidence firing check prior to the projectile being fired will increase the probability of hit by 10.95% compared to a held solution. As the crosswind values have changed over the delayed period in the engagement timeline the crosswind correction is invalid compared to the crosswind drift that will be experienced by the projectile.

3. Can the varying crosswind conditions move the projectile impact point outside of the NATO 0.3 mrad error window, reference to centre target mass?

Varying crosswind conditions will influence the flight of a projectile and will have the capability to shift a projectile flight outside of the NATO standard error window. For the reference target and range of 2 km, the 0.3 mrad error box centred on the target will be exceeded by the uncorrected crosswind. The held 1 s crosswind data will exceed the coincidence window 54.79%, but a corrected 4 s calculation will only exceed 43.84%. Taking closer measurement to the point of firing in the engagement timeline improves the likelihood of impacting the target within the NATO coincidence window. Taking the gustiness and changes in the crosswind conditions will enable for an increase in performance and chances to maintain coincidence in an FCS.

The Point Mass Model was updated to incorporate the new crosswind data from both a single sensor and a multiple wind sensor model. The multiple sensor crosswind data included interpolation of the wind conditions across the full flight height profile of the projectile in flight, which is not normally considered.

4. Can the FCS conditions be improved to support an improved crosswind assumption for the ballistic solution?

The study shows that an FCS needs to include the effects of crosswind drift into the ballistic solution to achieve a high probability of hit. All crosswind variables need to be factored into the FCS not just crosswind at the tank or vehicle as currently practised. Gustiness and the dynamics effects of crosswind in the height, range and time domain need to be considered in future FCS. Not considering the dynamic changing factors of wind will add further errors into the FCS hit probability and reduce hit performance.

There are a number of capability enhancements that can be considered and integrated into a modern FCS to enable improved crosswind ballistic calculations. Updating of legacy FCS to include coincidence firing checks, would improve the hit performance and accuracy by 10.95% compared to holding a ballistic solution.

New sensor and reference solutions to improve the crosswind sensing and data collection should be considered. A LIDAR based sensor (Bar-Tal, Tsadka and Azoulay, 1998) installed into the vehicle would enable downrange crosswind to be captured and analysed. Additional data collected from other vehicles or remote drones (ADIT - The Bulletin, 2019) could enhance the overall local meteorological picture to increase the reliability and crosswind readings.

7.2 Summary

In conclusion, this research project's hypothesis was to understand the effect meteorological crosswind has on a medium calibre projectile, when assessed in relation to the NATO coincidence window. The NATO coincidence (US Army Aberdeen Test Center, 2009b) requirement states that a system should be able to maintain a coincidence error window of 0.3 mrad. This thesis found that the crosswind collected by a vehicle and inputted into the FCC will have a 45.21% chance of correctly producing a NATO coincidence accuracy result.

The projectile hit probability in relation to the NATO coincidence window can be increased by 10.95% to 56.16% by using a crosswind value in the millisecond prior to firing in the engagement timeline. The later point in the engagement removes the errors generated by using an out of data crosswind value to calculate the ballistic solution.

The increase performance in the ballistic solution is required when considering modern vehicle are fitted with APS, which increase the protection levels. Reducing the drift effects of the medium calibre projectile would increase its hit probability and accuracy of the system. Future weapon systems should consider improved crosswind data inputs to reduce the error due to crosswind drift.

Real wind data was successfully extracted and modelled to show the wind gradient effects caused by changes in velocity and height. These crosswind factors were incorporated into the ballistic model and demonstrates that multiple crosswind sensors can be included into the calculation process. A multiple sensor wind source can be interpolated across both height and time to inform the wind

gradient profile and overall wind drift on the projectile flight path. This approach could be used to inform the ballistic model in downrange wind drift due gustiness.

7.3 Future Considerations

Further analysis in this subject area would need to consider the following possibilities.

1. Modelling the changes in crosswind conditions in relation to a modern FCS or a 6DOF ballistic model could be considered. Integrating the crosswind model into the higher order 6DOF ballistic model would improve the accuracy and precision in relation to the Point Mass Model.
2. UGS/UAS sensor system could be considered as an offboard solution to collecting meteorological crosswind data to be used to calculate the FCS ballistic solution. Integrating offboard crosswind sensors into an FCS design could enable local environmental picture to be produced. Additionally other vehicles in a squadron could be used as the offboard sensor, by sharing data across a squadron [Figure 142].



Figure 142 – Multiple fleet example sensor layout

3. Improving the onboard sensor is another consideration to investigate, using a different sensor compared to the traditional meteorological sensor could aid in crosswind collection. The LIDAR sensor (Bar-Tal, Tsadka and Azoulay, 1998) being developed would enable a vehicle based sensor to collected downrange crosswind data, that could be integrated into a vehicle FCS.

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APPENDICES

Appendix A Projectile Information



Figure A-1 - CT40 TP-T Technical Sheet (CTA International, 2018a)

Appendix B MATLAB Trajectory Code

Title - Model A - Point Mass Wind

Version = Model A Version 06

Author = Daniel Knight, daniel.knight@cranfield.ac.uk

MSc by Research

Date = 28 August 2022

Units = Metric

```
% Pre setup
close all % close all previous figures
clear % clear previous data
clc % clear command window
tic % Programme timer start
```

1. Starting Conditions

```
MV = 1000; % Muzzle Velocity (m/s) 1000
Cal = 40; % calibre (mm) 40
M_rd = 0.98; % Mass (kg) 0.98
DC = 0.40; % Drag Coefficient 0.4
Ele_d = 0.9; % angle of elevation (deg)
Air = 1.23; % air density (kg/m^3)
Ele_r = Ele_d*pi/180; % angle of elevation (rads)
CS_rd = (pi*(Cal/1000)^2)/4; % Cross sectional area (m^2)
g = 9.81; % gravity 9.81 m/s
```

2. Initial Math Conditions

```
Disp_x = 0;
Disp_y = 0;
Vx = MV*cos(Ele_r); % start velocity x axis
Vy = MV*sin(Ele_r); % start velocity y axis
```

3. Table Settings

```
% Table 1 - Wind Input Table

sz1 = [0 5];

vartypes1 = {'double','double','double','double','double'}; % variable
settings

varnames1 = {'WH','W_R1','W_R4','W_R5','W_R6'}; % variable name, column
headers

data1 =
table('Size',sz1,'VariableTypes',vartypes1,'VariableNames',varnames1); %
table set up

% Table 2 - Ballistic Table 1

sz2 = [0 12];

vartypes2 =
{'double','double','double','double','double','double','double','double',
'double','double','double','double'}; % variable settings

varnames2 =
{'time','Vel','angle','Drag','Fx','Fz','Acc_x','Acc_y','Vel_x','Vel_y','D
is_x','Dis_y'}; % variable name, column headers

data2 =
table('Size',sz2,'VariableTypes',vartypes2,'VariableNames',varnames2); %
table set up

% Table 3 - Ballistic Table 2

sz3 = [0 7]; % table size

vartypes3 =
{'double','double','double','double','double','double','double'}; %
variable settings

varnames3 =
{'Time_sec','Range_m','Hieght_m','Wind_1_m/s','Drift_Lase_m','Wind_2_m/s'
,'Drift_Fire_m'};% variable names, column titles

data3 =
table('Size',sz3,'VariableTypes',vartypes3,'VariableNames',varnames3); %
table set up

% Table 4 - Wind Data Table

sz4 = [0 8]; % table size
```

```

vartypes4 =
{'double','double','double','double','double','double','double','double'}
; % variable settings

varnames4 =
{'Wind_1','CWDF1','CWD1','Disz1','Wind_2','CWDF2','CWD2','Disz2'}; %
variable names

data4 =
table('Size',sz4,'VariableTypes',vartypes4,'VariableNames',varnames4); %
table set up

% Table 5 - Variables Saving

sz5 = [0 16]; % table size

vartypes5 =
{'double','double','double','double','double','double','double','double',
'double','double','double','double','double','double','double'};
% variable settings

varnames5 =
{'Muzzle_Vel','Calibre_rd','Mass_rd','Cross_Sec_Area_rd','Drag_Coef','Ele
v_deg','Elev_rad','Air','grav','Hit_L1','Hit_L2','Hit_L','Hit_F1','Hit_F2
','Hit_F','Coin'}; % variable names

data5 =
table('Size',sz5,'VariableTypes',vartypes5,'VariableNames',varnames5); %
table set up

```

4. Wind Settings Input

```

% Wind Input Arguments

Height_Ref = [2 5 10]; % Wind Sensor Heights

Wind_R1 = [-1.15 -1.60 -1.98]; % Wind at +1 Sec (lase)

Wind_R4 = [-1.15 -1.60 -1.98]; % Wind at +4 Sec (Fire)

Wind_R5 = [-1.31 -1.77 -2.62]; % Wind at +5 Sec (Fire +1 Sec)

Wind_R6 = [-1.28 -1.28 -2.18]; % Wind at +6 Sec (Fire +2 Sec)

% Calculating Frozen Wind Turbulance

xq = 0:0.5:10; % Interploation new Height range

wq1 = interp1(Height_Ref,Wind_R1,xq,'linear','extrap');
wq4 = interp1(Height_Ref,Wind_R4,xq,'linear','extrap');
wq5 = interp1(Height_Ref,Wind_R5,xq,'linear','extrap');
wq6 = interp1(Height_Ref,Wind_R6,xq,'linear','extrap');

```

```
% Re-shaping outputs
WH = reshape(xq,[21,1]);
W_R1 = reshape(wq1,[21,1]);
W_R4 = reshape(wq4,[21,1]);
W_R5 = reshape(wq5,[21,1]);
W_R6 = reshape(wq6,[21,1]);

% Wind data into a table
data1 = table(WH,W_R1,W_R4,W_R5,W_R6);
```

5. Trajectory calculations

```
for t = 0.05:0.05:3.00

    Vel_r = sqrt(Vx^2+Vy^2); % calculate the velocity magatude
    F_ag = atan(Vy/Vx); % calculate the angle of flight
    Dg_F = 0.5*Air*Vel_r^2*CS_rd*DC; % calculate the drag force
    Fx = -Dg_F*cos(F_ag); % force in x axis
    Fy = -Dg_F*sin(F_ag)-M_rd*g; % force in y axis
    Accx = Fx/M_rd; % acceleration in x axis
    Accy = Fy/M_rd; % acceleration in y axis
    Vx = Vx+Accx*0.05; % velocity in x axis
    Vy = Vy+Accy*0.05; % velocity in y axis
    Disp_x = Disp_x+0.5*(Vx+Vx)*0.05; % displacement in x axis range
    Disp_y = Disp_y+0.5*(Vy+Vy)*0.05; % displacement in y axis hieght
```

6. Cross wind velocity(m/s) - reference postions

Inputing a Negative Wind Value '-' is for a Right to Left drift across the firing line whilst facing the Target. (I.e. Target is "South", an West to East Cross Wind is '-' input)

Inputing a Positive Wind Value '+' if for a Left to Right drift across the firing line whilst facing the Target. (I.e. Target is "South", and East to West Cross Wind is '+' input)

```
if t > 0.00 && t < 1.00

    if Disp_y > -1 && Disp_y < 1

        Vw1 = data1{1,"W_R1"}; % m/s = Laser
        Vw2 = data1{1,"W_R4"}; % m/s = fire
```

```
elseif Disp_y > 1 && Disp_y < 2
    Vw1 = data1{3,"W_R1"}; % m/s = Laser
    Vw2 = data1{3,"W_R4"}; % m/s = fire
elseif Disp_y > 2 && Disp_y < 3
    Vw1 = data1{5,"W_R1"}; % m/s = Laser
    Vw2 = data1{5,"W_R4"}; % m/s = fire
elseif Disp_y > 3 && Disp_y < 4
    Vw1 = data1{7,"W_R1"}; % m/s = Laser
    Vw2 = data1{7,"W_R4"}; % m/s = fire
elseif Disp_y > 4 && Disp_y < 5
    Vw1 = data1{9,"W_R1"}; % m/s = Laser
    Vw2 = data1{9,"W_R4"}; % m/s = fire
elseif Disp_y > 5 && Disp_y < 6
    Vw1 = data1{11,"W_R1"}; % m/s = Laser
    Vw2 = data1{11,"W_R4"}; % m/s = fire
elseif Disp_y > 6 && Disp_y < 7
    Vw1 = data1{13,"W_R1"}; % m/s = Laser
    Vw2 = data1{13,"W_R4"}; % m/s = fire
elseif Disp_y > 7 && Disp_y < 8
    Vw1 = data1{15,"W_R1"}; % m/s = Laser
    Vw2 = data1{15,"W_R4"}; % m/s = fire
elseif Disp_y > 8 && Disp_y < 9
    Vw1 = data1{17,"W_R1"}; % m/s = Laser
    Vw2 = data1{17,"W_R4"}; % m/s = fire
else Disp_y > 9 && Disp_y < 10;
    Vw1 = data1{19,"W_R1"}; % m/s = Laser
    Vw2 = data1{19,"W_R4"}; % m/s = fire
end

else if t >= 1.00 && t < 2.00
    if Disp_y > -1 && Disp_y < 1
```

```
Vw1 = data1{1,"W_R1"}; % m/s = Laser
Vw2 = data1{1,"W_R5"}; % m/s = fire + 1 sec
elseif Disp_y > 1 && Disp_y < 2
    Vw1 = data1{3,"W_R1"}; % m/s = Laser
    Vw2 = data1{3,"W_R5"}; % m/s = fire + 1 sec
elseif Disp_y > 2 && Disp_y < 3
    Vw1 = data1{5,"W_R1"}; % m/s = Laser
    Vw2 = data1{5,"W_R5"}; % m/s = fire + 1 sec
elseif Disp_y > 3 && Disp_y < 4
    Vw1 = data1{7,"W_R1"}; % m/s = Laser
    Vw2 = data1{7,"W_R5"}; % m/s = fire + 1 sec
elseif Disp_y > 4 && Disp_y < 5
    Vw1 = data1{9,"W_R1"}; % m/s = Laser
    Vw2 = data1{9,"W_R5"}; % m/s = fire + 1 sec
elseif Disp_y > 5 && Disp_y < 6
    Vw1 = data1{11,"W_R1"}; % m/s = Laser
    Vw2 = data1{11,"W_R5"}; % m/s = fire + 1 sec
elseif Disp_y > 6 && Disp_y < 7
    Vw1 = data1{13,"W_R1"}; % m/s = Laser
    Vw2 = data1{13,"W_R5"}; % m/s = fire + 1 sec
elseif Disp_y > 7 && Disp_y < 8
    Vw1 = data1{15,"W_R1"}; % m/s = Laser
    Vw2 = data1{15,"W_R5"}; % m/s = fire + 1 sec
elseif Disp_y > 8 && Disp_y < 9
    Vw1 = data1{17,"W_R1"}; % m/s = Laser
    Vw2 = data1{17,"W_R5"}; % m/s = fire + 1 sec
else Disp_y > 9 && Disp_y < 10;
    Vw1 = data1{19,"W_R1"}; % m/s = Laser
    Vw2 = data1{19,"W_R5"}; % m/s = fire + 1 sec
end
```

```
else t >= 2.00 && t < 3.00;
    if Disp_y > -1 && Disp_y < 1
        Vw1 = data1{1,"W_R1"}; % m/s = Laser
        Vw2 = data1{1,"W_R6"}; % m/s = fire + 2 sec
    elseif Disp_y > 1 && Disp_y < 2
        Vw1 = data1{3,"W_R1"}; % m/s = Laser
        Vw2 = data1{3,"W_R6"}; % m/s = fire + 2 sec
    elseif Disp_y > 2 && Disp_y < 3
        Vw1 = data1{5,"W_R1"}; % m/s = Laser
        Vw2 = data1{5,"W_R6"}; % m/s = fire + 2 sec
    elseif Disp_y > 3 && Disp_y < 4
        Vw1 = data1{7,"W_R1"}; % m/s = Laser
        Vw2 = data1{7,"W_R6"}; % m/s = fire + 2 sec
    elseif Disp_y > 4 && Disp_y < 5
        Vw1 = data1{9,"W_R1"}; % m/s = Laser
        Vw2 = data1{9,"W_R6"}; % m/s = fire + 2 sec
    elseif Disp_y > 5 && Disp_y < 6
        Vw1 = data1{11,"W_R1"}; % m/s = Laser
        Vw2 = data1{11,"W_R6"}; % m/s = fire + 2 sec
    elseif Disp_y > 6 && Disp_y < 7
        Vw1 = data1{13,"W_R1"}; % m/s = Laser
        Vw2 = data1{13,"W_R6"}; % m/s = fire + 2 sec
    elseif Disp_y > 7 && Disp_y < 8
        Vw1 = data1{15,"W_R1"}; % m/s = Laser
        Vw2 = data1{15,"W_R6"}; % m/s = fire + 2 sec
    elseif Disp_y > 8 && Disp_y < 9
        Vw1 = data1{17,"W_R1"}; % m/s = Laser
        Vw2 = data1{17,"W_R6"}; % m/s = fire + 2 sec
    else Disp_y > 9 && Disp_y < 10;
        Vw1 = data1{19,"W_R1"}; % m/s = Laser
```

```

        Vw2 = data1{19,"W_R6"}; % m/s = fire + 2 sec

    end

end

end

% Laser

CWD1 = Vw1*(t-(Disp_x/MV)); % crosswind displacement, from rhienmetal
book

CWDF1 = (0.5*Air*(Vw1^2)*CS_rd*DC); % calculate the drag force in z
direction using wind speed

% Wind at Point of Firing (+3 seconds)

CWD2 = Vw2*(t-(Disp_x/MV)); % crosswind displacement, from rhienmetal
book

CWDF2 = (0.5*Air*(Vw2^2)*CS_rd*DC); % calculate the drag force in z
direction using wind speed

Disp_z1 = CWD1-CWDF1; % displacement in z axis drift - Laser

Disp_z2 = CWD2-CWDF2; % displacement in z axis drift - Firing + 3 sec

```

7. Tables

```

    data2(end+1,:) =
{t, Vel_r, F_ag, Dg_F, Fx, Fy, Accx, Accy, Vx, Vy, Disp_x, Disp_y}; % Ballistic table
1

    data3(end+1,:) = {t, Disp_x, Disp_y, Vw1, Disp_z1, Vw2, Disp_z2}; %
Ballistic table 2

    data4(end+1,:) = {Vw1, CWDF1, CWD1, Disp_z1, Vw2, CWDF2, CWD2, Disp_z2}; %
wind table 1

```

8. Plots

```

figure(1)

plot(Disp_x, Disp_y, 'xb')

hold on

title('Range, Hight Trajectory Plot')

xlabel('Range (m)')

ylabel('Height (m)')

```

```

figure(2)
plot(Disp_x,Disp_z1,'og',Disp_x,Disp_z2,'xr')
hold on
axis ij
title('Range vs Drift')
xlabel('Range (m)')
ylabel('Drift (m)')
legend({'Z1 - Point of Lase','Z2 - Point of Fire'},'location','best')

% for loop break conditions
if Disp_y < 0 % once y axis, height reaches 0 for loop stops
    break % function stops for loop
end
end

```

9. Ballistic Output Calculation

```

% Firing Line for point of Lase - Ballistic Line 1
% fit line to data using polyfit
BL_L = polyfit(data3.Range_m,data3.Drift_Lase_m,1);
% Display evaluated equation z = m*x+b
disp(['Equation is z1=' num2str(BL_L(1)) '*x+' num2str(BL_L(2))'])
Equation is z1=-0.00052118*x+0.12923
% Evaluate fit equation using polyval
Z_lase=polyval(BL_L,data3.Range_m);

% Firing Line for point of Fire - Ballistic Line 2
% fit line to data using polyfit

```

```

BL_F = polyfit(data3.Range_m,data3.Drift_Fire_m,1);
% Display evaluated equation z = m*x+b
disp(['Equation is z2 = ' num2str(BL_F(1)) '*x+' num2str(BL_F(2))])
Equation is z2 =-0.00058*x+0.13806
% Evaluate fit equation using polyval
Z_fire=polyval(BL_F,data3.Range_m);

figure(3)
plot(data3.Range_m,data3.Drift_Lase_m,'og',data3.Range_m,data3.Drift_Fire_m,'xr',data3.Range_m,Z_lase,'g--',data3.Range_m,Z_fire,'r--')
axis ij
title('Range vs Drift')
xlabel('Range (m)')
ylabel('Drift (m)')
legend({'Z1 - Point of Lase','Z2 - Point of Fire','Trajectory Z1','Trajectory Z2'},'location','best')

% Coincidence window
% Calculating Lase Hit position at 2000 meters.
Hit_L1 = str2double(num2str(BL_L(1)));
Hit_L2 = str2double(num2str(BL_L(2)));
Hit_L = (Hit_L1*2000+Hit_L2)*100 % Lase Hit Coincidence Position in "CM"
Hit_L = -91.3130

% Calculating Fire Hit position at 2000 meters.
Hit_F1 = str2double(num2str(BL_F(1)));
Hit_F2 = str2double(num2str(BL_F(2)));
Hit_F = (Hit_F1*2000+Hit_F2)*100 % Fire Hit Coincidence Position in "CM"
Hit_F = -102.1940

% Calculating the Coincidence Error
% Coincidence Error is 0.30 mil, or at 2000 meters, 0.60 meters, or 60 cm. in "CM"

```

```

Coin = Hit_F-Hit_L
Coin = -10.8810

% If the difference between Hit_L "Lase wind" and Hit_F "Firing Wind" is
% greater than +/-60 cm, for either drift offset, then at the point of
% firing the round will be out of coincidence.

% Averde MBT is 2.5 meter tall, so the wind senors will read the following
% value:
Wind2_5m = data1{6,"W_R1"}
Wind2_5m = -1.2250

```

10. Data Saving

```

data5(1,:) =
{MV,Cal,M_rd,CS_rd,DC,Ele_d,Ele_r,Air,g,Hit_L1,Hit_L2,Hit_L,Hit_F1,Hit_F2
,Hit_F,Coin}; % step data

writetable(data1,'Model_A_V6_WTI_01_Oct_22_DS30-A1.xls'); % Wind Table
Input (WTI)

writetable(data2,'Model_A_V6_BT1_01_Oct_22_DS30-A1.xls'); % Ballistic
Table 1 (BT1)

writetable(data3,'Model_A_V6_BT2_01_Oct_22_DS30-A1.xls'); % Ballistic
Table 2 (BT2)

writetable(data4,'Model_A_V6_WT_01_Oct_22_DS30-A1.xls'); % Wind Table (WT)

writetable(data5,'Model_A_V6_VL_01_Oct_22_DS30-A1.xls'); % variables list
(VL)

saveas(figure(1),'Model_A_V6_Figure1_01_Oct_22_DS30-A1.jpg'); % figure 1
save

saveas(figure(2),'Model_A_V6_Figure2_01_Oct_22_DS30-A1.jpg'); % figure 2
save

saveas(figure(3),'Model_A_V6_Figure3_01_Oct_22_DS30-A1.jpg'); % figure 3
save

```

```
toc % programme time end, output elapsed time in sec's.
```

```
Elapsed time is 5.093458 seconds.
```

End

End of MATLAB Code

Appendix C Meteorological Data Sets

C.1 Data Set 1

Table C-1 – Data Set 1, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2	2.5	2.4	NNW [-0.17]	-0.34	-0.43	-0.41	1.00
08:00:01	2.6	2	2.4	WSW [-1]	-2.60	-2.00	-2.40	2.00
08:00:02	2.4	1.8	2.3	NW [-0.64]	-1.54	-1.15	-1.47	3.00
08:00:03	2.2	1.7	2.1	W [-0.98]	-2.16	-1.67	-2.06	4.00
08:00:04	1.9	1.6	2.2	W [-0.98]	-1.86	-1.57	-2.16	5.00
08:00:05	1.5	1.7	2	W [-0.94]	-1.41	-1.60	-1.88	6.00
09:00:00	4	5.2	6.4	NNW [-0.34]	-1.36	-1.77	-2.18	1.00
09:00:01	4.8	5.5	6.4	NNE [0.64]	3.07	3.52	4.10	2.00
09:00:02	6.5	6.9	5.1	N [0.34]	2.21	2.35	1.73	3.00
09:00:03	4.8	5.9	5.8	NNW [-0.34]	-1.63	-2.01	-1.97	4.00
09:00:04	3.4	4.4	6.4	NNW [-0.34]	-1.16	-1.50	-2.18	5.00
09:00:05	2.9	3.6	6	N [0.34]	0.99	1.22	2.04	6.00
10:00:00	4.3	4.7	7	NNW [-0.17]	-0.73	-0.80	-1.19	1.00
10:00:01	4.8	4.7	7.7	NNW [-0.17]	-0.82	-0.80	-1.31	2.00
10:00:02	6	6.5	6.3	N [0.34]	2.04	2.21	2.14	3.00
10:00:03	5.9	5.9	4.9	NNE [0.64]	3.78	3.78	3.14	4.00
10:00:04	5.6	5.2	3.8	NE [0.94]	5.26	4.89	3.57	5.00
10:00:05	5.4	4.5	3.2	N [0.34]	1.84	1.53	1.09	6.00
11:00:00	2.8	3.5	3.7	N [0.34]	0.95	1.19	1.26	1.00
11:00:01	3.1	3.8	4.3	N [0.5]	1.55	1.90	2.15	2.00
11:00:02	3.5	4	3.9	NNE [0.5]	1.75	2.00	1.95	3.00
11:00:03	3.5	4.4	4.1	NNE [0.34]	1.75	2.20	2.05	4.00
11:00:04	3.3	4.3	3.8	N [0.34]	1.12	1.46	1.29	5.00
11:00:05	3.3	5.1	3.5	NNE [0.64]	2.11	3.26	2.24	6.00
12:00:00	4.8	4.9	6.1	N [0.34]	1.63	1.67	2.07	1.00
12:00:01	4.3	4.1	5.9	NNW [-0.34]	-1.46	-1.39	-2.01	2.00
12:00:02	3.9	4.1	6.1	NW [-0.77]	-3.00	-3.16	-4.70	3.00
12:00:03	3.5	4.7	4.4	NW [-0.77]	-2.70	-3.62	-3.39	4.00
12:00:04	2.6	3.7	3.1	N [0.34]	0.88	1.26	1.05	5.00
12:00:05	2	3.8	5	N [0.34]	0.68	1.29	1.70	6.00

C.2 Data Set 2

Table C-2 – Data Set 2, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2.10	3.00	3.10	N [0.17]	0.36	0.51	0.53	1.00
08:00:01	2.00	3.00	3.00	N [0.17]	0.34	0.51	0.51	2.00
08:00:02	2.20	2.90	3.10	N [0.34]	0.75	0.99	1.05	3.00
08:00:03	2.40	2.80	3.20	N [0.17]	0.41	0.48	0.54	4.00
08:00:04	2.40	2.80	3.10	N [0.17]	0.41	0.48	0.53	5.00
08:00:05	2.20	3.00	3.10	N [0.17]	0.37	0.51	0.53	6.00
09:00:00	1.40	2.00	1.80	N [0.17]	0.24	0.34	0.31	1.00
09:00:01	1.60	2.10	1.90	N [0.34]	0.54	0.71	0.65	2.00
09:00:02	1.80	2.20	1.80	N [0.17]	0.31	0.37	0.31	3.00
09:00:03	1.80	2.00	1.90	N [0.34]	0.61	0.68	0.65	4.00
09:00:04	1.90	1.80	2.00	N [0.34]	0.65	0.61	0.68	5.00
09:00:05	1.80	1.60	2.20	N [0.17]	0.31	0.27	0.37	6.00
10:00:00	1.70	2.10	1.70	NNE [0.64]	1.09	1.34	1.09	1.00
10:00:01	1.60	2.00	1.70	NE [0.77]	1.23	1.54	1.31	2.00
10:00:02	1.60	1.90	1.60	NNE [0.77]	1.23	1.46	1.23	3.00
10:00:03	1.70	1.80	1.70	NNE [0.64]	1.09	1.15	1.09	4.00
10:00:04	1.80	1.80	1.80	NNE [0.64]	1.15	1.15	1.15	5.00
10:00:05	1.70	1.90	2.00	NNE [0.77]	1.31	1.46	1.54	6.00
11:00:00	0.40	1.30	2.40	NNW [-0.34]	-0.14	-0.44	-0.82	1.00
11:00:01	0.40	1.50	2.30	NW [-0.5]	-0.20	-0.75	-1.15	2.00
11:00:02	0.50	1.70	2.00	NW [-0.77]	-0.39	-1.31	-1.54	3.00
11:00:03	1.10	1.90	1.70	NNW [-0.17]	-0.19	-0.32	-0.29	4.00
11:00:04	1.60	1.80	2.10	NW [-0.64]	-1.02	-1.15	-1.34	5.00
11:00:05	1.70	1.90	2.70	NNW [-0.34]	-0.58	-0.65	-0.92	6.00
12:00:00	0.90	1.60	1.60	NNE [0.64]	0.58	1.02	1.02	1.00
12:00:01	0.90	1.60	1.70	NE [0.77]	0.69	1.23	1.31	2.00
12:00:02	1.00	1.40	1.90	NNE [0.5]	0.50	0.70	0.95	3.00
12:00:03	1.00	1.30	1.80	NE [0.94]	0.94	1.22	1.69	4.00
12:00:04	1.10	1.20	1.80	NE [0.77]	0.85	0.92	1.39	5.00
12:00:05	1.20	1.20	1.80	NE [0.77]	0.92	0.92	1.39	6.00

C.3 Data Set 3

Table C-3 – Data Set 3, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.1	0	1.5	NNW [-0.17]	-0.02	0.00	-0.26	1.00
08:00:01	0	0	1.4	NNW [-0.34]	0.00	0.00	-0.48	2.00
08:00:02	0	0	1.2	NW [-0.5]	0.00	0.00	-0.60	3.00
08:00:03	0	0	1.2	WNW [-0.94]	0.00	0.00	-1.13	4.00
08:00:04	0	0	1.2	WNW [-0.86]	0.00	0.00	-1.03	5.00
08:00:05	0	0.2	1.3	WNW [-0.86]	0.00	-0.17	-1.12	6.00
09:00:00	1.5	1.3	2.1	WSW [-1]	-1.50	-1.30	-2.10	1.00
09:00:01	1.5	1.3	2.1	WSW [-1]	-1.50	-1.30	-2.10	2.00
09:00:02	1.5	1.4	2	WSW [-0.98]	-1.47	-1.37	-1.96	3.00
09:00:03	1.5	1.4	1.8	WSW [-1]	-1.50	-1.40	-1.80	4.00
09:00:04	1.5	1.4	1.7	WSW [-1]	-1.50	-1.40	-1.70	5.00
09:00:05	1.5	1.3	1.6	WSW [-1]	-1.50	-1.30	-1.60	6.00
10:00:00	1.5	1.4	1.4	WNW [-0.77]	-1.16	-1.08	-1.08	1.00
10:00:01	1.5	1.4	1.7	NW [-0.64]	-0.96	-0.90	-1.09	2.00
10:00:02	1.5	1.4	2	W [-0.98]	-1.47	-1.37	-1.96	3.00
10:00:03	1.6	1.5	1.9	WNW [-0.77]	-1.23	-1.16	-1.46	4.00
10:00:04	2.2	1.5	1.9	WNW [-0.86]	-1.89	-1.29	-1.63	5.00
10:00:05	2.1	1.3	1.8	WNW [-0.86]	-1.81	-1.12	-1.55	6.00
11:00:00	1.9	1.9	2	NW [-0.77]	-1.46	-1.46	-1.54	1.00
11:00:01	1.9	1.8	2.3	WNW [-0.77]	-1.46	-1.39	-1.77	2.00
11:00:02	1.6	1.9	2.2	WNW [-0.86]	-1.38	-1.63	-1.89	3.00
11:00:03	1.5	2.1	2.2	WNW [-0.86]	-1.29	-1.81	-1.89	4.00
11:00:04	1.4	1.9	2.1	W [-0.94]	-1.32	-1.79	-1.97	5.00
11:00:05	1.3	1.9	2	NW [-0.5]	-0.65	-0.95	-1.00	6.00
12:00:00	2.4	2.5	3.3	NNW [-0.17]	-0.41	-0.43	-0.56	1.00
12:00:01	1.9	3.3	3.5	NNW [-0.17]	-0.32	-0.56	-0.60	2.00
12:00:02	1.9	3.3	3.6	NNW [-0.17]	-0.32	-0.56	-0.61	3.00
12:00:03	2.5	3.6	3.8	NNW [-0.17]	-0.43	-0.61	-0.65	4.00
12:00:04	2.6	3.5	3.7	NNW [-0.17]	-0.44	-0.60	-0.63	5.00
12:00:05	2.4	3.4	3.5	NNW [-0.34]	-0.82	-1.16	-1.19	6.00

C.4 Data Set 4

Table C-4 – Data Set 4, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	3.9	4.3	4.1	WSW [-0.94]	-3.67	-4.04	-3.85	1.00
08:00:01	3.3	3.9	3.6	WSW [-0.98]	-3.23	-3.82	-3.53	2.00
08:00:02	3.1	3.8	3.7	WSW [-0.98]	-3.04	-3.72	-3.63	3.00
08:00:03	3.3	4	3.8	WSW [-1]	-3.30	-4.00	-3.80	4.00
08:00:04	3.3	4.6	3.8	WSW [-0.98]	-3.23	-4.51	-3.72	5.00
08:00:05	4	4.4	3.7	SW [-0.94]	-3.76	-4.14	-3.48	6.00
09:00:00	4	3.2	3.7	SW [-0.86]	-3.44	-2.75	-3.18	1.00
09:00:01	3.8	3.8	3.5	WSW [-1]	-3.80	-3.80	-3.50	2.00
09:00:02	3.2	3.2	3.9	WSW [-0.98]	-3.14	-3.14	-3.82	3.00
09:00:03	2.9	2.5	4.1	WSW [-0.94]	-2.73	-2.35	-3.85	4.00
09:00:04	2.6	2.7	3.9	SSW [-0.77]	-2.00	-2.08	-3.00	5.00
09:00:05	2.5	2.6	3.2	W [-0.98]	-2.45	-2.55	-3.14	6.00
10:00:00	2.3	2.8	3	WSW [-0.94]	-2.16	-2.63	-2.82	1.00
10:00:01	2.2	2.9	3.2	SW [-0.94]	-2.07	-2.73	-3.01	2.00
10:00:02	2.4	3.1	3.3	SW [-0.94]	-2.26	-2.91	-3.10	3.00
10:00:03	2.7	2.9	3	SW [-0.94]	-2.54	-2.73	-2.82	4.00
10:00:04	2.8	2.8	3	SW [-0.86]	-2.41	-2.41	-2.58	5.00
10:00:05	3.2	2.7	3.1	SW [-0.77]	-2.46	-2.08	-2.39	6.00
11:00:00	3.4	4.3	4.3	WSW [-1]	-3.40	-4.30	-4.30	1.00
11:00:01	3.6	4.4	4.5	WSW [-0.98]	-3.53	-4.31	-4.41	2.00
11:00:02	3.8	4.3	4.1	WSW [-1]	-3.80	-4.30	-4.10	3.00
11:00:03	3.6	4.1	4.2	W [-1]	-3.60	-4.10	-4.20	4.00
11:00:04	3	3.8	4.3	WSW [-1]	-3.00	-3.80	-4.30	5.00
11:00:05	2.5	3.1	3.7	WSW [-1]	-2.50	-3.10	-3.70	6.00
12:00:00	1.8	1.9	2	WNW [-0.94]	-1.69	-1.79	-1.88	1.00
12:00:01	1.6	2	1.9	W [-0.98]	-1.57	-1.96	-1.86	2.00
12:00:02	1.6	2.1	2	W [-0.98]	-1.57	-2.06	-1.96	3.00
12:00:03	1.5	2	2	W [-0.98]	-1.47	-1.96	-1.96	4.00
12:00:04	1.4	1.8	2	W [-0.98]	-1.37	-1.76	-1.96	5.00
12:00:05	1.3	1.5	2.1	WSW [-1]	-1.30	-1.50	-2.10	6.00

C.5 Data Set 5

Table C-5 – Data Set 5, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2.2	3	3.6	WSW [-1]	-2.20	-3.00	-3.60	1.00
08:00:01	2.3	2.8	4	W [-0.94]	-2.16	-2.63	-3.76	2.00
08:00:02	2.3	3	4.8	WNW [-0.94]	-2.16	-2.82	-4.51	3.00
08:00:03	2.4	3.1	5.2	W [-0.98]	-2.35	-3.04	-5.10	4.00
08:00:04	3	2.9	5.8	W [-0.98]	-2.94	-2.84	-5.68	5.00
08:00:05	2.8	3.3	5.9	W [-0.98]	-2.74	-3.23	-5.78	6.00
09:00:00	2	2.3	2.4	WNW [-0.94]	-1.88	-2.16	-2.26	1.00
09:00:01	1.8	2.2	2.5	WNW [-0.94]	-1.69	-2.07	-2.35	2.00
09:00:02	1.7	2.1	2.6	WNW [-0.86]	-1.46	-1.81	-2.24	3.00
09:00:03	1.8	2	2.7	WNW [-0.86]	-1.55	-1.72	-2.32	4.00
09:00:04	1.8	2	2.8	WNW [-0.94]	-1.69	-1.88	-2.63	5.00
09:00:05	1.7	2.1	2.6	WNW [-0.86]	-1.46	-1.81	-2.24	6.00
10:00:00	1.9	3.5	3.2	WSW [-1]	-1.90	-3.50	-3.20	1.00
10:00:01	2	3.4	2.9	W [-1]	-2.00	-3.40	-2.90	2.00
10:00:02	2.5	3.2	2.8	W [-1]	-2.50	-3.20	-2.80	3.00
10:00:03	2.6	2.9	2.6	WSW [-1]	-2.60	-2.90	-2.60	4.00
10:00:04	2.5	2.8	2.7	WSW [-1]	-2.50	-2.80	-2.70	5.00
10:00:05	2.5	3	2.7	WSW [-1]	-2.50	-3.00	-2.70	6.00
11:00:00	1.7	2.6	3.1	WSW [-1]	-1.70	-2.60	-3.10	1.00
11:00:01	1.8	2.8	3.6	WSW [-0.94]	-1.69	-2.63	-3.38	2.00
11:00:02	2.3	3	3.7	SW [-0.94]	-2.16	-2.82	-3.48	3.00
11:00:03	2.4	3.1	4.2	WSW [-0.98]	-2.35	-3.04	-4.12	4.00
11:00:04	2.4	3.3	3.7	W [-1]	-2.40	-3.30	-3.70	5.00
11:00:05	2.2	3.1	3.9	SW [-0.86]	-1.89	-2.67	-3.35	6.00
12:00:00	2.1	2.1	2.3	WSW [-0.98]	-2.06	-2.06	-2.25	1.00
12:00:01	2	2.2	2.3	SW [-0.86]	-1.72	-1.89	-1.98	2.00
12:00:02	1.8	2.4	3.1	SW [-0.77]	-1.39	-1.85	-2.39	3.00
12:00:03	1.4	2.4	3.1	WSW [-0.98]	-1.37	-2.35	-3.04	4.00
12:00:04	1.2	2.3	3.1	SW [-0.94]	-1.13	-2.16	-2.91	5.00
12:00:05	1.3	2.5	3	WSW [-0.98]	-1.27	-2.45	-2.94	6.00

C.6 Data Set 6

Table C-6 – Data Set 6, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	3.3	4.6	4.1	SW [-0.77]	-2.54	-3.54	-3.16	1.00
08:00:01	3.6	4.4	4.1	SSW [-0.64]	-2.30	-2.82	-2.62	2.00
08:00:02	3	4.3	4.5	SSW [-0.77]	-2.31	-3.31	-3.47	3.00
08:00:03	2.5	3.9	4.3	SW [-0.77]	-1.93	-3.00	-3.31	4.00
08:00:04	2.9	3.9	4	SW [-0.86]	-2.49	-3.35	-3.44	5.00
08:00:05	2.9	4.3	3.5	SW [-0.86]	-2.49	-3.70	-3.01	6.00
09:00:00	2.1	2.9	4.8	SSW [-0.5]	-1.05	-1.45	-2.40	1.00
09:00:01	2.2	3.1	4.6	S [-0.34]	-0.75	-1.05	-1.56	2.00
09:00:02	2.3	3.2	4	SSW [-0.5]	-1.15	-1.60	-2.00	3.00
09:00:03	2.6	3.6	4.7	SW [-0.86]	-2.24	-3.10	-4.04	4.00
09:00:04	3	4.4	5.5	SW [-0.94]	-2.82	-4.14	-5.17	5.00
09:00:05	4	4.9	6	SW [-0.86]	-3.44	-4.21	-5.16	6.00
10:00:00	2	3	3.4	WSW [-1]	-2.00	-3.00	-3.40	1.00
10:00:01	2	2.6	3.3	SW [-0.86]	-1.72	-2.24	-2.84	2.00
10:00:02	2.1	3.2	4.1	WSW [-0.98]	-2.06	-3.14	-4.02	3.00
10:00:03	3.4	3.3	4.9	WSW [-1]	-3.40	-3.30	-4.90	4.00
10:00:04	3.8	3.7	4.7	WSW [-1]	-3.80	-3.70	-4.70	5.00
10:00:05	4.1	4.3	4.6	WSW [-0.98]	-4.02	-4.21	-4.51	6.00
11:00:00	6	5.7	5.6	SW [-0.86]	-5.16	-4.90	-4.82	1.00
11:00:01	5.9	6.6	6.8	WSW [-0.98]	-5.78	-6.47	-6.66	2.00
11:00:02	5.7	6.8	7.5	SW [-0.86]	-4.90	-5.85	-6.45	3.00
11:00:03	5.6	6.1	6.4	WSW [-0.98]	-5.49	-5.98	-6.27	4.00
11:00:04	5.2	5.5	6	SW [-0.77]	-4.00	-4.24	-4.62	5.00
11:00:05	4.5	5.9	4.6	W [-1]	-4.50	-5.90	-4.60	6.00
12:00:00	5.1	5.3	5	SW [-0.94]	-4.79	-4.98	-4.70	1.00
12:00:01	4.8	4.8	5	SW [-0.86]	-4.13	-4.13	-4.30	2.00
12:00:02	4.1	3.9	4.4	WSW [-0.98]	-4.02	-3.82	-4.31	3.00
12:00:03	3.2	4.5	5.2	SW [-0.77]	-2.46	-3.47	-4.00	4.00
12:00:04	3.8	6.2	5.3	SW [-0.94]	-3.57	-5.83	-4.98	5.00
12:00:05	4	4.7	6.4	SW [-0.86]	-3.44	-4.04	-5.50	6.00

C.7 Data Set 7

Table C-7 – Data Set 7, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2	1.9	1.9	WSW [-1]	-2.00	-1.90	-1.90	1.00
08:00:01	2.1	2	2.1	WSW [-1]	-2.10	-2.00	-2.10	2.00
08:00:02	2	2	1.9	WSW [-1]	-2.00	-2.00	-1.90	3.00
08:00:03	1.9	1.9	1.6	SW [-0.94]	-1.79	-1.79	-1.50	4.00
08:00:04	2	1.9	1.6	WSW [-1]	-2.00	-1.90	-1.60	5.00
08:00:05	1.9	2.1	1.8	W [-0.98]	-1.86	-2.06	-1.76	6.00
09:00:00	5.9	6.7	7.9	WSW [-0.98]	-5.78	-6.57	-7.74	1.00
09:00:01	5.2	7.1	8.1	WSW [-1]	-5.20	-7.10	-8.10	2.00
09:00:02	5.7	7.2	8	WSW [-0.98]	-5.59	-7.06	-7.84	3.00
09:00:03	5.3	7.2	7.4	WSW [-0.98]	-5.19	-7.06	-7.25	4.00
09:00:04	4.5	6.1	7.9	W [-1]	-4.50	-6.10	-7.90	5.00
09:00:05	3.6	4.2	5.6	WNW [-0.94]	-3.38	-3.95	-5.26	6.00
10:00:00	6.2	7	7.6	SW [-0.94]	-5.83	-6.58	-7.14	1.00
10:00:01	5.8	7	7.5	WSW [-1]	-5.80	-7.00	-7.50	2.00
10:00:02	6	5.8	8	WSW [-0.98]	-5.88	-5.68	-7.84	3.00
10:00:03	5.9	6.5	7.7	W [-1]	-5.90	-6.50	-7.70	4.00
10:00:04	5.9	7.2	7.4	W [-0.98]	-5.78	-7.06	-7.25	5.00
10:00:05	4.9	6.9	7.1	W [-0.98]	-4.80	-6.76	-6.96	6.00
11:00:00	5.4	7.5	7.4	WNW [-0.94]	-5.08	-7.05	-6.96	1.00
11:00:01	6.3	8.4	7.1	W [-1]	-6.30	-8.40	-7.10	2.00
11:00:02	5.2	7.5	7.5	WSW [-0.98]	-5.10	-7.35	-7.35	3.00
11:00:03	7.1	7.1	9.1	WSW [-1]	-7.10	-7.10	-9.10	4.00
11:00:04	5.7	5.4	10.6	W [-1]	-5.70	-5.40	-10.60	5.00
11:00:05	4	5.7	12.1	W [-0.98]	-3.92	-5.59	-11.86	6.00
12:00:00	7.4	8	8.3	WSW [-0.98]	-7.25	-7.84	-8.13	1.00
12:00:01	7.6	9.2	11.3	WSW [-1]	-7.60	-9.20	-11.30	2.00
12:00:02	5.2	9.9	12.9	WSW [-1]	-5.20	-9.90	-12.90	3.00
12:00:03	4.9	11.2	13.3	W [-1]	-4.90	-11.20	-13.30	4.00
12:00:04	7.6	11.6	13.6	W [-1]	-7.60	-11.60	-13.60	5.00
12:00:05	8.8	11.9	12.8	W [-1]	-8.80	-11.90	-12.80	6.00

C.8 Data Set 8

Table C-8 – Data Set 8, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.8	1.2	1.2	NNE [0.64]	0.51	0.77	0.77	1.00
08:00:01	0.9	1.3	1.2	NNE [0.64]	0.58	0.83	0.77	2.00
08:00:02	0.9	1.4	1.2	NNE [0.64]	0.58	0.90	0.77	3.00
08:00:03	0.9	1.4	1.2	NNE [0.77]	0.69	1.08	0.92	4.00
08:00:04	0.8	1.3	1.1	NE [0.77]	0.62	1.00	0.85	5.00
08:00:05	0.8	1.3	1.1	NE [0.86]	0.69	1.12	0.95	6.00
09:00:00	0.6	1.4	1.6	ENE [0.98]	0.59	1.37	1.57	1.00
09:00:01	0.6	1.4	1.6	E [1]	0.60	1.40	1.60	2.00
09:00:02	0.6	1.3	1.5	E [0.94]	0.56	1.22	1.41	3.00
09:00:03	0.7	1.3	1.5	E [0.94]	0.66	1.22	1.41	4.00
09:00:04	0.8	1.5	1.3	E [0.94]	0.75	1.41	1.22	5.00
09:00:05	0.9	1.5	1.1	E [0.94]	0.85	1.41	1.03	6.00
10:00:00	1	0.6	1	NNE [0.64]	0.64	0.38	0.64	1.00
10:00:01	0.9	0.6	1.1	NE [0.77]	0.69	0.46	0.85	2.00
10:00:02	0.8	0.7	1.1	NE [0.77]	0.62	0.54	0.85	3.00
10:00:03	0.7	0.7	1.1	NE [0.77]	0.54	0.54	0.85	4.00
10:00:04	0.7	0.9	0.9	NE [0.77]	0.54	0.69	0.69	5.00
10:00:05	0.7	1	0.9	NE [0.77]	0.54	0.77	0.69	6.00
11:00:00	0.4	0.9	1.2	NE [0.86]	0.34	0.77	1.03	1.00
11:00:01	0.4	0.9	1.1	NE [0.86]	0.34	0.77	0.95	2.00
11:00:02	0.4	1.1	1.1	NE [0.86]	0.34	0.95	0.95	3.00
11:00:03	0.4	1.3	1	NE [0.86]	0.34	1.12	0.86	4.00
11:00:04	0.4	1.3	1.2	NE [0.94]	0.38	1.22	1.13	5.00
11:00:05	0.5	1.2	1.6	NE [0.86]	0.43	1.03	1.38	6.00
12:00:00	1.3	1.4	1.4	NNE [0.5]	0.65	0.70	0.70	1.00
12:00:01	1.4	1.2	1.2	NNE [0.5]	0.70	0.60	0.60	2.00
12:00:02	1.6	1.1	1.1	NNE [0.5]	0.80	0.55	0.55	3.00
12:00:03	1.5	1	1	NNE [0.5]	0.75	0.50	0.50	4.00
12:00:04	1.3	1	0.8	NNE [0.5]	0.65	0.50	0.40	5.00
12:00:05	1.1	1	0.8	N [0.34]	0.37	0.34	0.27	6.00

C.9 Data Set 9

Table C-9 – Data Set 9, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.9	1.2	2.3	W [-0.94]	-0.85	-1.13	-2.16	1.00
08:00:01	1.1	1.4	2.2	W [-0.98]	-1.08	-1.37	-2.16	2.00
08:00:02	1	1.8	2.1	W [-0.98]	-0.98	-1.76	-2.06	3.00
08:00:03	1	1.9	2.1	W [-0.98]	-0.98	-1.86	-2.06	4.00
08:00:04	1	1.8	2.1	WSW [-1]	-1.00	-1.80	-2.10	5.00
08:00:05	1.3	1.7	2.1	W [-1]	-1.30	-1.70	-2.10	6.00
09:00:00	1.60	2.50	2.60	WNW [-0.94]	-1.50	-2.35	-2.44	1.00
09:00:01	1.40	2.40	2.40	W [-0.98]	-1.37	-2.35	-2.35	2.00
09:00:02	1.50	2.60	2.00	WSW [-1]	-1.50	-2.60	-2.00	3.00
09:00:03	1.90	2.80	2.10	WSW [-1]	-1.90	-2.80	-2.10	4.00
09:00:04	2.30	2.90	2.40	WSW [-0.98]	-2.25	-2.84	-2.35	5.00
09:00:05	2.90	2.50	2.40	W [-0.98]	-2.84	-2.45	-2.35	6.00
10:00:00	2.6	1.7	2.3	WNW [-0.94]	-2.44	-1.60	-2.16	1.00
10:00:01	2.9	1.7	2	WNW [-0.86]	-2.49	-1.46	-1.72	2.00
10:00:02	2.6	2.1	2.1	WNW [-0.94]	-2.44	-1.97	-1.97	3.00
10:00:03	2.4	2.2	2.1	WNW [-0.94]	-2.26	-2.07	-1.97	4.00
10:00:04	2.5	2	2.2	WNW [-0.77]	-1.93	-1.54	-1.69	5.00
10:00:05	2.5	1.7	2.7	NW [-0.64]	-1.60	-1.09	-1.73	6.00
11:00:00	2.2	2.5	2.7	WNW [-0.94]	-2.07	-2.35	-2.54	1.00
11:00:01	2.1	2.5	2.8	W [-0.94]	-1.97	-2.35	-2.63	2.00
11:00:02	1.8	2.3	2.6	W [-0.94]	-1.69	-2.16	-2.44	3.00
11:00:03	1.7	2	2.7	WNW [-0.94]	-1.60	-1.88	-2.54	4.00
11:00:04	1.6	2	2.9	W [-0.94]	-1.50	-1.88	-2.73	5.00
11:00:05	1.5	1.9	2.8	WNW [-0.94]	-1.41	-1.79	-2.63	6.00
12:00:00	0.6	1	1.5	WNW [-0.77]	-0.46	-0.77	-1.16	1.00
12:00:01	1	0.9	1.4	W [-0.94]	-0.94	-0.85	-1.32	2.00
12:00:02	1.7	1	1.2	W [-0.94]	-1.60	-0.94	-1.13	3.00
12:00:03	1.5	1.4	1.6	W [-0.98]	-1.47	-1.37	-1.57	4.00
12:00:04	1.2	1.6	1.8	W [-1]	-1.20	-1.60	-1.80	5.00
12:00:05	1.2	1.5	2.2	WSW [-1]	-1.20	-1.50	-2.20	6.00

C.10 Data Set 10

Table C-10 – Data Set 10, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.5	0.4	0.8	ESE [0.86]	0.43	0.34	0.69	1.00
08:00:01	0.5	0.3	0.8	ESE [0.86]	0.43	0.26	0.69	2.00
08:00:02	0.5	0.4	0.9	ESE [0.86]	0.43	0.34	0.77	3.00
08:00:03	0.5	0.5	1	ESE [0.86]	0.43	0.43	0.86	4.00
08:00:04	0.5	0.4	1	ESE [0.86]	0.43	0.34	0.86	5.00
08:00:05	0.5	0.5	1	ESE [0.86]	0.43	0.43	0.86	6.00
09:00:00	0.3	0.2	0.4	S [-0.17]	-0.05	-0.03	-0.07	1.00
09:00:01	0.4	0.1	0.5	S [-0.17]	-0.07	-0.02	-0.09	2.00
09:00:02	0.4	0	0.6	S [-0.17]	-0.07	0.00	-0.10	3.00
09:00:03	0.4	0	0.7	S [-0.17]	-0.07	0.00	-0.12	4.00
09:00:04	0.5	0	0.6	S [-0.17]	-0.09	0.00	-0.10	5.00
09:00:05	0.6	0	0.6	S [-0.17]	-0.10	0.00	-0.10	6.00
10:00:00	1.7	1.3	2	SSE [0.17]	0.29	0.22	0.34	1.00
10:00:01	1.6	1.7	1.6	SE [0.64]	1.02	1.09	1.02	2.00
10:00:02	1.6	2.3	1.5	SSE [0.34]	0.54	0.78	0.51	3.00
10:00:03	1.8	2.2	1.8	S [-0.17]	-0.31	-0.37	-0.31	4.00
10:00:04	1.9	2	1.7	SSE [0.34]	0.65	0.68	0.58	5.00
10:00:05	2.6	2.1	2.6	SSE [0.34]	0.88	0.71	0.88	6.00
11:00:00	3.4	3.7	5.4	SSW [-0.5]	-1.70	-1.85	-2.70	1.00
11:00:01	3.4	3.7	5.4	SSW [-0.5]	-1.70	-1.85	-2.70	2.00
11:00:02	3.2	4	5.6	SSW [-0.64]	-2.05	-2.56	-3.58	3.00
11:00:03	3.6	4.6	5.9	SSW [-0.5]	-1.80	-2.30	-2.95	4.00
11:00:04	4.4	5	5.9	SSW [-0.64]	-2.82	-3.20	-3.78	5.00
11:00:05	4.4	5.5	5.7	SSW [-0.5]	-2.20	-2.75	-2.85	6.00
12:00:00	1.8	2.4	2.3	ESE [0.94]	1.69	2.26	2.16	1.00
12:00:01	1.6	2.3	2.2	ESE [0.86]	1.38	1.98	1.89	2.00
12:00:02	1.8	2.2	2.1	ESE [0.77]	1.39	1.69	1.62	3.00
12:00:03	1.9	2.1	2	ESE [0.77]	1.46	1.62	1.54	4.00
12:00:04	1.7	2.1	2.1	SE [0.77]	1.31	1.62	1.62	5.00
12:00:05	1.5	2	2	SE [0.77]	1.16	1.54	1.54	6.00

C.11 Data Set 21

Table C-11 – Data Set 21, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.9	0.8	0.9	SW [-0.94]	-0.85	-0.75	-0.85	1.00
08:00:01	0.8	0.7	0.9	SW [-0.94]	-0.75	-0.66	-0.85	2.00
08:00:02	0.7	0.7	0.8	SW [-0.94]	-0.66	-0.66	-0.75	3.00
08:00:03	0.7	0.7	0.7	WSW [-0.98]	-0.69	-0.69	-0.69	4.00
08:00:04	0.7	0.7	0.8	W [-0.98]	-0.69	-0.69	-0.78	5.00
08:00:05	0.6	0.7	1	W [-0.98]	-0.59	-0.69	-0.98	6.00
09:00:00	1.7	2.3	2.6	W [-1]	-1.70	-2.30	-2.60	1.00
09:00:01	1.6	2.4	2.6	WSW [-1]	-1.60	-2.40	-2.60	2.00
09:00:02	1.7	2.4	2.6	WSW [-1]	-1.70	-2.40	-2.60	3.00
09:00:03	1.8	2.6	2.7	W [-1]	-1.80	-2.60	-2.70	4.00
09:00:04	2.1	2.8	2.6	W [-1]	-2.10	-2.80	-2.60	5.00
09:00:05	2.3	2.8	2.6	W [-1]	-2.30	-2.80	-2.60	6.00
10:00:00	1.8	2	2.8	W [-0.98]	-1.76	-1.96	-2.74	1.00
10:00:01	1.8	2.3	2.7	W [-0.98]	-1.76	-2.25	-2.65	2.00
10:00:02	2.8	2.6	2.8	W [-0.98]	-2.74	-2.55	-2.74	3.00
10:00:03	2.9	2.9	3.3	W [-0.98]	-2.84	-2.84	-3.23	4.00
10:00:04	2.6	2.5	3.1	W [-0.98]	-2.55	-2.45	-3.04	5.00
10:00:05	2.6	2.4	3	WNW [-0.86]	-2.24	-2.06	-2.58	6.00
11:00:00	1	0.8	0.9	NNW [-0.34]	-0.34	-0.27	-0.31	1.00
11:00:01	0.9	0.7	0.8	NNW [-0.34]	-0.31	-0.24	-0.27	2.00
11:00:02	0.9	0.7	0.8	NNW [-0.17]	-0.15	-0.12	-0.14	3.00
11:00:03	0.8	0.8	1.1	NNW [-0.5]	-0.40	-0.40	-0.55	4.00
11:00:04	0.8	0.9	1.1	NW [-0.64]	-0.51	-0.58	-0.70	5.00
11:00:05	0.8	0.9	1.2	NW [-0.64]	-0.51	-0.58	-0.77	6.00
12:00:00	3.5	3.6	3.7	NE [0.86]	3.01	3.10	3.18	1.00
12:00:01	3.4	4.1	4	NE [0.86]	2.92	3.53	3.44	2.00
12:00:02	3.4	4.4	4.5	ENE [0.98]	3.33	4.31	4.41	3.00
12:00:03	3.4	3.8	4	ENE [0.98]	3.33	3.72	3.92	4.00
12:00:04	3.4	3.7	3.1	ENE [0.98]	3.33	3.63	3.04	5.00
12:00:05	3.4	3.7	3.3	E [1]	3.40	3.70	3.30	6.00

C.12 Data Set 22

Table C-12 – Data Set 22, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.5	0.1	0.5	N [0.34]	0.17	0.03	0.17	1.00
08:00:01	0.4	0.1	0.4	N [0.34]	0.14	0.03	0.14	2.00
08:00:02	0.5	0	0.4	N [0.34]	0.17	0.00	0.14	3.00
08:00:03	0.5	0	0.3	N [0.34]	0.17	0.00	0.10	4.00
08:00:04	0.5	0.1	0.3	N [0.34]	0.17	0.03	0.10	5.00
08:00:05	0.5	0.1	0.2	N [0.34]	0.17	0.03	0.07	6.00
09:00:00	1.7	2.8	3.8	ESE [0.94]	1.60	2.63	3.57	1.00
09:00:01	1.7	2.2	3.9	ESE [0.94]	1.60	2.07	3.67	2.00
09:00:02	2.3	2.3	3.7	E [0.98]	2.25	2.25	3.63	3.00
09:00:03	2.3	3.3	3.9	E [0.98]	2.25	3.23	3.82	4.00
09:00:04	2.8	3.7	3.9	E [0.98]	2.74	3.63	3.82	5.00
09:00:05	3.2	3.4	3.7	ESE [0.86]	2.75	2.92	3.18	6.00
10:00:00	0	0.4	0.9	ENE [1]	0.00	0.40	0.90	1.00
10:00:01	0	0.3	1	ENE [1]	0.00	0.30	1.00	2.00
10:00:02	0	0.3	0.9	ENE [1]	0.00	0.30	0.90	3.00
10:00:03	0	0.2	0.8	ENE [1]	0.00	0.20	0.80	4.00
10:00:04	0	0.2	0.7	ENE [1]	0.00	0.20	0.70	5.00
10:00:05	0	0.1	0.6	ENE [1]	0.00	0.10	0.60	6.00
11:00:00	0.7	0.4	0.6	SW [-0.86]	-0.60	-0.34	-0.52	1.00
11:00:01	0.6	0.4	0.7	SW [-0.86]	-0.52	-0.34	-0.60	2.00
11:00:02	0.6	0.4	0.7	SW [-0.86]	-0.52	-0.34	-0.60	3.00
11:00:03	0.6	0.3	0.6	SW [-0.86]	-0.52	-0.26	-0.52	4.00
11:00:04	0.5	0.3	0.6	SW [-0.86]	-0.43	-0.26	-0.52	5.00
11:00:05	0.4	0.3	0.5	SW [-0.86]	-0.34	-0.26	-0.43	6.00
12:00:00	2.3	2.8	2.5	ESE [0.86]	1.98	2.41	2.15	1.00
12:00:01	2.4	2.7	2.7	ESE [0.86]	2.06	2.32	2.32	2.00
12:00:02	2.2	2.6	2.6	SE [0.77]	1.69	2.00	2.00	3.00
12:00:03	2	2.4	2.6	ESE [0.94]	1.88	2.26	2.44	4.00
12:00:04	1.8	2.2	2.5	ESE [0.86]	1.55	1.89	2.15	5.00
12:00:05	1.7	1.9	2.5	SE [0.77]	1.31	1.46	1.93	6.00

C.13 Data Set 23

Table C-13 – Data Set 23, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.8	1.4	1.8	NNE [0.64]	0.51	0.90	1.15	1.00
08:00:01	0.7	1.7	2.2	N [0.17]	0.12	0.29	0.37	2.00
08:00:02	0.8	1.6	2.6	NNW [-0.17]	-0.14	-0.27	-0.44	3.00
08:00:03	1.1	1.6	2.4	N [0.17]	0.19	0.27	0.41	4.00
08:00:04	1.2	1.5	2.3	N [0.17]	0.20	0.26	0.39	5.00
08:00:05	1.3	1.3	2.2	NNW [-0.17]	-0.22	-0.22	-0.37	6.00
09:00:00	2.6	3.1	3.1	NNE [0.64]	1.66	1.98	1.98	1.00
09:00:01	2.8	2.9	3	NNE [0.64]	1.79	1.86	1.92	2.00
09:00:02	2.5	2.8	2.8	NNE [0.64]	1.60	1.79	1.79	3.00
09:00:03	2.2	2.8	2.8	N [0.5]	1.10	1.40	1.40	4.00
09:00:04	2.2	2.3	2.8	NNE [0.64]	1.41	1.47	1.79	5.00
09:00:05	2	2.1	2.6	NNE [0.5]	1.00	1.05	1.30	6.00
10:00:00	1.6	2.2	1.8	E [1]	1.60	2.20	1.80	1.00
10:00:01	1.6	2	1.8	E [0.98]	1.57	1.96	1.76	2.00
10:00:02	1.5	1.9	1.8	E [0.98]	1.47	1.86	1.76	3.00
10:00:03	1.5	1.9	1.7	E [0.98]	1.47	1.86	1.67	4.00
10:00:04	1.4	1.8	1.6	E [0.98]	1.37	1.76	1.57	5.00
10:00:05	1.3	1.9	1.6	E [0.94]	1.22	1.79	1.50	6.00
11:00:00	1.6	1.9	2.2	NNE [0.64]	1.02	1.22	1.41	1.00
11:00:01	1.5	1.9	2	NNE [0.64]	0.96	1.22	1.28	2.00
11:00:02	1.5	2	1.9	NNE [0.64]	0.96	1.28	1.22	3.00
11:00:03	1.4	1.9	1.9	NNE [0.5]	0.70	0.95	0.95	4.00
11:00:04	1.6	1.8	1.8	NNE [0.5]	0.80	0.90	0.90	5.00
11:00:05	1.6	1.8	1.7	NNE [0.64]	1.02	1.15	1.09	6.00
12:00:00	2.7	2.8	3.5	ENE [1]	2.70	2.80	3.50	1.00
12:00:01	2.4	2.6	3.4	E [1]	2.40	2.60	3.40	2.00
12:00:02	2.5	2.1	3.3	ENE [1]	2.50	2.10	3.30	3.00
12:00:03	2.7	2.5	3.4	ENE [0.98]	2.65	2.45	3.33	4.00
12:00:04	2.6	3.2	3.4	E [1]	2.60	3.20	3.40	5.00
12:00:05	2.4	3.1	3.7	ENE [1]	2.40	3.10	3.70	6.00

C.14 Data Set 24

Table C-14 – Data Set 24, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	3.6	4.6	3.9	ENE [0.98]	3.53	4.51	3.82	1.00
08:00:01	3.1	4.2	3.6	NNE [0.64]	1.98	2.69	2.30	2.00
08:00:02	3.4	3.9	3.6	NE [0.77]	2.62	3.00	2.77	3.00
08:00:03	3.8	3.9	3.4	NE [0.77]	2.93	3.00	2.62	4.00
08:00:04	3.3	3.6	3.7	N [0.34]	1.12	1.22	1.26	5.00
08:00:05	3.1	3.8	3.6	NNE [0.64]	1.98	2.43	2.30	6.00
09:00:00	0.9	1.2	3	ENE [0.98]	0.88	1.18	2.94	1.00
09:00:01	0.8	1.3	2.8	ENE [1]	0.80	1.30	2.80	2.00
09:00:02	0.8	1.6	2.3	N [0.34]	0.27	0.54	0.78	3.00
09:00:03	0.8	1.5	2.6	NE [0.94]	0.75	1.41	2.44	4.00
09:00:04	0.9	1.5	3.5	ENE [0.98]	0.88	1.47	3.43	5.00
09:00:05	1	1.5	4.1	NE [0.86]	0.86	1.29	3.53	6.00
10:00:00	2	2.6	2.2	NE [0.86]	1.72	2.24	1.89	1.00
10:00:01	2	2.4	2.2	NNE [0.64]	1.28	1.54	1.41	2.00
10:00:02	1.9	2.4	2	ENE [1]	1.90	2.40	2.00	3.00
10:00:03	1.9	2.4	2	NNE [0.64]	1.22	1.54	1.28	4.00
10:00:04	1.8	2	1.8	ENE [1]	1.80	2.00	1.80	5.00
10:00:05	1.9	1.8	1.8	NE [0.86]	1.63	1.55	1.55	6.00
11:00:00	2.3	3.3	3.8	NE [0.86]	1.98	2.84	3.27	1.00
11:00:01	2.2	4	3.6	ENE [0.98]	2.16	3.92	3.53	2.00
11:00:02	2.8	3.6	4	ENE [1]	2.80	3.60	4.00	3.00
11:00:03	3.5	3.6	4.3	ENE [0.98]	3.43	3.53	4.21	4.00
11:00:04	3.2	3.9	4.7	NE [0.86]	2.75	3.35	4.04	5.00
11:00:05	2.8	3.4	4.8	ENE [1]	2.80	3.40	4.80	6.00
12:00:00	4.6	5.4	7.7	E [0.98]	4.51	5.29	7.55	1.00
12:00:01	5.2	6.6	6.6	ENE [0.98]	5.10	6.47	6.47	2.00
12:00:02	4.9	6.3	5.5	E [0.98]	4.80	6.17	5.39	3.00
12:00:03	4.8	6.5	6.1	ESE [0.94]	4.51	6.11	5.73	4.00
12:00:04	4.6	6.9	7.2	E [0.94]	4.32	6.49	6.77	5.00
12:00:05	3.9	4.8	5.9	ENE [1]	3.90	4.80	5.90	6.00

C.15 Data Set 25

Table C-15 – Data Set 25, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	1.8	1.1	0.8	N [0.17]	0.31	0.19	0.14	1.00
08:00:01	1.7	0.9	0.8	N [0.17]	0.29	0.15	0.14	2.00
08:00:02	1.7	0.8	0.8	N [0.17]	0.29	0.14	0.14	3.00
08:00:03	1.5	0.8	0.8	N [0.17]	0.26	0.14	0.14	4.00
08:00:04	1.5	1	0.8	N [0.34]	0.51	0.34	0.27	5.00
08:00:05	1.4	1	0.8	NNE [0.5]	0.70	0.50	0.40	6.00
09:00:00	1.3	1.5	2	NE [0.86]	1.12	1.29	1.72	1.00
09:00:01	1.3	1.8	2.4	NNE [0.64]	0.83	1.15	1.54	2.00
09:00:02	1.2	1.8	2.7	N [0.17]	0.20	0.31	0.46	3.00
09:00:03	1.3	1.7	2.8	N [0.17]	0.22	0.29	0.48	4.00
09:00:04	1.3	1.4	2.8	N [0.34]	0.44	0.48	0.95	5.00
09:00:05	1.1	1.2	2.6	NNE [0.5]	0.55	0.60	1.30	6.00
10:00:00	1.8	1.7	2.1	NNE [0.77]	1.39	1.31	1.62	1.00
10:00:01	1.6	1.6	2.3	NNE [0.77]	1.23	1.23	1.77	2.00
10:00:02	1.5	1.6	2.5	NE [0.86]	1.29	1.38	2.15	3.00
10:00:03	1.5	1.7	2.6	NE [0.77]	1.16	1.31	2.00	4.00
10:00:04	1.5	1.9	2.4	NE [0.77]	1.16	1.46	1.85	5.00
10:00:05	1.5	2	2.4	NE [0.94]	1.41	1.88	2.26	6.00
11:00:00	0.7	1	1.4	E [1]	0.70	1.00	1.40	1.00
11:00:01	0.6	0.9	1.4	ENE [1]	0.60	0.90	1.40	2.00
11:00:02	0.7	1	1.6	ENE [1]	0.70	1.00	1.60	3.00
11:00:03	0.6	1	1.6	ENE [0.98]	0.59	0.98	1.57	4.00
11:00:04	0.6	1	1.5	NE [0.94]	0.56	0.94	1.41	5.00
11:00:05	0.7	0.9	1.4	ENE [0.94]	0.66	0.85	1.32	6.00
12:00:00	1.5	1.6	1.7	N [0.5]	0.75	0.80	0.85	1.00
12:00:01	1.6	2	1.7	N [0.5]	0.80	1.00	0.85	2.00
12:00:02	1.7	1.9	2	N [0.5]	0.85	0.95	1.00	3.00
12:00:03	1.8	2	2.3	N [0.34]	0.61	0.68	0.78	4.00
12:00:04	1.7	2	2.3	NNE [0.5]	0.85	1.00	1.15	5.00
12:00:05	1.7	2	2.2	NNE [0.5]	0.85	1.00	1.10	6.00

C.16 Data Set 26

Table C-16 – Data Set 26, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.9	1.3	1.4	W [-0.98]	-0.88	-1.27	-1.37	1.00
08:00:01	1.1	1.3	1.3	W [-0.98]	-1.08	-1.27	-1.27	2.00
08:00:02	1.2	1.3	1.2	WNW [-0.94]	-1.13	-1.22	-1.13	3.00
08:00:03	1.1	1.3	1.3	WNW [-0.94]	-1.03	-1.22	-1.22	4.00
08:00:04	1.1	1.3	1.2	W [-0.94]	-1.03	-1.22	-1.13	5.00
08:00:05	1	1.3	1.1	W [-1]	-1.00	-1.30	-1.10	6.00
09:00:00	0.2	0.1	0.5	WNW [-0.94]	-0.19	-0.09	-0.47	1.00
09:00:01	0.2	0.1	0.5	WNW [-0.94]	-0.19	-0.09	-0.47	2.00
09:00:02	0.3	0.1	0.4	WNW [-0.94]	-0.28	-0.09	-0.38	3.00
09:00:03	0.3	0.1	0.4	WNW [-0.94]	-0.28	-0.09	-0.38	4.00
09:00:04	0.3	0	0.3	WNW [-0.94]	-0.28	0.00	-0.28	5.00
09:00:05	0.3	0.1	0.3	WNW [-0.94]	-0.28	-0.09	-0.28	6.00
10:00:00	0.9	1.1	1.5	WSW [-0.94]	-0.85	-1.03	-1.41	1.00
10:00:01	1.1	1.4	1.3	WSW [-0.94]	-1.03	-1.32	-1.22	2.00
10:00:02	1.2	1.6	1.2	WSW [-0.94]	-1.13	-1.50	-1.13	3.00
10:00:03	1.2	1.6	1.1	WSW [-0.94]	-1.13	-1.50	-1.03	4.00
10:00:04	1.2	1.5	1	WSW [-0.94]	-1.13	-1.41	-0.94	5.00
10:00:05	1.1	1.5	1	WSW [-0.94]	-1.03	-1.41	-0.94	6.00
11:00:00	0.9	1.1	0.8	W [-0.98]	-0.88	-1.08	-0.78	1.00
11:00:01	1	1	0.8	W [-0.98]	-0.98	-0.98	-0.78	2.00
11:00:02	1	0.9	0.8	W [-0.98]	-0.98	-0.88	-0.78	3.00
11:00:03	0.9	0.9	1	W [-0.98]	-0.88	-0.88	-0.98	4.00
11:00:04	0.9	1	1.1	W [-0.98]	-0.88	-0.98	-1.08	5.00
11:00:05	0.9	0.9	1.1	W [-0.98]	-0.88	-0.88	-1.08	6.00
12:00:00	2.1	2.3	2.1	W [-0.98]	-2.06	-2.25	-2.06	1.00
12:00:01	2	2.1	2.1	W [-0.98]	-1.96	-2.06	-2.06	2.00
12:00:02	1.8	1.8	2	WNW [-0.94]	-1.69	-1.69	-1.88	3.00
12:00:03	1.7	1.6	1.8	W [-0.94]	-1.60	-1.50	-1.69	4.00
12:00:04	1.8	1.5	1.5	W [-0.98]	-1.76	-1.47	-1.47	5.00
12:00:05	1.6	1.5	1.5	W [-1]	-1.60	-1.50	-1.50	6.00

C.17 Data Set 27

Table C-17 – Data Set 27, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.6	0.6	0.4	NNE [0.64]	0.38	0.38	0.26	1.00
08:00:01	0.6	0.8	0.3	NNE [0.64]	0.38	0.51	0.19	2.00
08:00:02	0.6	0.8	0.3	NNE [0.64]	0.38	0.51	0.19	3.00
08:00:03	0.5	0.9	0.3	NNE [0.64]	0.32	0.58	0.19	4.00
08:00:04	0.5	0.8	0.3	NNE [0.64]	0.32	0.51	0.19	5.00
08:00:05	0.5	0.8	0.3	NNE [0.64]	0.32	0.51	0.19	6.00
09:00:00	0.5	0.5	1	SE [0.5]	0.25	0.25	0.50	1.00
09:00:01	0.5	0.4	0.8	SE [0.5]	0.25	0.20	0.40	2.00
09:00:02	0.4	0.3	0.7	SE [0.5]	0.20	0.15	0.35	3.00
09:00:03	0.4	0.3	0.7	SSE [0.17]	0.07	0.05	0.12	4.00
09:00:04	0.4	0.3	0.8	SSE [0.17]	0.07	0.05	0.14	5.00
09:00:05	0.4	0.2	1	SSE [0.17]	0.07	0.03	0.17	6.00
10:00:00	1	1.6	1.9	S [-0.17]	-0.17	-0.27	-0.32	1.00
10:00:01	1	1.8	1.8	S [-0.34]	-0.34	-0.61	-0.61	2.00
10:00:02	0.9	2	2	SSE [0.17]	0.15	0.34	0.34	3.00
10:00:03	0.9	1.9	1.9	SSE [0.17]	0.15	0.32	0.32	4.00
10:00:04	0.9	1.8	2.1	SSE [0.17]	0.15	0.31	0.36	5.00
10:00:05	1.2	1.8	2.2	S [-0.17]	-0.20	-0.31	-0.37	6.00
11:00:00	2.3	2.3	3	S [-0.34]	-0.78	-0.78	-1.02	1.00
11:00:01	2.4	2.7	3.3	S [-0.17]	-0.41	-0.46	-0.56	2.00
11:00:02	2.4	3	3.3	S [-0.17]	-0.41	-0.51	-0.56	3.00
11:00:03	2.6	2.9	3	S [-0.17]	-0.44	-0.49	-0.51	4.00
11:00:04	2.4	2.6	2.9	S [-0.17]	-0.41	-0.44	-0.49	5.00
11:00:05	2.2	2.8	2.9	S [-0.17]	-0.37	-0.48	-0.49	6.00
12:00:00	0.9	0.8	0.8	SSW [-0.64]	-0.58	-0.51	-0.51	1.00
12:00:01	0.8	0.7	0.9	SSW [-0.64]	-0.51	-0.45	-0.58	2.00
12:00:02	0.9	0.8	1.1	S [-0.17]	-0.15	-0.14	-0.19	3.00
12:00:03	1	1.3	1.3	S [-0.5]	-0.50	-0.65	-0.65	4.00
12:00:04	1.3	1.7	1.1	S [-0.34]	-0.44	-0.58	-0.37	5.00
12:00:05	1.9	1.8	1.1	SSE [0.34]	0.65	0.61	0.37	6.00

C.18 Data Set 28

Table C-18 – Data Set 28, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	4.2	3.8	2.3	WSW [-0.98]	-4.12	-3.72	-2.25	1.00
08:00:01	4.2	4.1	2.3	SW [-0.77]	-3.23	-3.16	-1.77	2.00
08:00:02	3.6	4.6	2.6	WSW [-1]	-3.60	-4.60	-2.60	3.00
08:00:03	3	4.6	2.2	WSW [-0.98]	-2.94	-4.51	-2.16	4.00
08:00:04	2.8	3.9	2.7	W [-0.98]	-2.74	-3.82	-2.65	5.00
08:00:05	2.6	3.4	5.1	WSW [-1]	-2.60	-3.40	-5.10	6.00
09:00:00	0.2	0.9	1.1	SW [-0.86]	-0.17	-0.77	-0.95	1.00
09:00:01	0.2	1.1	1.4	WSW [-0.98]	-0.20	-1.08	-1.37	2.00
09:00:02	0.2	1.3	1.5	WNW [-0.94]	-0.19	-1.22	-1.41	3.00
09:00:03	0.3	1.4	1.7	W [-0.98]	-0.29	-1.37	-1.67	4.00
09:00:04	0.3	1.5	1.9	W [-1]	-0.30	-1.50	-1.90	5.00
09:00:05	0.3	1.9	1.7	WSW [-1]	-0.30	-1.90	-1.70	6.00
10:00:00	2.6	3.2	4.1	WNW [-0.77]	-2.00	-2.46	-3.16	1.00
10:00:01	4.2	3.3	3.8	WNW [-0.94]	-3.95	-3.10	-3.57	2.00
10:00:02	3.9	3	3.2	W [-0.98]	-3.82	-2.94	-3.14	3.00
10:00:03	3.5	3.2	3.8	W [-1]	-3.50	-3.20	-3.80	4.00
10:00:04	3.1	3.2	4.4	W [-0.98]	-3.04	-3.14	-4.31	5.00
10:00:05	2.5	2.5	4.9	W [-0.98]	-2.45	-2.45	-4.80	6.00
11:00:00	1.9	2.3	3	W [-1]	-1.90	-2.30	-3.00	1.00
11:00:01	1.9	2.4	2.6	W [-1]	-1.90	-2.40	-2.60	2.00
11:00:02	1.7	2.3	2.5	W [-0.94]	-1.60	-2.16	-2.35	3.00
11:00:03	1.7	2.2	2.6	W [-1]	-1.70	-2.20	-2.60	4.00
11:00:04	1.7	2	2.7	WSW [-0.98]	-1.67	-1.96	-2.65	5.00
11:00:05	1.6	1.8	2.3	WSW [-0.98]	-1.57	-1.76	-2.25	6.00
12:00:00	5.3	4.6	3.9	WSW [-0.98]	-5.19	-4.51	-3.82	1.00
12:00:01	5.7	4.6	4	WSW [-1]	-5.70	-4.60	-4.00	2.00
12:00:02	4.7	5	5	WSW [-1]	-4.70	-5.00	-5.00	3.00
12:00:03	4.4	4.6	5.6	W [-1]	-4.40	-4.60	-5.60	4.00
12:00:04	4.1	4.3	5.1	W [-1]	-4.10	-4.30	-5.10	5.00
12:00:05	3.1	4.1	5.3	WSW [-0.98]	-3.04	-4.02	-5.19	6.00

C.19 Data Set 29

Table C-19 – Data Set 29, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	1.8	4.2	4.4	WSW [-0.94]	-1.69	-3.95	-4.14	1.00
08:00:01	2.2	4.2	4.2	SW [-0.94]	-2.07	-3.95	-3.95	2.00
08:00:02	2.4	4.2	4.3	SW [-0.94]	-2.26	-3.95	-4.04	3.00
08:00:03	2.4	4.1	4	WSW [-0.98]	-2.35	-4.02	-3.92	4.00
08:00:04	2.6	3.9	3.5	WSW [-1]	-2.60	-3.90	-3.50	5.00
08:00:05	3.2	3.8	3.5	WSW [-0.98]	-3.14	-3.72	-3.43	6.00
09:00:00	1.7	2.1	3.4	SW [-0.94]	-1.60	-1.97	-3.20	1.00
09:00:01	1.7	2.1	3	SW [-0.94]	-1.60	-1.97	-2.82	2.00
09:00:02	1.7	2	3	WSW [-0.98]	-1.67	-1.96	-2.94	3.00
09:00:03	1.7	2	3.3	WSW [-0.98]	-1.67	-1.96	-3.23	4.00
09:00:04	1.9	2.2	3.9	WSW [-1]	-1.90	-2.20	-3.90	5.00
09:00:05	2.7	2.5	4.4	WSW [-0.98]	-2.65	-2.45	-4.31	6.00
10:00:00	2.8	3.2	4.3	WSW [-1]	-2.80	-3.20	-4.30	1.00
10:00:01	2.8	3.2	4.1	WSW [-1]	-2.80	-3.20	-4.10	2.00
10:00:02	2.6	3.2	3.9	WSW [-1]	-2.60	-3.20	-3.90	3.00
10:00:03	2.2	2.8	4.7	W [-1]	-2.20	-2.80	-4.70	4.00
10:00:04	2.3	2.9	4	W [-1]	-2.30	-2.90	-4.00	5.00
10:00:05	2.4	2.9	3.6	WSW [-1]	-2.40	-2.90	-3.60	6.00
11:00:00	2.5	3.1	4	SW [-0.94]	-2.35	-2.91	-3.76	1.00
11:00:01	2.3	3.5	3.9	SW [-0.86]	-1.98	-3.01	-3.35	2.00
11:00:02	2.1	3.5	3.8	WSW [-0.98]	-2.06	-3.43	-3.72	3.00
11:00:03	2.1	3	3.3	WSW [-1]	-2.10	-3.00	-3.30	4.00
11:00:04	2.9	2.8	3.8	WSW [-0.98]	-2.84	-2.74	-3.72	5.00
11:00:05	3.1	4.3	3.9	WSW [-0.98]	-3.04	-4.21	-3.82	6.00
12:00:00	1.8	2.1	2.6	WSW [-1]	-1.80	-2.10	-2.60	1.00
12:00:01	1.8	2.2	2.5	WSW [-1]	-1.80	-2.20	-2.50	2.00
12:00:02	1.8	2.4	2.5	WSW [-0.98]	-1.76	-2.35	-2.45	3.00
12:00:03	1.9	2.6	2.7	SW [-0.94]	-1.79	-2.44	-2.54	4.00
12:00:04	2.1	3.1	3	WSW [-0.98]	-2.06	-3.04	-2.94	5.00
12:00:05	2.3	4.3	3.2	WSW [-0.98]	-2.25	-4.21	-3.14	6.00

C.20 Data Set 30**Table C-20 – Data Set 30, Samples A to E**

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2.5	3.1	3.2	SW [-0.94]	-2.35	-2.91	-3.01	1.00
08:00:01	2.4	2.9	3.2	SW [-0.86]	-2.06	-2.49	-2.75	2.00
08:00:02	2.1	2.5	2.8	SW [-0.94]	-1.97	-2.35	-2.63	3.00
08:00:03	1.8	2.5	3.1	SSW [-0.64]	-1.15	-1.60	-1.98	4.00
08:00:04	1.7	2.3	3.4	SSW [-0.77]	-1.31	-1.77	-2.62	5.00
08:00:05	2	2	3.4	SSW [-0.64]	-1.28	-1.28	-2.18	6.00
09:00:00	3.5	4.5	2.9	SW [-0.77]	-2.70	-3.47	-2.23	1.00
09:00:01	3.4	3.7	3.4	SSW [-0.64]	-2.18	-2.37	-2.18	2.00
09:00:02	3.3	2.9	3.2	SSW [-0.64]	-2.11	-1.86	-2.05	3.00
09:00:03	3.1	3.1	2.7	SW [-0.94]	-2.91	-2.91	-2.54	4.00
09:00:04	2.9	2.9	2.8	SSW [-0.77]	-2.23	-2.23	-2.16	5.00
09:00:05	2.8	2.8	2.9	SSW [-0.77]	-2.16	-2.16	-2.23	6.00
10:00:00	2	1.9	2.2	SW [-0.86]	-1.72	-1.63	-1.89	1.00
10:00:01	2.1	1.7	2	SW [-0.86]	-1.81	-1.46	-1.72	2.00
10:00:02	1.8	2.3	3	SW [-0.77]	-1.39	-1.77	-2.31	3.00
10:00:03	1.4	3.1	3.5	SW [-0.86]	-1.20	-2.67	-3.01	4.00
10:00:04	1.1	2.9	3.4	WSW [-1]	-1.10	-2.90	-3.40	5.00
10:00:05	1.1	2	3.2	WSW [-0.98]	-1.08	-1.96	-3.14	6.00
11:00:00	3.3	3.5	7.5	SSW [-0.5]	-1.65	-1.75	-3.75	1.00
11:00:01	3.1	4.1	5.9	SW [-0.86]	-2.67	-3.53	-5.07	2.00
11:00:02	3.7	5	5.1	SW [-0.77]	-2.85	-3.85	-3.93	3.00
11:00:03	4.2	5	4.9	SSW [-0.77]	-3.23	-3.85	-3.77	4.00
11:00:04	3.6	4.4	5.2	SSW [-0.64]	-2.30	-2.82	-3.33	5.00
11:00:05	2.9	3.6	4.4	SSW [-0.5]	-1.45	-1.80	-2.20	6.00
12:00:00	4.2	4.5	5.6	SW [-0.94]	-3.95	-4.23	-5.26	1.00
12:00:01	3.9	4.1	5.3	SW [-0.86]	-3.35	-3.53	-4.56	2.00
12:00:02	3.7	4.3	4.8	SW [-0.86]	-3.18	-3.70	-4.13	3.00
12:00:03	2.9	4	4.4	SSW [-0.64]	-1.86	-2.56	-2.82	4.00
12:00:04	3.2	3.5	4.7	SW [-0.86]	-2.75	-3.01	-4.04	5.00
12:00:05	3.5	4.1	4.2	WSW [-1]	-3.50	-4.10	-4.20	6.00

C.21 Data Set 41**Table C-21 – Data Set 41, Samples A to E**

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	1.2	2.1	3	WSW [-1]	-1.20	-2.10	-3.00	1.00
08:00:01	1.3	2	2.6	WSW [-1]	-1.30	-2.00	-2.60	2.00
08:00:02	1.5	1.8	1.8	W [-0.98]	-1.47	-1.76	-1.76	3.00
08:00:03	1.6	1.8	1.8	W [-0.98]	-1.57	-1.76	-1.76	4.00
08:00:04	1.6	1.8	2.4	WSW [-1]	-1.60	-1.80	-2.40	5.00
08:00:05	1.7	1.8	2.5	W [-1]	-1.70	-1.80	-2.50	6.00
09:00:00	2.9	3.5	3.8	WSW [-1]	-2.90	-3.50	-3.80	1.00
09:00:01	3.4	3.1	4.2	WSW [-1]	-3.40	-3.10	-4.20	2.00
09:00:02	3.1	3.2	4.2	WSW [-1]	-3.10	-3.20	-4.20	3.00
09:00:03	3.1	3.6	3.6	WNW [-0.86]	-2.67	-3.10	-3.10	4.00
09:00:04	3.6	3.5	3.6	WNW [-0.94]	-3.38	-3.29	-3.38	5.00
09:00:05	2.9	3.4	4.2	WNW [-0.94]	-2.73	-3.20	-3.95	6.00
10:00:00	2.8	2.9	3.1	WNW [-0.77]	-2.16	-2.23	-2.39	1.00
10:00:01	2.8	2.5	2.9	NW [-0.77]	-2.16	-1.93	-2.23	2.00
10:00:02	2.7	2.5	2.8	WNW [-0.86]	-2.32	-2.15	-2.41	3.00
10:00:03	2.3	2.3	2.4	WNW [-0.77]	-1.77	-1.77	-1.85	4.00
10:00:04	2.2	2.4	2.2	W [-0.98]	-2.16	-2.35	-2.16	5.00
10:00:05	1.9	3.3	2.6	W [-1]	-1.90	-3.30	-2.60	6.00
11:00:00	6.7	6.6	5.6	W [-1]	-6.70	-6.60	-5.60	1.00
11:00:01	5.7	6.7	6.1	W [-1]	-5.70	-6.70	-6.10	2.00
11:00:02	4.8	5.6	6.3	WSW [-1]	-4.80	-5.60	-6.30	3.00
11:00:03	4.9	4.8	7.7	W [-1]	-4.90	-4.80	-7.70	4.00
11:00:04	5	5.5	8.6	W [-0.98]	-4.90	-5.39	-8.43	5.00
11:00:05	4.8	7.2	8.2	W [-0.98]	-4.70	-7.06	-8.04	6.00
12:00:00	1.2	1.4	3	WNW [-0.94]	-1.13	-1.32	-2.82	1.00
12:00:01	1.4	1.8	5.1	WNW [-0.94]	-1.32	-1.69	-4.79	2.00
12:00:02	1.5	2.8	5.8	W [-0.98]	-1.47	-2.74	-5.68	3.00
12:00:03	1.8	4.7	5.2	W [-0.98]	-1.76	-4.61	-5.10	4.00
12:00:04	2.5	5.5	5.2	WNW [-0.94]	-2.35	-5.17	-4.89	5.00
12:00:05	4.1	4.5	7.2	W [-0.98]	-4.02	-4.41	-7.06	6.00

C.22 Data Set 42

Table C-22 – Data Set 42, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2.6	3.2	3.5	WNW [-0.94]	-2.44	-3.01	-3.29	1.00
08:00:01	2.8	3.3	3.9	W [-0.98]	-2.74	-3.23	-3.82	2.00
08:00:02	2.2	3.4	4.1	W [-0.94]	-2.07	-3.20	-3.85	3.00
08:00:03	2.3	2.9	3.6	WNW [-0.86]	-1.98	-2.49	-3.10	4.00
08:00:04	2.1	2.6	3.5	WNW [-0.77]	-1.62	-2.00	-2.70	5.00
08:00:05	2	2.7	3.2	W [-1]	-2.00	-2.70	-3.20	6.00
09:00:00	2.4	2.4	3.1	NW [-0.64]	-1.54	-1.54	-1.98	1.00
09:00:01	2.3	2.6	3.2	WNW [-0.77]	-1.77	-2.00	-2.46	2.00
09:00:02	2.1	2.6	3.2	NW [-0.64]	-1.34	-1.66	-2.05	3.00
09:00:03	1.6	1.9	3.1	WNW [-0.86]	-1.38	-1.63	-2.67	4.00
09:00:04	1.8	1.8	2.7	WNW [-0.94]	-1.69	-1.69	-2.54	5.00
09:00:05	1.5	1.7	2.4	NW [-0.77]	-1.16	-1.31	-1.85	6.00
10:00:00	1.2	1.4	3.3	NW [-0.77]	-0.92	-1.08	-2.54	1.00
10:00:01	1.7	1.7	2.6	WNW [-0.77]	-1.31	-1.31	-2.00	2.00
10:00:02	2.1	2	2.8	W [-0.94]	-1.97	-1.88	-2.63	3.00
10:00:03	2.1	2	2.8	W [-0.98]	-2.06	-1.96	-2.74	4.00
10:00:04	2	2.2	2.7	W [-0.98]	-1.96	-2.16	-2.65	5.00
10:00:05	1.7	2.2	2.5	WNW [-0.77]	-1.31	-1.69	-1.93	6.00
11:00:00	7.1	8.4	9.5	W [-0.94]	-6.67	-7.90	-8.93	1.00
11:00:01	6.6	7.6	8.2	WNW [-0.86]	-5.68	-6.54	-7.05	2.00
11:00:02	7.7	7	8.2	NW [-0.77]	-5.93	-5.39	-6.31	3.00
11:00:03	6.6	6.7	7.1	NW [-0.77]	-5.08	-5.16	-5.47	4.00
11:00:04	4.6	5.6	7.3	WNW [-0.86]	-3.96	-4.82	-6.28	5.00
11:00:05	4.7	6	6.7	WNW [-0.86]	-4.04	-5.16	-5.76	6.00
12:00:00	3.2	4.2	5	N [0.17]	0.54	0.71	0.85	1.00
12:00:01	2.8	4.3	5.2	N [0.17]	0.48	0.73	0.88	2.00
12:00:02	2.4	3.5	5.4	NNW [-0.17]	-0.41	-0.60	-0.92	3.00
12:00:03	2.1	3.4	5	N [0.17]	0.36	0.58	0.85	4.00
12:00:04	2.3	3	3.9	NNW [-0.34]	-0.78	-1.02	-1.33	5.00
12:00:05	2.5	3.2	3.3	NNW [-0.17]	-0.43	-0.54	-0.56	6.00

C.23 Data Set 43

Table C-23 – Data Set 43, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	1.9	1.8	2.4	SSW [-0.64]	-1.22	-1.15	-1.54	1.00
08:00:01	1.9	1.9	2.6	SSW [-0.77]	-1.46	-1.46	-2.00	2.00
08:00:02	1.9	2.3	2.7	S [-0.34]	-0.65	-0.78	-0.92	3.00
08:00:03	2	2.4	2.5	SSW [-0.77]	-1.54	-1.85	-1.93	4.00
08:00:04	2.2	2.3	2.3	SSW [-0.64]	-1.41	-1.47	-1.47	5.00
08:00:05	2.4	2.2	2.2	SSW [-0.64]	-1.54	-1.41	-1.41	6.00
09:00:00	1.3	1.4	1.4	NW [-0.64]	-0.83	-0.90	-0.90	1.00
09:00:01	1.3	1.4	1.3	NW [-0.64]	-0.83	-0.90	-0.83	2.00
09:00:02	1.3	1.4	1.3	NW [-0.64]	-0.83	-0.90	-0.83	3.00
09:00:03	1.3	1.4	1.4	NW [-0.64]	-0.83	-0.90	-0.90	4.00
09:00:04	1.3	1.3	1.4	NW [-0.64]	-0.83	-0.83	-0.90	5.00
09:00:05	1.2	1.2	1.4	NW [-0.64]	-0.77	-0.77	-0.90	6.00
10:00:00	1	1.1	1.5	SW [-0.86]	-0.86	-0.95	-1.29	1.00
10:00:01	1	1.2	1.5	SW [-0.86]	-0.86	-1.03	-1.29	2.00
10:00:02	1	1.2	1.5	SW [-0.86]	-0.86	-1.03	-1.29	3.00
10:00:03	0.9	1.1	1.5	SW [-0.86]	-0.77	-0.95	-1.29	4.00
10:00:04	1	1	1.5	SW [-0.86]	-0.86	-0.86	-1.29	5.00
10:00:05	1.2	1	1.5	SW [-0.86]	-1.03	-0.86	-1.29	6.00
11:00:00	1.3	1.7	1.5	SW [-0.94]	-1.22	-1.60	-1.41	1.00
11:00:01	1.4	1.6	1.6	SW [-0.94]	-1.32	-1.50	-1.50	2.00
11:00:02	1.4	1.5	1.7	SW [-0.94]	-1.32	-1.41	-1.60	3.00
11:00:03	1.4	1.6	1.5	WSW [-1]	-1.40	-1.60	-1.50	4.00
11:00:04	1.4	1.7	1.7	WSW [-0.98]	-1.37	-1.67	-1.67	5.00
11:00:05	1.3	1.8	1.7	WSW [-0.98]	-1.27	-1.76	-1.67	6.00
12:00:00	1.3	1.5	1.7	W [-0.94]	-1.22	-1.41	-1.60	1.00
12:00:01	1.4	1.5	1.6	W [-0.98]	-1.37	-1.47	-1.57	2.00
12:00:02	1.5	1.5	1.7	W [-0.98]	-1.47	-1.47	-1.67	3.00
12:00:03	1.4	1.6	1.8	W [-0.98]	-1.37	-1.57	-1.76	4.00
12:00:04	1.3	1.5	1.9	W [-0.98]	-1.27	-1.47	-1.86	5.00
12:00:05	1.3	1.5	1.9	W [-0.98]	-1.27	-1.47	-1.86	6.00

C.24 Data Set 44

Table C-24 – Data Set 44, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2.1	2	1.9	WNW [-0.77]	-1.62	-1.54	-1.46	1.00
08:00:01	1.8	2	1.7	W [-0.98]	-1.76	-1.96	-1.67	2.00
08:00:02	1.5	1.9	1.6	W [-0.94]	-1.41	-1.79	-1.50	3.00
08:00:03	1.2	2	1.7	W [-0.98]	-1.18	-1.96	-1.67	4.00
08:00:04	1	2.1	2.2	WNW [-0.86]	-0.86	-1.81	-1.89	5.00
08:00:05	1.1	2.5	2.5	WNW [-0.86]	-0.95	-2.15	-2.15	6.00
09:00:00	3.1	3	3	WSW [-0.94]	-2.91	-2.82	-2.82	1.00
09:00:01	3	2.9	3	SW [-0.94]	-2.82	-2.73	-2.82	2.00
09:00:02	3.1	3.2	3	SW [-0.94]	-2.91	-3.01	-2.82	3.00
09:00:03	3	2.9	2.8	SW [-0.77]	-2.31	-2.23	-2.16	4.00
09:00:04	3	2.9	2.6	SW [-0.86]	-2.58	-2.49	-2.24	5.00
09:00:05	2.8	3.1	2.5	SW [-0.94]	-2.63	-2.91	-2.35	6.00
10:00:00	1.9	2.5	2.5	WSW [-1]	-1.90	-2.50	-2.50	1.00
10:00:01	1.7	2.4	2.2	W [-1]	-1.70	-2.40	-2.20	2.00
10:00:02	1.6	2.4	2.2	W [-1]	-1.60	-2.40	-2.20	3.00
10:00:03	1.6	2.2	2.2	W [-1]	-1.60	-2.20	-2.20	4.00
10:00:04	1.6	2.1	2.5	W [-1]	-1.60	-2.10	-2.50	5.00
10:00:05	1.4	2	2.3	WSW [-0.98]	-1.37	-1.96	-2.25	6.00
11:00:00	4.7	6.3	4.3	W [-1]	-4.70	-6.30	-4.30	1.00
11:00:01	5	5.9	4.5	W [-0.98]	-4.90	-5.78	-4.41	2.00
11:00:02	4.8	5.9	4.6	WNW [-0.94]	-4.51	-5.55	-4.32	3.00
11:00:03	4.5	5	4.8	WNW [-0.86]	-3.87	-4.30	-4.13	4.00
11:00:04	3.9	4.3	4.8	WNW [-0.94]	-3.67	-4.04	-4.51	5.00
11:00:05	3.5	3.8	4.2	W [-0.98]	-3.43	-3.72	-4.12	6.00
12:00:00	3.3	4.7	5.4	WSW [-0.98]	-3.23	-4.61	-5.29	1.00
12:00:01	3	4.9	5.4	WSW [-1]	-3.00	-4.90	-5.40	2.00
12:00:02	2.9	4.3	4.7	WSW [-0.98]	-2.84	-4.21	-4.61	3.00
12:00:03	2.7	4.2	4.3	WSW [-1]	-2.70	-4.20	-4.30	4.00
12:00:04	2.6	4	4.2	WSW [-1]	-2.60	-4.00	-4.20	5.00
12:00:05	3	3.4	4.7	W [-0.98]	-2.94	-3.33	-4.61	6.00

C.25 Data Set 45

Table C-25 – Data Set 45, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2.6	3.7	7.8	W [-1]	-2.60	-3.70	-7.80	1.00
08:00:01	3.4	3.2	6.8	W [-1]	-3.40	-3.20	-6.80	2.00
08:00:02	3.8	3.7	4.3	W [-1]	-3.80	-3.70	-4.30	3.00
08:00:03	2.8	3.1	3.1	WNW [-0.86]	-2.41	-2.67	-2.67	4.00
08:00:04	2.1	3.1	2.7	NW [-0.64]	-1.34	-1.98	-1.73	5.00
08:00:05	2.2	3.5	3.6	NNW [-0.17]	-0.37	-0.60	-0.61	6.00
09:00:00	5.1	5.7	4.7	NW [-0.77]	-3.93	-4.39	-3.62	1.00
09:00:01	5.1	5.2	5.3	NW [-0.64]	-3.26	-3.33	-3.39	2.00
09:00:02	4.4	4.8	5.6	WNW [-0.86]	-3.78	-4.13	-4.82	3.00
09:00:03	3.6	5	5.4	W [-0.98]	-3.53	-4.90	-5.29	4.00
09:00:04	4.2	5.8	5.5	NW [-0.5]	-2.10	-2.90	-2.75	5.00
09:00:05	4.7	4.9	4.2	WNW [-0.86]	-4.04	-4.21	-3.61	6.00
10:00:00	2.3	3.6	4.4	NNE [0.64]	1.47	2.30	2.82	1.00
10:00:01	3	3.7	4.2	N [0.34]	1.02	1.26	1.43	2.00
10:00:02	2.6	4	4.3	NNW [-0.17]	-0.44	-0.68	-0.73	3.00
10:00:03	2.6	3.3	4.1	N [0.34]	0.88	1.12	1.39	4.00
10:00:04	2.5	3.5	3.4	N [0.17]	0.43	0.60	0.58	5.00
10:00:05	2.1	3.3	3.4	NNE [0.5]	1.05	1.65	1.70	6.00
11:00:00	2.8	3.6	3.6	NNW [-0.5]	-1.40	-1.80	-1.80	1.00
11:00:01	2.6	3.1	4.1	WNW [-0.86]	-2.24	-2.67	-3.53	2.00
11:00:02	2.2	3.5	3.4	WNW [-0.94]	-2.07	-3.29	-3.20	3.00
11:00:03	1.8	3.4	3.5	W [-0.94]	-1.69	-3.20	-3.29	4.00
11:00:04	1.6	2.8	3.8	WNW [-0.86]	-1.38	-2.41	-3.27	5.00
11:00:05	1.6	2.2	3.7	NNW [-0.34]	-0.54	-0.75	-1.26	6.00
12:00:00	2.7	2.1	3.7	WNW [-0.86]	-2.32	-1.81	-3.18	1.00
12:00:01	2.7	2.2	3.7	WNW [-0.77]	-2.08	-1.69	-2.85	2.00
12:00:02	2.8	3	3.7	WNW [-0.86]	-2.41	-2.58	-3.18	3.00
12:00:03	2.6	4.7	4.7	NW [-0.77]	-2.00	-3.62	-3.62	4.00
12:00:04	3.3	6	5.6	WNW [-0.86]	-2.84	-5.16	-4.82	5.00
12:00:05	4.3	6.5	7.1	NW [-0.77]	-3.31	-5.01	-5.47	6.00

C.26 Data Set 46

Table C-26 – Data Set 46, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	1.6	1.2	1.5	SSW [-0.5]	-0.80	-0.60	-0.75	1.00
08:00:01	1.5	1.2	1.5	SSW [-0.5]	-0.75	-0.60	-0.75	2.00
08:00:02	1.4	1.2	1.8	S [-0.17]	-0.24	-0.20	-0.31	3.00
08:00:03	1.3	1.2	2	SSE [0.17]	0.22	0.20	0.34	4.00
08:00:04	1.3	1.2	2.1	S [-0.17]	-0.22	-0.20	-0.36	5.00
08:00:05	1.3	1.1	1.8	S [-0.34]	-0.44	-0.37	-0.61	6.00
09:00:00	1.1	1.4	1.7	S [-0.34]	-0.37	-0.48	-0.58	1.00
09:00:01	1.1	1.6	1.6	SSW [-0.5]	-0.55	-0.80	-0.80	2.00
09:00:02	1.1	1.7	1.7	SSW [-0.64]	-0.70	-1.09	-1.09	3.00
09:00:03	1.2	1.8	1.9	SSW [-0.64]	-0.77	-1.15	-1.22	4.00
09:00:04	1.7	1.6	2.1	S [-0.34]	-0.58	-0.54	-0.71	5.00
09:00:05	1.7	1.5	2	S [-0.34]	-0.58	-0.51	-0.68	6.00
10:00:00	1.5	1.6	1.7	SSW [-0.5]	-0.75	-0.80	-0.85	1.00
10:00:01	1.4	1.5	1.7	SSW [-0.5]	-0.70	-0.75	-0.85	2.00
10:00:02	1.3	1.4	1.4	SSW [-0.64]	-0.83	-0.90	-0.90	3.00
10:00:03	1.2	1.4	1.5	S [-0.34]	-0.41	-0.48	-0.51	4.00
10:00:04	1.2	1.5	1.5	S [-0.34]	-0.41	-0.51	-0.51	5.00
10:00:05	1.1	1.5	1.6	S [-0.34]	-0.37	-0.51	-0.54	6.00
11:00:00	2.5	2.4	1.6	SE [0.64]	1.60	1.54	1.02	1.00
11:00:01	2.5	2.3	1.4	SSE [0.34]	0.85	0.78	0.48	2.00
11:00:02	2.1	2.5	1.7	ESE [0.86]	1.81	2.15	1.46	3.00
11:00:03	1.7	2.4	2.4	ESE [0.86]	1.46	2.06	2.06	4.00
11:00:04	1.3	2.4	2.7	ESE [0.86]	1.12	2.06	2.32	5.00
11:00:05	1	2.2	2.7	SSE [0.34]	0.34	0.75	0.92	6.00
12:00:00	2.2	3.7	4.9	SSW [-0.5]	-1.10	-1.85	-2.45	1.00
12:00:01	1.9	3.9	5.4	S [-0.34]	-0.65	-1.33	-1.84	2.00
12:00:02	1.5	3.4	4.7	S [-0.5]	-0.75	-1.70	-2.35	3.00
12:00:03	1.4	3	4.4	SSW [-0.5]	-0.70	-1.50	-2.20	4.00
12:00:04	1.6	3.2	4	SSW [-0.5]	-0.80	-1.60	-2.00	5.00
12:00:05	1.5	2.9	4.6	S [-0.34]	-0.51	-0.99	-1.56	6.00

C.27 Data Set 47**Table C-27 – Data Set 47, Samples A to E**

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	0.4	0.8	0.9	SSE [0.34]	0.14	0.27	0.31	1.00
08:00:01	0.3	0.9	0.8	SE [0.64]	0.19	0.58	0.51	2.00
08:00:02	0.2	0.9	1.1	SE [0.77]	0.15	0.69	0.85	3.00
08:00:03	0.2	0.9	1.1	ESE [0.86]	0.17	0.77	0.95	4.00
08:00:04	0.2	0.9	1.1	ESE [0.86]	0.17	0.77	0.95	5.00
08:00:05	0.1	0.8	1.1	ESE [0.86]	0.09	0.69	0.95	6.00
09:00:00	1.5	2.3	2.3	ESE [0.77]	1.16	1.77	1.77	1.00
09:00:01	1.4	1.9	2.2	SSE [0.34]	0.48	0.65	0.75	2.00
09:00:02	1.7	1.6	2.5	SSE [0.34]	0.58	0.54	0.85	3.00
09:00:03	1.7	1.4	2.8	S [-0.17]	-0.29	-0.24	-0.48	4.00
09:00:04	1.8	1.3	2.9	SSE [0.34]	0.61	0.44	0.99	5.00
09:00:05	1.6	1.5	2.1	SE [0.64]	1.02	0.96	1.34	6.00
10:00:00	3.6	3.5	3.7	SE [0.64]	2.30	2.24	2.37	1.00
10:00:01	3.2	3.4	3.8	E [0.94]	3.01	3.20	3.57	2.00
10:00:02	3.1	4.2	4.8	E [0.94]	2.91	3.95	4.51	3.00
10:00:03	3.9	5.1	3.9	ESE [0.86]	3.35	4.39	3.35	4.00
10:00:04	4.5	5.3	4.1	SSE [0.34]	1.53	1.80	1.39	5.00
10:00:05	4.5	5	3.8	SE [0.5]	2.25	2.50	1.90	6.00
11:00:00	5.6	7.8	9.8	S [-0.5]	-2.80	-3.90	-4.90	1.00
11:00:01	5.3	9.3	9.9	S [-0.5]	-2.65	-4.65	-4.95	2.00
11:00:02	5.7	11.3	11.5	S [-0.34]	-1.94	-3.84	-3.91	3.00
11:00:03	7.8	12.9	14.3	SSW [-0.5]	-3.90	-6.45	-7.15	4.00
11:00:04	7.7	8.8	12.2	SE [0.64]	4.93	5.63	7.81	5.00
11:00:05	8.3	8.4	9.3	S [-0.17]	-1.41	-1.43	-1.58	6.00
12:00:00	1.3	1.9	2.2	SSW [-0.64]	-0.83	-1.22	-1.41	1.00
12:00:01	1.3	1.8	2	SSW [-0.77]	-1.00	-1.39	-1.54	2.00
12:00:02	1.5	1.7	2.2	S [-0.5]	-0.75	-0.85	-1.10	3.00
12:00:03	1.6	1.4	2.4	S [-0.5]	-0.80	-0.70	-1.20	4.00
12:00:04	1.5	1.4	2.3	S [-0.5]	-0.75	-0.70	-1.15	5.00
12:00:05	1.4	1.5	2.4	S [-0.17]	-0.24	-0.26	-0.41	6.00

C.28 Data Set 48

Table C-28 – Data Set 48, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	1.6	2.1	2.6	S [-0.34]	-0.54	-0.71	-0.88	1.00
08:00:01	1.5	2	2.4	SSW [-0.5]	-0.75	-1.00	-1.20	2.00
08:00:02	1.4	2	2.1	SW [-0.77]	-1.08	-1.54	-1.62	3.00
08:00:03	1.7	1.8	2	SW [-0.77]	-1.31	-1.39	-1.54	4.00
08:00:04	2.1	1.7	2.1	SSW [-0.64]	-1.34	-1.09	-1.34	5.00
08:00:05	2	2.4	2.4	SSW [-0.64]	-1.28	-1.54	-1.54	6.00
09:00:00	2.1	2.9	2.5	SW [-0.86]	-1.81	-2.49	-2.15	1.00
09:00:01	2.3	3.2	2.9	SW [-0.77]	-1.77	-2.46	-2.23	2.00
09:00:02	2.3	3.2	3.4	SSW [-0.77]	-1.77	-2.46	-2.62	3.00
09:00:03	2.4	3.3	3.5	SSW [-0.77]	-1.85	-2.54	-2.70	4.00
09:00:04	2.5	3.2	3.4	SSW [-0.64]	-1.60	-2.05	-2.18	5.00
09:00:05	2.6	3.2	4.1	SSW [-0.5]	-1.30	-1.60	-2.05	6.00
10:00:00	2.6	3.1	3.7	SSW [-0.64]	-1.66	-1.98	-2.37	1.00
10:00:01	2.6	2.8	3.6	SW [-0.86]	-2.24	-2.41	-3.10	2.00
10:00:02	2.8	2.5	3.6	SW [-0.94]	-2.63	-2.35	-3.38	3.00
10:00:03	3.5	2.9	3.5	WSW [-1]	-3.50	-2.90	-3.50	4.00
10:00:04	3.3	3.5	3.2	SW [-0.94]	-3.10	-3.29	-3.01	5.00
10:00:05	3.1	2.8	4.1	SW [-0.77]	-2.39	-2.16	-3.16	6.00
11:00:00	2.1	4.4	3.8	SSW [-0.77]	-1.62	-3.39	-2.93	1.00
11:00:01	3	4.1	3.9	SSW [-0.64]	-1.92	-2.62	-2.50	2.00
11:00:02	2.8	3.7	4	SW [-0.86]	-2.41	-3.18	-3.44	3.00
11:00:03	3.4	4.1	4.3	SW [-0.86]	-2.92	-3.53	-3.70	4.00
11:00:04	3.4	3.9	4.2	WSW [-0.94]	-3.20	-3.67	-3.95	5.00
11:00:05	3.2	3.3	3.3	W [-0.98]	-3.14	-3.23	-3.23	6.00
12:00:00	5.4	5.1	5.4	WSW [-0.94]	-5.08	-4.79	-5.08	1.00
12:00:01	5.1	4.7	4.8	SW [-0.94]	-4.79	-4.42	-4.51	2.00
12:00:02	5	4.5	4.2	WSW [-1]	-5.00	-4.50	-4.20	3.00
12:00:03	4.3	4.6	4.5	SW [-0.86]	-3.70	-3.96	-3.87	4.00
12:00:04	3.6	4	3.9	W [-0.98]	-3.53	-3.92	-3.82	5.00
12:00:05	3.4	4.5	3.6	WSW [-1]	-3.40	-4.50	-3.60	6.00

C.29 Data Set 49**Table C-29 – Data Set 49, Samples A to E**

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	1.2	1.4	2.4	WSW [-0.94]	-1.13	-1.32	-2.26	1.00
08:00:01	1.3	1.3	2.4	SW [-0.94]	-1.22	-1.22	-2.26	2.00
08:00:02	1.2	1.6	2.3	SW [-0.86]	-1.03	-1.38	-1.98	3.00
08:00:03	1.1	1.7	2.3	WSW [-0.98]	-1.08	-1.67	-2.25	4.00
08:00:04	1.1	1.7	2.5	SW [-0.94]	-1.03	-1.60	-2.35	5.00
08:00:05	1.2	1.7	2.4	SW [-0.94]	-1.13	-1.60	-2.26	6.00
09:00:00	1.1	1.3	1.2	SW [-0.86]	-0.95	-1.12	-1.03	1.00
09:00:01	1.1	1.3	1.2	WSW [-0.94]	-1.03	-1.22	-1.13	2.00
09:00:02	1.2	1.3	1.4	WSW [-0.98]	-1.18	-1.27	-1.37	3.00
09:00:03	1.2	1.2	1.4	WSW [-0.98]	-1.18	-1.18	-1.37	4.00
09:00:04	1.2	1.2	1.3	SW [-0.94]	-1.13	-1.13	-1.22	5.00
09:00:05	1.2	1.3	1.2	SW [-0.94]	-1.13	-1.22	-1.13	6.00
10:00:00	2.9	3.3	3.4	SW [-0.86]	-2.49	-2.84	-2.92	1.00
10:00:01	2.7	3.2	3.4	SW [-0.86]	-2.32	-2.75	-2.92	2.00
10:00:02	2.7	2.9	3.3	SW [-0.86]	-2.32	-2.49	-2.84	3.00
10:00:03	2.9	2.8	3.3	SW [-0.86]	-2.49	-2.41	-2.84	4.00
10:00:04	2.8	2.7	3.1	SW [-0.94]	-2.63	-2.54	-2.91	5.00
10:00:05	2.7	2.6	3	WSW [-0.94]	-2.54	-2.44	-2.82	6.00
11:00:00	0.9	1.2	1.9	SW [-0.86]	-0.77	-1.03	-1.63	1.00
11:00:01	0.8	1.3	1.8	SW [-0.86]	-0.69	-1.12	-1.55	2.00
11:00:02	0.9	1.4	2	SW [-0.86]	-0.77	-1.20	-1.72	3.00
11:00:03	1	1.4	1.8	SW [-0.86]	-0.86	-1.20	-1.55	4.00
11:00:04	0.9	1.4	1.8	SW [-0.86]	-0.77	-1.20	-1.55	5.00
11:00:05	0.9	1.4	1.8	SW [-0.77]	-0.69	-1.08	-1.39	6.00
12:00:00	4.1	4.3	4.6	WSW [-1]	-4.10	-4.30	-4.60	1.00
12:00:01	3.9	4.1	4.9	WSW [-1]	-3.90	-4.10	-4.90	2.00
12:00:02	3.8	4.1	4.9	WSW [-1]	-3.80	-4.10	-4.90	3.00
12:00:03	3.7	4	5.1	WSW [-1]	-3.70	-4.00	-5.10	4.00
12:00:04	4.1	4.1	5.2	WSW [-1]	-4.10	-4.10	-5.20	5.00
12:00:05	4.7	4.5	5.5	WSW [-0.98]	-4.61	-4.41	-5.39	6.00

C.30 Data Set 50

Table C-30 – Data Set 50, Samples A to E

Time [UTC]	U2 [m/s]	U5 [m/s]	U10 [m/s]	Crosswind [CW] Factor	2m CW	5m CW	10m CW	Sec
08:00:00	2.9	4.3	5.7	NNW [-0.34]	-0.99	-1.46	-1.94	1.00
08:00:01	3	3.9	4.5	NW [-0.5]	-1.50	-1.95	-2.25	2.00
08:00:02	3.4	3.9	4.1	NW [-0.77]	-2.62	-3.00	-3.16	3.00
08:00:03	3.4	3.6	3.6	WNW [-0.86]	-2.92	-3.10	-3.10	4.00
08:00:04	3.6	3.5	3.3	W [-0.98]	-3.53	-3.43	-3.23	5.00
08:00:05	3.5	3.1	3.2	W [-0.98]	-3.43	-3.04	-3.14	6.00
09:00:00	3.5	4.6	5.6	W [-0.94]	-3.29	-4.32	-5.26	1.00
09:00:01	4.5	5.1	5.2	WNW [-0.86]	-3.87	-4.39	-4.47	2.00
09:00:02	5.2	4.9	5.4	W [-0.94]	-4.89	-4.61	-5.08	3.00
09:00:03	4.7	4.6	4.9	WNW [-0.94]	-4.42	-4.32	-4.61	4.00
09:00:04	3.8	4.3	5.1	WSW [-1]	-3.80	-4.30	-5.10	5.00
09:00:05	3.4	3.7	5.1	W [-1]	-3.40	-3.70	-5.10	6.00
10:00:00	3.7	4.3	4.6	WNW [-0.77]	-2.85	-3.31	-3.54	1.00
10:00:01	3	3.1	4.8	NW [-0.64]	-1.92	-1.98	-3.07	2.00
10:00:02	2.6	2.9	4.1	NW [-0.77]	-2.00	-2.23	-3.16	3.00
10:00:03	2.3	2.5	3.5	WNW [-0.86]	-1.98	-2.15	-3.01	4.00
10:00:04	2	2.2	3.5	WNW [-0.94]	-1.88	-2.07	-3.29	5.00
10:00:05	1.7	1.7	3.7	WNW [-0.86]	-1.46	-1.46	-3.18	6.00
11:00:00	2.2	1.3	1.7	SW [-0.86]	-1.89	-1.12	-1.46	1.00
11:00:01	2.2	1.2	1.3	NW [-0.77]	-1.69	-0.92	-1.00	2.00
11:00:02	2.1	1.1	1.2	NW [-0.5]	-1.05	-0.55	-0.60	3.00
11:00:03	2.1	1.5	1.3	SW [-0.94]	-1.97	-1.41	-1.22	4.00
11:00:04	2.2	1.7	1.4	WNW [-0.86]	-1.89	-1.46	-1.20	5.00
11:00:05	2.3	2.2	2.5	WNW [-0.94]	-2.16	-2.07	-2.35	6.00
12:00:00	1.8	2.5	4.2	NNW [-0.17]	-0.31	-0.43	-0.71	1.00
12:00:01	2	2.9	4.7	N [0.17]	0.34	0.49	0.80	2.00
12:00:02	1.8	2.6	4	N [0.34]	0.61	0.88	1.36	3.00
12:00:03	1.7	2.2	3.8	NW [-0.64]	-1.09	-1.41	-2.43	4.00
12:00:04	1.9	2.6	3.4	NNW [-0.17]	-0.32	-0.44	-0.58	5.00
12:00:05	1.9	2.9	2.6	SW [-0.86]	-1.63	-2.49	-2.24	6.00

C.31 Data Sets 1-10 Averages

Table C-31 – Data Set 1-10 Wind Averages

Data Set		Wind Speed [m/s]			10mph ref	NW Euro Stand Dev	
		1-3 Av	4-6 Av	All Av	Tgt - 4.47 m/s	Tgt - 1.49 m/s	Tgt - 1.82 m/s
1	A	-1.49	-1.81	-1.65	-37%	-111%	-91%
	B	1.31	-0.60	0.35	8%	24%	19%
	C	0.16	3.63	1.89	42%	127%	104%
	D	1.42	1.66	1.54	34%	103%	85%
	E	-0.94	-0.38	-0.66	-15%	-44%	-36%
2	A	0.48	0.40	0.44	10%	29%	24%
	B	0.36	0.52	0.44	10%	30%	24%
	C	1.18	1.18	1.18	26%	79%	65%
	D	-0.24	-0.60	-0.42	-9%	-28%	-23%
	E	0.59	0.90	0.75	17%	50%	41%
3	A	-0.01	0.00	0.00	0%	0%	0%
	B	-1.49	-1.50	-1.50	-33%	-100%	-82%
	C	-1.20	-1.64	-1.42	-32%	-95%	-78%
	D	-1.43	-1.09	-1.26	-28%	-85%	-69%
	E	-0.35	-0.56	-0.46	-10%	-31%	-25%
4	A	-3.31	-3.43	-3.37	-75%	-226%	-185%
	B	-3.46	-2.39	-2.93	-65%	-196%	-161%
	C	-2.16	-2.47	-2.32	-52%	-155%	-127%
	D	-3.58	-3.03	-3.30	-74%	-222%	-182%
	E	-1.61	-1.38	-1.50	-33%	-100%	-82%
5	A	-2.17	-2.68	-2.43	-54%	-163%	-133%
	B	-1.68	-1.57	-1.62	-36%	-109%	-89%
	C	-2.13	-2.53	-2.33	-52%	-157%	-128%
	D	-1.85	-2.21	-2.03	-45%	-136%	-112%
	E	-1.72	-1.26	-1.49	-33%	-100%	-82%
6	A	-2.39	-2.30	-2.34	-52%	-157%	-129%
	B	-0.98	-2.83	-1.91	-43%	-128%	-105%
	C	-1.93	-3.74	-2.83	-63%	-190%	-156%
	D	-5.28	-4.66	-4.97	-111%	-334%	-273%

Data Set	Wind Speed [m/s]			10mph ref	NW Euro Stand Dev	
	1-3 Av	4-6 Av	All Av	Tgt - 4.47 m/s	Tgt - 1.49 m/s	Tgt - 1.82 m/s
7	E	-4.31	-3.16	-3.74	-84%	-251%
	A	-2.03	-1.88	-1.96	-44%	-131%
	B	-5.52	-4.36	-4.94	-111%	-332%
	C	-5.84	-5.49	-5.67	-127%	-380%
	D	-5.49	-5.57	-5.53	-124%	-371%
8	E	-6.68	-7.10	-6.89	-154%	-463%
	A	0.55	0.67	0.61	14%	41%
	B	0.58	0.75	0.67	15%	45%
	C	0.65	0.54	0.59	13%	40%
	D	0.34	0.38	0.36	8%	24%
9	E	0.72	0.59	0.65	15%	44%
	A	-0.97	-1.09	-1.03	-23%	-69%
	B	-1.46	-2.33	-1.90	-42%	-127%
	C	-2.46	-1.93	-2.19	-49%	-147%
	D	-1.91	-1.50	-1.71	-38%	-115%
10	E	-1.00	-1.29	-1.15	-26%	-77%
	A	0.43	0.43	0.43	10%	29%
	B	-0.06	-0.09	-0.07	-2%	-5%
	C	0.62	0.41	0.51	11%	34%
	D	-1.82	-2.27	-2.04	-46%	-137%
	E	1.48	1.31	1.40	31%	94%

C.32 Data Sets 21-30 Averages

Table C-32 - Data Set 21-30 Wind Averages

Data Set		Wind Speed [m/s]			10mph ref	NW Euro Stand Dev	
		1-3 Av	4-6 Av	All Av	Tgt - 4.47 m/s	Tgt - 1.49 m/s	Tgt - 1.82 m/s
21	A	-0.752	-0.653	-0.7	-16%	-47%	-39%
	B	-1.667	-2.067	-1.87	-42%	-125%	-103%
	C	-2.091	-2.542	-2.32	-52%	-155%	-127%
	D	-0.266	-0.475	-0.37	-8%	-25%	-20%
	E	3.089	3.355	3.222	72%	216%	177%
22	A	0.159	0.17	0.164	4%	11%	9%
	B	1.817	2.583	2.2	49%	148%	121%
	C	0	0	0	0%	0%	0%
	D	-0.545	-0.43	-0.49	-11%	-33%	-27%
	E	1.912	1.579	1.746	39%	117%	96%
23	A	0.165	0.057	0.111	2%	7%	6%
	B	1.685	1.169	1.427	32%	96%	78%
	C	1.546	1.355	1.45	32%	97%	80%
	D	0.981	0.841	0.911	20%	61%	50%
	E	2.533	2.549	2.541	57%	171%	140%
24	A	2.71	2.011	2.36	53%	158%	130%
	B	0.651	0.831	0.741	17%	50%	41%
	C	1.633	1.55	1.592	36%	107%	87%
	D	2.311	2.994	2.653	59%	178%	146%
	E	4.802	4.245	4.524	101%	304%	249%
25	A	0.295	0.488	0.392	9%	26%	22%
	B	0.718	0.404	0.561	13%	38%	31%
	C	1.303	1.24	1.271	28%	85%	70%
	D	0.667	0.603	0.635	14%	43%	35%
	E	0.8	0.771	0.785	18%	53%	43%
26	A	-1.029	-1.023	-1.03	-23%	-69%	-56%
	B	-0.219	-0.282	-0.25	-6%	-17%	-14%
	C	-1.003	-1.097	-1.05	-23%	-70%	-58%
	D	-0.947	-0.882	-0.91	-20%	-61%	-50%

Data Set		Wind Speed [m/s]			10mph ref	NW Euro Stand Dev	
		1-3 Av	4-6 Av	All Av	Tgt - 4.47 m/s	Tgt - 1.49 m/s	Tgt - 1.82 m/s
	E	-1.903	-1.654	-1.78	-40%	-119%	-98%
27	A	0.384	0.32	0.352	8%	24%	19%
	B	0.233	0.068	0.151	3%	10%	8%
	C	-0.119	0.034	-0.04	-1%	-3%	-2%
	D	-0.533	-0.408	-0.47	-11%	-32%	-26%
	E	-0.414	-0.099	-0.26	-6%	-17%	-14%
28	A	-3.65	-2.761	-3.21	-72%	-215%	-176%
	B	-0.185	-0.298	-0.24	-5%	-16%	-13%
	C	-3.257	-2.996	-3.13	-70%	-210%	-172%
	D	-1.799	-1.645	-1.72	-39%	-116%	-95%
	E	-5.198	-3.846	-4.52	-101%	-303%	-248%
29	A	-2.005	-2.696	-2.35	-53%	-158%	-129%
	B	-1.621	-2.071	-1.85	-41%	-124%	-101%
	C	-2.733	-2.3	-2.52	-56%	-169%	-138%
	D	-2.129	-2.66	-2.39	-54%	-161%	-132%
	E	-1.788	-2.033	-1.91	-43%	-128%	-105%
30	A	-2.129	-1.247	-1.69	-38%	-113%	-93%
	B	-2.328	-2.434	-2.38	-53%	-160%	-131%
	C	-1.637	-1.127	-1.38	-31%	-93%	-76%
	D	-2.388	-2.329	-2.36	-53%	-158%	-130%
	E	-3.495	-2.703	-3.1	-69%	-208%	-170%

C.33 Data Sets 41-50 Averages

Table C-33 - Data Set 41-50 Wind Averages

Data Set		Wind Speed [m/s]			10mph ref	NW Euro Stand Dev	
		1-3 Av	4-6 Av	All Av	Tgt - 4.47 m/s	Tgt - 1.49 m/s	Tgt - 1.82 m/s
41	A	-1.323	-1.623	-1.47	-33%	-99%	-81%
	B	-3.133	-2.925	-3.03	-68%	-203%	-166%
	C	-2.211	-1.942	-2.08	-46%	-139%	-114%
	D	-5.733	-4.835	-5.28	-118%	-355%	-290%
	E	-1.305	-2.711	-2.01	-45%	-135%	-110%
42	A	-2.419	-1.865	-2.14	-48%	-144%	-118%
	B	-1.55	-1.408	-1.48	-33%	-99%	-81%
	C	-1.402	-1.776	-1.59	-36%	-107%	-87%
	D	-6.093	-4.36	-5.23	-117%	-351%	-287%
	E	0.204	-0.283	-0.04	-1%	-3%	-2%
43	A	-1.108	-1.495	-1.3	-29%	-87%	-72%
	B	-0.832	-0.811	-0.82	-18%	-55%	-45%
	C	-0.86	-0.889	-0.87	-20%	-59%	-48%
	D	-1.285	-1.349	-1.32	-29%	-88%	-72%
	E	-1.355	-1.307	-1.33	-30%	-89%	-73%
44	A	-1.597	-0.994	-1.3	-29%	-87%	-71%
	B	-2.883	-2.507	-2.7	-60%	-181%	-148%
	C	-1.733	-1.524	-1.63	-36%	-109%	-89%
	D	-4.704	-3.655	-4.18	-94%	-281%	-230%
	E	-3.025	-2.747	-2.89	-65%	-194%	-159%
45	A	-3.267	-1.375	-2.32	-52%	-156%	-128%
	B	-3.658	-3.223	-3.44	-77%	-231%	-189%
	C	0.683	0.786	0.735	16%	49%	40%
	D	-1.901	-1.204	-1.55	-35%	-104%	-85%
	E	-2.27	-2.717	-2.49	-56%	-167%	-137%
46	A	-0.596	-0.147	-0.37	-8%	-25%	-20%
	B	-0.543	-0.641	-0.59	-13%	-40%	-33%
	C	-0.761	-0.397	-0.58	-13%	-39%	-32%
	D	1.419	0.973	1.196	27%	80%	66%
	E	-0.832	-0.67	-0.75	-17%	-50%	-41%
47	A	0.161	0.143	0.152	3%	10%	8%
	B	0.736	0.449	0.593	13%	40%	33%

Data Set		Wind Speed [m/s]			10mph ref	NW Euro Stand Dev	
		1-3 Av	4-6 Av	All Av	Tgt - 4.47 m/s	Tgt - 1.49 m/s	Tgt - 1.82 m/s
	C	2.742	2.378	2.56	57%	172%	141%
	D	-2.463	-0.128	-1.3	-29%	-87%	-71%
	E	-0.861	-0.596	-0.73	-16%	-49%	-40%
48	A	-0.791	-1.311	-1.05	-24%	-71%	-58%
	B	-1.783	-1.583	-1.68	-38%	-113%	-92%
	C	-2.177	-2.996	-2.59	-58%	-174%	-142%
	D	-1.982	-3.085	-2.53	-57%	-170%	-139%
	E	-4.957	-3.542	-4.25	-95%	-285%	-233%
49	A	-1.127	-1.08	-1.1	-25%	-74%	-61%
	B	-1.052	-1.144	-1.1	-25%	-74%	-60%
	C	-2.379	-2.555	-2.47	-55%	-166%	-136%
	D	-0.745	-0.776	-0.76	-17%	-51%	-42%
	E	-3.933	-4.135	-4.03	-90%	-271%	-222%
50	A	-1.701	-3.294	-2.5	-56%	-168%	-137%
	B	-4.016	-3.873	-3.94	-88%	-265%	-217%
	C	-2.257	-1.773	-2.02	-45%	-135%	-111%
	D	-1.545	-2.009	-1.78	-40%	-119%	-98%
	E	0.215	-1.015	-0.4	-9%	-27%	-22%

Appendix D Ballistic Test Summary

Table D-1 – Ballistic Hit Results and Coincidence Summary

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
1	29_Aug_22_DS1-A	1 Sec Dynamic	-24.77	-104.37	-79.59	-0.398	Out	Out	under corrected
1	25_Sep_22_DS1-A1	1 Sec Fixed	-23.70	-104.37	-80.66	-0.403	Out	Out	under corrected
1	25_Sep_22_DS1-A2	2 Sec Dynamic	-167.10	-104.37	62.73	0.314	Out	Out	over corrected
1	25_Sep_22_DS1-A3	3 Sec Dynamic	-98.98	-104.37	-5.38	-0.027	In	In	under corrected
1	25_Sep_22_DS1-A4	4 Sec Dynamic	-139.54	-104.37	35.17	0.176	Out	In	over corrected
1	29_Aug_22_DS1-B	1 Sec Dynamic	-104.97	28.48	133.46	0.667	Out	Out	over corrected
1	25_Sep_22_DS1-B1	1 Sec Fixed	-96.21	28.48	124.69	0.623	Out	Out	over corrected
1	25_Sep_22_DS1-B2	2 Sec Dynamic	222.77	28.48	-194.29	-0.971	Out	Out	under corrected
1	25_Sep_22_DS1-B3	3 Sec Dynamic	146.57	28.48	-118.09	-0.590	Out	Out	under corrected
1	25_Sep_22_DS1-B4	4 Sec Dynamic	-118.30	28.48	146.78	0.734	Out	Out	over corrected
1	29_Aug_22_DS1-C	1 Sec Dynamic	-54.71	154.90	209.61	1.048	Out	Out	over corrected
1	25_Sep_22_DS1-C1	1 Sec Fixed	-50.12	154.90	205.02	1.025	Out	Out	over corrected
1	25_Sep_22_DS1-C2	2 Sec Dynamic	-60.01	154.90	214.91	1.075	Out	Out	over corrected
1	25_Sep_22_DS1-C3	3 Sec Dynamic	140.99	154.90	13.91	0.070	In	In	over corrected
1	25_Sep_22_DS1-C4	4 Sec Dynamic	249.39	154.90	-94.49	-0.472	Out	Out	under corrected
1	29_Aug_22_DS1-D	1 Sec Dynamic	70.14	138.57	68.43	0.342	Out	Out	over corrected
1	25_Sep_22_DS1-D1	1 Sec Fixed	67.00	138.57	71.57	0.358	Out	Out	over corrected
1	25_Sep_22_DS1-D2	2 Sec Dynamic	114.80	138.57	23.77	0.119	In	In	over corrected
1	25_Sep_22_DS1-D3	3 Sec Dynamic	123.30	138.57	15.27	0.076	In	In	over corrected
1	25_Sep_22_DS1-D4	4 Sec Dynamic	126.65	138.57	11.92	0.060	In	In	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrاد	0.15 mrاد	0.30 mrاد	FCC correction
1	29_Aug_22_DS1-E	1 Sec Dynamic	114.97	60.17	-54.80	-0.274	Out	In	under corrected
1	25_Sep_22_DS1-E1	1 Sec Fixed	110.28	60.17	-50.11	-0.251	Out	In	under corrected
1	25_Sep_22_DS1-E2	2 Sec Dynamic	-103.38	60.17	163.55	0.818	Out	Out	over corrected
1	25_Sep_22_DS1-E3	3 Sec Dynamic	-221.76	60.17	281.93	1.410	Out	Out	over corrected
1	25_Sep_22_DS1-E4	4 Sec Dynamic	-200.79	60.17	260.96	1.305	Out	Out	over corrected
2	29_Aug_22_DS2-A	1 Sec Dynamic	27.80	28.07	0.27	0.001	In	In	over corrected
2	29_Aug_22_DS2-B	1 Sec Dynamic	18.12	25.68	7.50	0.038	In	In	over corrected
2	29_Aug_22_DS2-C	1 Sec Dynamic	76.76	87.53	10.77	0.054	In	In	over corrected
2	29_Aug_22_DS2-D	1 Sec Dynamic	-19.61	-50.39	-30.78	-0.154	Out	In	under corrected
2	29_Aug_22_DS2-E	1 Sec Dynamic	48.75	66.63	17.88	0.089	In	In	over corrected
3	29_Aug_22_DS3-A	1 Sec Dynamic	-3.41	-11.00	-7.50	-0.038	In	In	under corrected
3	29_Aug_22_DS3-B	1 Sec Dynamic	-105.01	-101.63	3.37	0.017	In	In	over corrected
3	29_Aug_22_DS3-C	1 Sec Dynamic	-76.85	-113.70	-36.85	-0.184	Out	In	under corrected
3	29_Aug_22_DS3-D	1 Sec Dynamic	-99.69	-64.16	35.53	0.178	Out	In	over corrected
3	29_Aug_22_DS3-E	1 Sec Dynamic	-29.44	-55.13	-25.68	-0.128	In	In	under corrected
4	29_Aug_22_DS4-A	1 Sec Dynamic	-255.12	-261.47	-6.34	-0.032	In	In	under corrected
4	29_Aug_22_DS4-B	1 Sec Dynamic	-222.47	-169.69	52.77	0.264	Out	In	over corrected
4	01_Oct_22_DS4-B1	4 Sec Dynamic	-191.31	-169.69	21.61	0.108	In	In	over corrected
4	06_Feb_23_DS04-B4	1 Sec Fixed	-225.14	-169.69	55.45	0.277	Out	In	over corrected
4	29_Aug_22_DS4-C	1 Sec Dynamic	-158.42	-164.96	-6.54	-0.033	In	In	under corrected
4	29_Aug_22_DS4-D	1 Sec Dynamic	-250.13	-197.32	52.81	0.264	Out	In	over corrected
4	29_Aug_22_DS4-E	1 Sec Dynamic	-117.55	-98.49	19.06	0.095	In	In	over corrected
5	29_Aug_22_DS5-A	1 Sec Dynamic	-172.26	-217.85	-45.58	-0.228	Out	In	under corrected
5	02_Sep_22_DS5-B	1 Sec Dynamic	-134.44	-114.42	20.01	0.100	In	In	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
5	02_Sep_22_DS5-C	1 Sec Dynamic	-160.59	-176.15	-15.56	-0.078	In	In	under corrected
5	02_Sep_22_DS5-D	1 Sec Dynamic	-139.53	-158.37	-18.83	-0.094	In	In	under corrected
5	02_Sep_22_DS5-E	1 Sec Dynamic	-141.45	-114.20	27.22	0.136	In	In	over corrected
6	02_Sep_22_DS6-A	1 Sec Dynamic	-190.23	-190.11	0.11	0.001	In	In	over corrected
6	25_Sep_22_DS6-A1	1 Sec Fixed	-183.04	-190.11	-7.07	-0.035	In	In	under corrected
6	25_Sep_22_DS6-A2	2 Sec Dynamic	-165.25	-190.11	-24.86	-0.124	In	In	under corrected
6	25_Sep_22_DS6-A3	3 Sec Dynamic	-179.83	-190.11	-10.28	-0.051	In	In	under corrected
6	25_Sep_22_DS6-A4	4 Sec Dynamic	-157.00	-190.11	-33.10	-0.166	Out	In	under corrected
6	02_Sep_22_DS6-B	1 Sec Dynamic	-88.94	-259.56	-170.62	-0.853	Out	Out	under corrected
6	25_Sep_22_DS6-B1	1 Sec Fixed	-75.19	-259.56	-184.40	-0.922	Out	Out	under corrected
6	25_Sep_22_DS6-B2	2 Sec Dynamic	-62.19	-259.56	-197.36	-0.987	Out	Out	under corrected
6	25_Sep_22_DS6-B3	3 Sec Dynamic	-91.50	-259.56	-168.06	-0.840	Out	Out	under corrected
6	25_Sep_22_DS6-B4	4 Sec Dynamic	-179.57	-259.56	-79.99	-0.400	Out	Out	under corrected
6	02_Sep_22_DS6-C	1 Sec Dynamic	-161.10	-278.47	-117.37	-0.587	Out	Out	under corrected
6	02_Sep_22_DS6-C1	1 Sec Fixed	-146.40	-278.47	-132.07	-0.660	Out	Out	under corrected
6	25_Sep_22_DS6-C2	2 Sec Dynamic	-133.61	-278.47	-144.86	-0.724	Out	Out	under corrected
6	25_Sep_22_DS6-C3	3 Sec Dynamic	-171.55	-278.47	-106.92	-0.535	Out	Out	under corrected
6	25_Sep_22_DS6-C4	4 Sec Dynamic	-243.88	-278.47	-34.59	-0.173	Out	In	under corrected
6	02_Sep_22_DS6-D	1 Sec Dynamic	-343.77	-312.21	31.55	0.158	Out	In	over corrected
6	25_Sep_22_DS6-D1	1 Sec Fixed	-346.80	-312.21	34.58	0.173	Out	In	over corrected
6	25_Sep_22_DS6-D2	2 Sec Dynamic	-409.30	-312.21	97.08	0.485	Out	Out	over corrected
6	25_Sep_22_DS6-D3	3 Sec Dynamic	-359.05	-312.21	46.83	0.234	Out	In	over corrected
6	25_Sep_22_DS6-D4	4 Sec Dynamic	-386.16	-312.21	73.94	0.370	Out	Out	over corrected
6	02_Sep_22_DS6-E	1 Sec Dynamic	-326.47	-268.24	58.22	0.291	Out	In	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrاد	0.15 mrاد	0.30 mrاد	FCC correction
6	25_Sep_22_DS6-E1	1 Sec Fixed	-327.08	-268.24	58.84	0.294	Out	In	over corrected
6	25_Sep_22_DS6-E2	2 Sec Dynamic	-281.81	-268.24	13.57	0.068	In	In	over corrected
6	25_Sep_22_DS6-E3	3 Sec Dynamic	-273.09	-268.24	4.85	0.024	In	In	over corrected
6	25_Sep_22_DS6-E4	4 Sec Dynamic	-193.80	-268.24	-74.43	-0.372	Out	Out	under corrected
7	02_Sep_22_DS7-A	1 Sec Dynamic	-133.38	-125.23	8.14	0.041	In	In	over corrected
7	02_Sep_22_DS7-B	1 Sec Dynamic	-421.01	-289.11	131.90	0.660	Out	Out	over corrected
7	01_Oct_22_DS7-B1	4 Sec Dynamic	-394.91	-289.11	105.80	0.529	Out	Out	over corrected
7	06_Feb_23_DS07-B4	1 Sec Fixed	-401.26	-289.11	112.15	0.561	Out	Out	over corrected
7	02_Sep_22_DS7-C	1 Sec Dynamic	-417.62	-374.73	42.89	0.214	Out	In	over corrected
7	02_Sep_22_DS7-D	1 Sec Dynamic	-386.88	-350.19	36.69	0.183	Out	In	over corrected
7	02_Sep_22_DS7-E	1 Sec Dynamic	-508.27	-681.21	-172.94	-0.865	Out	Out	under corrected
7	06_Feb_23_DS07-E1	1 Sec Fixed	-498.66	-681.21	-182.55	-0.913	Out	Out	under corrected
7	06_Feb_23_DS07-E4	4 Sec Dynamic	-491.20	-681.21	-190.00	-0.950	Out	Out	under corrected
8	02_Sep_22_DS8-A	1 Sec Dynamic	40.13	52.75	12.61	0.063	In	In	over corrected
8	02_Sep_22_DS8-B	1 Sec Dynamic	58.67	67.63	8.96	0.045	In	In	over corrected
8	02_Sep_22_DS8-C	1 Sec Dynamic	40.20	40.31	0.10	0.001	In	In	over corrected
8	02_Sep_22_DS8-D	1 Sec Dynamic	34.79	44.54	9.74	0.049	In	In	over corrected
8	02_Sep_22_DS8-E	1 Sec Dynamic	45.07	25.74	-19.33	-0.097	In	In	under corrected
9	02_Sep_22_DS9-A	1 Sec Dynamic	-73.55	-101.22	-27.67	-0.138	In	In	under corrected
9	02_Sep_22_DS9-B	1 Sec Dynamic	-120.92	-185.67	-64.74	-0.324	Out	Out	under corrected
9	01_Oct_22_DS9-B1	4 Sec Dynamic	-141.53	-185.67	-44.14	-0.221	Out	In	under corrected
9	06_Feb_23_DS09-B4	1 Sec Fixed	-111.13	-185.67	-74.54	-0.373	Out	Out	under corrected
9	02_Sep_22_DS9-C	1 Sec Dynamic	-152.59	-105.62	46.97	0.235	Out	In	over corrected
9	02_Sep_22_DS9-D	1 Sec Dynamic	-148.19	-113.23	34.96	0.175	Out	In	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
9	02_Sep_22_DS9-E	1 Sec Dynamic	-41.60	-91.86	-50.25	-0.251	Out	In	under corrected
10	04_Sep_22_DS10-A	1 Sec Dynamic	30.52	32.65	2.12	0.011	In	In	over corrected
10	04_Sep_22_DS10-B	1 Sec Dynamic	-3.33	-5.57	-2.23	-0.011	In	In	under corrected
10	04_Sep_22_DS10-C	1 Sec Dynamic	19.27	55.43	36.16	0.181	Out	In	over corrected
10	04_Sep_22_DS10-D	1 Sec Dynamic	-126.64	-173.06	-46.42	-0.232	Out	In	under corrected
10	04_Sep_22_DS10-E	1 Sec Dynamic	125.66	87.82	-37.83	-0.189	Out	In	under corrected
21	04_Sep_22_DS21-A	1 Sec Dynamic	-56.37	-43.22	13.14	0.066	In	In	over corrected
21	04_Sep_22_DS21-A1	1 Sec Fixed	-56.22	-43.22	12.99	0.065	In	In	over corrected
21	06_Feb_23_DS21-A4	4 Sec Dynamic	-46.73	-43.22	3.50	0.018	In	In	over corrected
21	04_Sep_22_DS21-B	1 Sec Dynamic	-131.09	-164.96	-33.86	-0.169	Out	In	under corrected
21	04_Sep_22_DS21-C	1 Sec Dynamic	-131.12	-158.92	-27.80	-0.139	In	In	under corrected
21	04_Sep_22_DS21-D	1 Sec Dynamic	-21.89	-37.38	-15.49	-0.077	In	In	under corrected
21	04_Sep_22_DS21-E	1 Sec Dynamic	206.23	229.82	23.58	0.118	In	In	over corrected
22	07_Sep_22_DS22-A	1 Sec Dynamic	9.83	9.13	-0.69	-0.003	In	In	under corrected
22	07_Sep_22_DS22-B	1 Sec Dynamic	139.40	201.91	62.51	0.313	Out	Out	over corrected
22	01_Oct_22_DS22-B1	4 Sec Dynamic	178.90	201.91	23.01	0.115	In	In	over corrected
22	06_Feb_23_DS22-B4	1 Sec Fixed	119.75	201.91	82.16	0.411	Out	Out	over corrected
22	07_Sep_22_DS22-C	1 Sec Dynamic	13.43	8.39	-5.03	-0.025	In	In	under corrected
22	07_Sep_22_DS22-D	1 Sec Dynamic	-36.74	-23.66	13.08	0.065	In	In	over corrected
22	07_Sep_22_DS22-E	1 Sec Dynamic	140.71	100.61	-40.10	-0.201	Out	In	under corrected
23	07_Sep_22_DS23-A	1 Sec Dynamic	45.33	-7.11	-52.45	-0.262	Out	In	under corrected
23	07_Sep_22_DS23-B	1 Sec Dynamic	119.20	77.82	-41.37	-0.207	Out	In	under corrected
23	07_Sep_22_DS23-C	1 Sec Dynamic	117.35	92.40	-24.95	-0.125	In	In	under corrected
23	07_Sep_22_DS23-D	1 Sec Dynamic	75.16	68.16	-6.99	-0.035	In	In	under corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrاد	0.15 mrاد	0.30 mrاد	FCC correction
23	07_Sep_22_DS23-E	1 Sec Dynamic	191.43	181.49	-9.94	-0.050	In	In	under corrected
24	07_Sep_22_DS24-A	1 Sec Dynamic	253.09	125.53	-127.56	-0.638	Out	Out	under corrected
24	24_Sep_22_DS24-A1	1 Sec Fixed	249.44	125.53	-123.91	-0.620	Out	Out	under corrected
24	24_Sep_22_DS24-A2	2 Sec Dynamic	145.49	125.53	-19.96	-0.100	In	In	under corrected
24	24_Sep_22_DS24-A3	3 Sec Dynamic	183.16	125.53	-57.63	-0.288	Out	In	under corrected
24	24_Sep_22_DS24-A4	4 Sec Dynamic	196.00	125.53	-70.47	-0.352	Out	Out	under corrected
24	24_Sep_22_DS24-A5	3 Sec Fixed	181.23	125.53	-55.70	-0.279	Out	In	under corrected
24	24_Sep_22_DS24-A6	4 Sec Fixed	198.80	125.53	-72.27	-0.361	Out	Out	under corrected
24	07_Sep_22_DS24-B	1 Sec Dynamic	82.87	89.25	6.38	0.032	In	In	over corrected
24	24_Sep_22_DS24-B1	1 Sec Fixed	62.94	89.25	23.31	0.117	In	In	over corrected
24	24_Sep_22_DS24-B2	2 Sec Dynamic	79.28	89.25	9.97	0.050	In	In	over corrected
24	24_Sep_22_DS24-B3	3 Sec Dynamic	26.40	89.25	62.84	0.314	Out	Out	over corrected
24	24_Sep_22_DS24-B4	4 Sec Dynamic	74.85	89.25	14.40	0.072	In	In	over corrected
24	07_Sep_22_DS24-C	1 Sec Dynamic	124.22	113.62	-10.59	-0.053	In	In	under corrected
24	24_Sep_22_DS24-C1	1 Sec Fixed	121.78	113.62	-8.15	-0.041	In	In	under corrected
24	24_Sep_22_DS24-C2	2 Sec Dynamic	90.98	113.62	22.64	0.113	In	In	over corrected
24	24_Sep_22_DS24-C3	3 Sec Dynamic	135.47	113.62	-21.84	-0.109	In	In	under corrected
24	24_Sep_22_DS24-C4	4 Sec Dynamic	86.97	113.62	26.65	0.133	In	In	over corrected
24	07_Sep_22_DS24-D	1 Sec Dynamic	156.55	208.86	52.30	0.262	Out	In	over corrected
24	24_Sep_22_DS24-D1	1 Sec Fixed	143.41	208.86	65.45	0.327	Out	Out	over corrected
24	24_Sep_22_DS24-D2	2 Sec Dynamic	180.21	208.86	28.64	0.143	In	In	over corrected
24	24_Sep_22_DS24-D3	3 Sec Dynamic	210.34	208.86	-1.48	-0.007	In	In	under corrected
24	24_Sep_22_DS24-D4	4 Sec Dynamic	242.41	208.86	-33.55	-0.168	Out	In	under corrected
24	07_Sep_22_DS24-E	1 Sec Dynamic	342.90	310.91	-31.99	-0.160	Out	In	under corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
24	24_Sep_22_DS24-E1	1 Sec Fixed	313.51	310.91	-2.59	-0.013	In	In	under corrected
24	24_Sep_22_DS24-E2	2 Sec Dynamic	373.84	310.91	-62.92	-0.315	Out	Out	under corrected
24	24_Sep_22_DS24-E3	3 Sec Dynamic	346.21	310.91	-35.30	-0.177	Out	In	under corrected
24	24_Sep_22_DS24-E4	4 Sec Dynamic	335.38	310.91	-24.47	-0.122	In	In	under corrected
25	07_Sep_22_DS25-A	1 Sec Dynamic	17.91	40.18	22.26	0.111	In	In	over corrected
25	07_Sep_22_DS25-B	1 Sec Dynamic	83.58	41.51	-42.07	-0.210	Out	In	under corrected
25	07_Sep_22_DS25-C	1 Sec Dynamic	95.30	103.28	7.97	0.040	In	In	over corrected
25	07_Sep_22_DS25-D	1 Sec Dynamic	57.68	54.55	-3.12	-0.016	In	In	under corrected
25	07_Sep_22_DS25-E	1 Sec Dynamic	52.32	62.31	9.99	0.050	In	In	over corrected
26	07_Sep_22_DS26-A	1 Sec Dynamic	-69.01	-72.06	-3.05	-0.015	In	In	under corrected
26	07_Sep_22_DS26-B	1 Sec Dynamic	-14.35	-16.09	-1.73	-0.009	In	In	under corrected
26	07_Sep_22_DS26-C	1 Sec Dynamic	-65.12	-73.42	-8.29	-0.041	In	In	under corrected
26	07_Sep_22_DS26-D	1 Sec Dynamic	-61.05	-62.18	-1.13	-0.006	In	In	under corrected
26	07_Sep_22_DS26-E	1 Sec Dynamic	-141.90	-105.79	36.11	0.181	Out	In	over corrected
27	07_Sep_22_DS27-A	1 Sec Dynamic	24.57	22.66	-1.90	-0.010	In	In	under corrected
27	07_Sep_22_DS27-B	1 Sec Dynamic	19.32	5.09	-14.23	-0.071	In	In	under corrected
27	07_Sep_22_DS27-C	1 Sec Dynamic	-14.15	-6.66	7.48	0.037	In	In	over corrected
27	07_Sep_22_DS27-D	1 Sec Dynamic	-55.14	-27.25	27.88	0.139	In	In	over corrected
27	07_Sep_22_DS27-E	1 Sec Dynamic	-37.76	27.58	65.35	0.327	Out	Out	over corrected
28	07_Sep_22_DS28-A	1 Sec Dynamic	-256.60	-191.67	64.92	0.325	Out	Out	over corrected
28	25_Sep_22_DS28-A1	1 Sec Fixed	-274.73	-191.67	83.05	0.415	Out	Out	over corrected
28	25_Sep_22_DS28-A2	2 Sec Dynamic	-204.10	-191.67	12.42	0.062	In	In	over corrected
28	25_Sep_22_DS28-A3	3 Sec Dynamic	-246.56	-191.67	54.88	0.274	Out	In	over corrected
28	25_Sep_22_DS28-A4	4 Sec Dynamic	-210.74	-191.67	19.06	0.095	In	In	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
28	07_Sep_22_DS28-B	1 Sec Dynamic	-26.21	-52.33	-26.11	-0.131	In	In	under corrected
28	25_Sep_22_DS28-B1	1 Sec Fixed	-18.28	-52.33	-34.04	-0.170	Out	In	under corrected
28	25_Sep_22_DS28-B2	2 Sec Dynamic	-35.36	-52.33	-16.96	-0.085	In	In	under corrected
28	25_Sep_22_DS28-B3	3 Sec Dynamic	-36.97	-52.33	-15.35	-0.077	In	In	under corrected
28	25_Sep_22_DS28-B4	4 Sec Dynamic	-45.89	-52.33	-6.44	-0.032	In	In	under corrected
28	07_Sep_22_DS28-C	1 Sec Dynamic	-152.27	-188.70	-36.43	-0.182	Out	In	under corrected
28	25_Sep_22_DS28-C1	1 Sec Fixed	-140.29	-188.70	-48.41	-0.242	Out	In	under corrected
28	25_Sep_22_DS28-C2	2 Sec Dynamic	-254.02	-188.70	65.31	0.327	Out	Out	over corrected
28	25_Sep_22_DS28-C3	3 Sec Dynamic	-241.92	-188.70	53.21	0.266	Out	In	over corrected
28	25_Sep_22_DS28-C4	4 Sec Dynamic	-236.65	-188.70	47.94	0.240	Out	In	over corrected
28	07_Sep_22_DS28-D	1 Sec Dynamic	-144.18	-119.68	24.50	0.123	In	In	over corrected
28	25_Sep_22_DS28-D1	1 Sec Fixed	-132.83	-119.68	13.14	0.066	In	In	over corrected
28	25_Sep_22_DS28-D2	2 Sec Dynamic	-141.53	-119.68	21.84	0.109	In	In	over corrected
28	25_Sep_22_DS28-D3	3 Sec Dynamic	-122.38	-119.68	2.70	0.014	In	In	over corrected
28	25_Sep_22_DS28-D4	4 Sec Dynamic	-129.89	-119.68	10.20	0.051	In	In	over corrected
28	07_Sep_22_DS28-E	1 Sec Dynamic	-330.77	-239.31	91.45	0.457	Out	Out	over corrected
28	25_Sep_22_DS28-E1	1 Sec Fixed	-344.10	-239.31	104.78	0.524	Out	Out	over corrected
28	25_Sep_22_DS28-E2	2 Sec Dynamic	-357.20	-239.31	117.88	0.589	Out	Out	over corrected
28	25_Sep_22_DS28-E3	3 Sec Dynamic	-325.45	-239.31	86.13	0.431	Out	Out	over corrected
28	25_Sep_22_DS28-E4	4 Sec Dynamic	-312.56	-239.31	73.24	0.366	Out	Out	over corrected
29	07_Sep_22_DS29-A	1 Sec Dynamic	-165.42	-224.43	-59.01	-0.295	Out	In	under corrected
29	07_Sep_22_DS29-B	1 Sec Dynamic	-128.29	-188.57	-60.27	-0.301	Out	Out	under corrected
29	01_Oct_22_DS29-B1	4 Sec Dynamic	-131.69	-188.57	-56.87	-0.284	Out	In	under corrected
29	06_Feb_23_DS29-B4	1 Sec Fixed	-112.48	-188.57	-76.08	-0.380	Out	Out	under corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrاد	0.15 mrاد	0.30 mrاد	FCC correction
29	07_Sep_22_DS29-C	1 Sec Dynamic	-209.15	-183.69	25.45	0.127	In	In	over corrected
29	07_Sep_22_DS29-D	1 Sec Dynamic	-179.64	-218.02	-38.37	-0.192	Out	In	under corrected
29	07_Sep_22_DS29-E	1 Sec Dynamic	-133.30	-176.24	-42.94	-0.215	Out	In	under corrected
30	07_Sep_22_DS30-A	1 Sec Dynamic	-172.41	-102.19	70.21	0.351	Out	Out	over corrected
30	01_Oct_22_DS30-A1	4 Sec Dynamic	-91.31	-102.19	-10.88	-0.054	In	In	under corrected
30	06_Feb_23_DS30-A4	1 Sec Fixed	-165.40	-102.19	63.21	0.316	Out	Out	over corrected
30	07_Sep_22_DS30-B	1 Sec Dynamic	-187.78	-146.50	41.28	0.206	Out	In	over corrected
30	07_Sep_22_DS30-C	1 Sec Dynamic	-117.11	-111.63	5.48	0.027	In	In	over corrected
30	07_Sep_22_DS30-D	1 Sec Dynamic	-133.26	-124.68	8.57	0.043	In	In	over corrected
30	07_Sep_22_DS30-E	1 Sec Dynamic	-284.00	-243.87	40.13	0.201	Out	In	over corrected
41	07_Sep_22_DS41-A	1 Sec Dynamic	-109.47	-123.34	-13.86	-0.069	In	In	under corrected
41	07_Sep_22_DS41-B	1 Sec Dynamic	-212.55	-198.39	14.15	0.071	In	In	over corrected
41	07_Sep_22_DS41-C	1 Sec Dynamic	-149.46	-143.16	6.29	0.031	In	In	over corrected
41	07_Sep_22_DS41-D	1 Sec Dynamic	-443.16	-373.29	69.87	0.349	Out	Out	over corrected
41	07_Sep_22_DS41-E	1 Sec Dynamic	-95.11	-293.74	-198.63	-0.993	Out	Out	under corrected
42	13_Sep_22_DS42-A	1 Sec Dynamic	-180.46	-146.85	33.60	0.168	Out	In	over corrected
42	13_Sep_22_DS42-A1	1 Sec Fixed	-171.50	-146.85	24.64	0.123	In	In	over corrected
42	06_Feb_23_DS42-A4	4 Sec Dynamic	-151.13	-146.85	4.27	0.021	In	In	over corrected
42	13_Sep_22_DS42-B	1 Sec Dynamic	-108.58	-95.12	13.45	0.067	In	In	over corrected
42	13_Sep_22_DS42-B1	1 Sec Fixed	-104.35	-95.12	9.22	0.046	In	In	over corrected
42	06_Feb_23_DS42-B4	4 Sec Dynamic	-105.92	-95.12	10.79	0.054	In	In	over corrected
42	13_Sep_22_DS42-C	1 Sec Dynamic	-79.84	-108.18	-28.34	-0.142	In	In	under corrected
42	13_Sep_22_DS42-C1	1 Sec Fixed	-63.67	-108.18	-44.50	-0.223	Out	In	under corrected
42	06_Feb_23_DS42-C4	4 Sec Dynamic	-144.97	-108.18	36.78	0.184	Out	In	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
42	13_Sep_22_DS42-D	1 Sec Dynamic	-489.95	-306.29	183.66	0.918	Out	Out	over corrected
42	13_Sep_22_DS42-D1	1 Sec Fixed	-466.64	-306.29	160.35	0.802	Out	Out	over corrected
42	06_Feb_23_DS42-D4	4 Sec Dynamic	-349.52	-306.29	43.23	0.216	Out	In	over corrected
42	13_Sep_22_DS42-E	1 Sec Dynamic	41.56	-41.91	-83.48	-0.417	Out	Out	under corrected
42	13_Sep_22_DS42-E1	1 Sec Fixed	37.90	-41.91	-79.82	-0.399	Out	Out	under corrected
42	06_Feb_23_DS42-E4	4 Sec Dynamic	31.70	-41.91	-73.62	-0.368	Out	Out	under corrected
43	13_Sep_22_DS43-A	1 Sec Dynamic	-84.89	-102.22	-17.33	-0.087	In	In	under corrected
43	13_Sep_22_DS43-A1	1 Sec Fixed	-81.97	-102.22	-20.24	-0.101	In	In	under corrected
43	06_Feb_23_DS43-A4	4 Sec Dynamic	-111.83	-102.22	9.61	0.048	In	In	over corrected
43	13_Sep_22_DS43-B	1 Sec Dynamic	-57.73	-53.73	3.99	0.020	In	In	over corrected
43	13_Sep_22_DS43-B1	1 Sec Fixed	-56.89	-53.73	3.16	0.016	In	In	over corrected
43	06_Feb_23_DS43-B4	4 Sec Dynamic	-57.73	-53.73	-3.99	-0.020	In	In	over corrected
43	13_Sep_22_DS43-C	1 Sec Dynamic	-63.47	-70.23	-6.75	-0.034	In	In	under corrected
43	13_Sep_22_DS43-C1	1 Sec Fixed	-58.93	-70.23	-11.29	-0.056	In	In	under corrected
43	06_Feb_23_DS43-C4	4 Sec Dynamic	-59.32	-70.23	-10.90	-0.055	In	In	under corrected
43	13_Sep_22_DS43-D	1 Sec Dynamic	-89.05	-95.26	-6.21	-0.031	In	In	under corrected
43	13_Sep_22_DS43-D1	1 Sec Fixed	-86.72	-95.26	-8.53	-0.043	In	In	under corrected
43	06_Feb_23_DS43-D4	4 Sec Dynamic	-98.22	-95.26	2.96	0.015	In	In	over corrected
43	13_Sep_22_DS43-E	1 Sec Dynamic	-88.59	-94.08	-5.48	-0.027	In	In	under corrected
43	13_Sep_22_DS43-E1	1 Sec Fixed	-84.68	-94.08	-9.39	-0.047	In	In	under corrected
43	06_Feb_23_DS43-E4	4 Sec Dynamic	-98.98	-94.08	4.90	0.025	In	In	over corrected
44	13_Sep_22_DS44-A	1 Sec Dynamic	-107.27	-86.01	21.25	0.106	In	In	over corrected
44	13_Sep_22_DS44-A1	1 Sec Fixed	-108.41	-86.01	22.40	0.112	In	In	over corrected
44	06_Feb_23_DS44-A4	4 Sec Dynamic	-94.04	-86.01	8.02	0.040	In	In	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
44	13_Sep_22_DS44-B	1 Sec Dynamic	-195.35	-175.64	19.70	0.099	In	In	over corrected
44	13_Sep_22_DS44-B1	1 Sec Fixed	-195.94	-175.64	20.29	0.101	In	In	over corrected
44	06_Feb_23_DS44-B4	4 Sec Dynamic	-154.16	-175.64	-21.47	-0.107	In	In	under corrected
44	13_Sep_22_DS44-C	1 Sec Dynamic	-141.77	-111.29	30.47	0.152	Out	In	over corrected
44	13_Sep_22_DS44-C1	1 Sec Fixed	-135.54	-111.29	24.25	0.121	In	In	over corrected
44	06_Feb_23_DS44-C4	4 Sec Dynamic	-121.42	-111.29	10.12	0.051	In	In	over corrected
44	13_Sep_22_DS44-D	1 Sec Dynamic	-334.40	-247.87	86.53	0.433	Out	Out	over corrected
44	13_Sep_22_DS44-D1	1 Sec Fixed	-336.60	-247.87	88.72	0.444	Out	Out	over corrected
44	06_Feb_23_DS44-D4	4 Sec Dynamic	-270.21	-247.87	22.34	0.112	In	In	over corrected
44	13_Sep_22_DS44-E	1 Sec Dynamic	-225.62	-220.75	34.86	0.174	Out	In	over corrected
44	13_Sep_22_DS44-E1	1 Sec Fixed	-234.65	-220.75	13.89	0.069	In	In	over corrected
44	06_Feb_23_DS44-E4	4 Sec Dynamic	-216.61	-220.75	-4.14	-0.021	In	In	under corrected
45	13_Sep_22_DS45-A	1 Sec Dynamic	-239.87	-47.31	192.56	0.963	Out	Out	over corrected
45	13_Sep_22_DS45-A1	1 Sec Fixed	-188.48	-47.31	141.17	0.706	Out	Out	over corrected
45	06_Feb_23_DS45-A4	4 Sec Dynamic	-169.00	-47.31	121.69	0.608	Out	Out	over corrected
45	13_Sep_22_DS45-B	1 Sec Dynamic	-269.14	-255.81	13.32	0.067	In	In	over corrected
45	13_Sep_22_DS45-B1	1 Sec Fixed	-271.34	-255.81	15.53	0.078	In	In	over corrected
45	06_Feb_23_DS45-B4	4 Sec Dynamic	-272.98	-255.81	17.17	0.086	In	In	over corrected
45	13_Sep_22_DS45-C	1 Sec Dynamic	122.30	68.51	-53.79	-0.269	Out	In	under corrected
45	13_Sep_22_DS45-C1	1 Sec Fixed	108.93	68.51	-40.42	-0.202	Out	In	under corrected
45	06_Feb_23_DS45-C4	4 Sec Dynamic	67.32	68.51	1.19	0.006	In	In	over corrected
45	13_Sep_22_DS45-D	1 Sec Dynamic	-103.52	-72.53	30.98	0.155	Out	In	over corrected
45	13_Sep_22_DS45-D1	1 Sec Fixed	-98.92	-72.53	26.38	0.132	In	In	over corrected
45	06_Feb_23_DS45-D4	4 Sec Dynamic	-148.14	-72.53	75.61	0.378	Out	Out	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
45	13_Sep_22_DS45-E	1 Sec Dynamic	-159.41	-262.25	-102.83	-0.514	Out	Out	under corrected
45	13_Sep_22_DS45-E1	1 Sec Fixed	-151.15	-262.25	-111.10	-0.556	Out	Out	under corrected
45	06_Feb_23_DS45-E4	4 Sec Dynamic	-170.71	-262.25	-91.54	-0.458	Out	Out	under corrected
46	13_Sep_22_DS46-A	1 Sec Dynamic	-51.30	-27.56	23.56	0.118	In	In	over corrected
46	13_Sep_22_DS46-A1	1 Sec Fixed	-51.47	-27.74	23.73	0.119	In	In	over corrected
46	06_Feb_23_DS46-A4	4 Sec Dynamic	15.80	-27.74	-43.54	-0.218	Out	In	under corrected
46	13_Sep_22_DS46-B	1 Sec Dynamic	-28.39	-39.53	-11.14	-0.056	In	In	under corrected
46	13_Sep_22_DS46-B1	1 Sec Fixed	-25.73	-39.53	-13.80	-0.069	In	In	under corrected
46	06_Feb_23_DS46-B4	4 Sec Dynamic	-61.05	-39.53	21.51	0.108	In	In	over corrected
46	13_Sep_22_DS46-C	1 Sec Dynamic	-52.36	-28.12	24.23	0.121	In	In	over corrected
46	13_Sep_22_DS46-C1	1 Sec Fixed	-50.80	-28.13	22.67	0.113	In	In	over corrected
46	06_Feb_23_DS46-C4	4 Sec Dynamic	-29.56	-28.12	1.43	0.007	In	In	over corrected
46	13_Sep_22_DS46-D	1 Sec Dynamic	101.98	53.02	-48.96	-0.245	Out	In	under corrected
46	13_Sep_22_DS46-D1	1 Sec Fixed	107.58	53.02	-54.56	-0.273	Out	In	under corrected
46	06_Feb_23_DS46-D4	4 Sec Dynamic	111.71	53.02	-58.69	-0.293	Out	In	under corrected
46	13_Sep_22_DS46-E	1 Sec Dynamic	-96.54	-57.82	38.72	0.194	Out	In	over corrected
46	13_Sep_22_DS46-E1	1 Sec Fixed	-82.65	-57.82	24.83	0.124	In	In	over corrected
46	06_Feb_23_DS46-E4	4 Sec Dynamic	-71.47	-57.82	13.64	0.068	In	In	over corrected
47	13_Sep_22_DS47-A	1 Sec Dynamic	12.67	22.01	9.34	0.047	In	In	over corrected
47	13_Sep_22_DS47-A1	1 Sec Fixed	10.83	22.01	11.18	0.056	In	In	over corrected
47	06_Feb_23_DS47-A4	4 Sec Dynamic	26.18	22.01	-4.16	-0.021	In	In	over corrected
47	13_Sep_22_DS47-B	1 Sec Dynamic	91.64	65.79	-25.85	-0.129	In	In	under corrected
47	13_Sep_22_DS47-B1	1 Sec Fixed	85.26	65.79	-19.47	-0.097	In	In	under corrected
47	06_Feb_23_DS47-B4	4 Sec Dynamic	-20.86	65.79	86.66	0.433	Out	Out	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrاد	0.15 mrاد	0.30 mrاد	FCC correction
47	13_Sep_22_DS47-C	1 Sec Dynamic	155.52	142.15	-13.37	-0.067	In	In	under corrected
47	13_Sep_22_DS47-C1	1 Sec Fixed	154.89	142.15	-12.74	-0.064	In	In	under corrected
47	06_Feb_23_DS47-C4	4 Sec Dynamic	238.89	142.15	-96.73	-0.484	Out	Out	over corrected
47	13_Sep_22_DS47-D	1 Sec Dynamic	-223.41	29.55	254.96	1.275	Out	Out	over corrected
47	13_Sep_22_DS47-D1	1 Sec Fixed	-202.06	29.55	231.61	1.158	Out	Out	over corrected
47	06_Feb_23_DS47-D4	4 Sec Dynamic	-326.92	29.55	356.47	1.782	Out	Out	over corrected
47	18_Sep_22_DS47-E	1 Sec Dynamic	-66.49	-26.92	39.56	0.198	Out	In	over corrected
47	18_Sep_22_DS47-E1	1 Sec Fixed	-60.28	-26.92	33.35	0.167	Out	In	over corrected
47	06_Feb_23_DS47-E4	4 Sec Dynamic	-56.83	-26.92	29.90	0.150	In	In	over corrected
48	18_Sep_22_DS48-A	1 Sec Dynamic	-41.88	-87.79	-45.91	-0.230	Out	In	under corrected
48	18_Sep_22_DS48-A1	1 Sec Fixed	-37.92	-87.79	-49.86	-0.249	Out	In	under corrected
48	24_Sep_22_DS48-A2	2 Sec Dynamic	-58.13	-87.79	-29.65	-0.148	In	In	under corrected
48	24_Sep_22_DS48-A3	3 Sec Dynamic	-83.89	-87.79	-3.90	-0.020	In	In	under corrected
48	24_Sep_22_DS48-A4	4 Sec Dynamic	-91.93	-87.79	4.13	0.021	In	In	over corrected
48	18_Sep_22_DS48-B	1 Sec Dynamic	-134.12	-102.43	31.68	0.158	Out	In	over corrected
48	18_Sep_22_DS48-B1	1 Sec Fixed	-130.12	-102.43	27.68	0.138	In	In	over corrected
48	24_Sep_22_DS48-B2	2 Sec Dynamic	-132.68	-102.43	30.24	0.151	Out	In	over corrected
48	24_Sep_22_DS48-B3	3 Sec Dynamic	-136.44	-102.43	34.01	0.170	Out	In	over corrected
48	24_Sep_22_DS48-B4	4 Sec Dynamic	-141.87	-102.43	39.44	0.197	Out	In	over corrected
48	18_Sep_22_DS48-C	1 Sec Dynamic	-123.18	-172.25	-49.07	-0.245	Out	In	under corrected
48	18_Sep_22_DS48-C1	1 Sec Fixed	-115.87	-172.25	-56.38	-0.282	Out	In	under corrected
48	24_Sep_22_DS48-C2	2 Sec Dynamic	-162.17	-172.25	-10.08	-0.050	In	In	under corrected
48	24_Sep_22_DS48-C3	3 Sec Dynamic	-182.16	-172.25	9.90	0.050	In	In	over corrected
48	24_Sep_22_DS48-C4	4 Sec Dynamic	-230.14	-172.25	57.88	0.289	Out	In	over corrected

Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
48	18_Sep_22_DS48-D	1 Sec Dynamic	-143.73	-223.73	-80.00	-0.400	Out	Out	under corrected
48	18_Sep_22_DS48-D1	1 Sec Fixed	-129.44	-223.73	-94.29	-0.471	Out	Out	under corrected
48	24_Sep_22_DS48-D2	2 Sec Dynamic	-144.14	-223.73	-79.59	-0.398	Out	Out	under corrected
48	24_Sep_22_DS48-D3	3 Sec Dynamic	-182.58	-223.73	-41.15	-0.206	Out	In	under corrected
48	24_Sep_22_DS48-D4	4 Sec Dynamic	-212.87	-223.73	-10.86	-0.054	In	In	under corrected
48	03_Dec_22_DS48-D5	4 Sec Fixed	-171.50	-223.73	-52.23	-0.261	Out	In	under corrected
48	03_Dec_22_DS48-D6	3 Sec Fixed	-204.76	-223.73	-18.97	-0.095	In	In	under corrected
48	18_Sep_22_DS48-E	1 Sec Dynamic	-341.25	-244.02	97.23	0.486	Out	Out	over corrected
48	18_Sep_22_DS48-E1	1 Sec Fixed	-341.37	-244.02	97.34	0.487	Out	Out	over corrected
48	24_Sep_22_DS48-E2	2 Sec Dynamic	-317.86	-244.02	73.83	0.369	Out	Out	over corrected
48	24_Sep_22_DS48-E3	3 Sec Dynamic	-325.55	-244.02	81.52	0.408	Out	Out	over corrected
48	24_Sep_22_DS48-E4	4 Sec Dynamic	-255.72	-244.02	11.70	0.059	In	In	over corrected
49	18_Sep_22_DS49-A	1 Sec Dynamic	-89.71	-93.82	-4.10	-0.021	In	In	under corrected
49	18_Sep_22_DS49-A1	1 Sec Fixed	-78.58	-93.82	-15.23	-0.076	In	In	under corrected
49	06_Feb_23_DS49-A4	4 Sec Dynamic	-91.52	-93.82	-2.29	-0.011	In	In	under corrected
49	18_Sep_22_DS49-B	1 Sec Dynamic	-67.16	-77.80	-10.63	-0.053	In	In	under corrected
49	18_Sep_22_DS49-B1	1 Sec Fixed	-65.71	-77.80	-12.09	-0.060	In	In	under corrected
49	06_Feb_23_DS49-B4	4 Sec Dynamic	-81.77	-77.80	3.96	0.020	In	In	over corrected
49	18_Sep_22_DS49-C	1 Sec Dynamic	-177.15	-175.12	2.03	0.010	In	In	over corrected
49	18_Sep_22_DS49-C1	1 Sec Fixed	-172.18	-175.12	-2.93	-0.015	In	In	under corrected
49	06_Feb_23_DS49-C4	4 Sec Dynamic	-171.20	-175.12	-3.91	-0.020	In	In	under corrected
49	18_Sep_22_DS49-D	1 Sec Dynamic	-63.55	-60.21	3.34	0.017	In	In	over corrected
49	18_Sep_22_DS49-D1	1 Sec Fixed	-54.86	-60.21	-5.34	-0.027	In	In	under corrected
49	06_Feb_23_DS49-D4	4 Sec Dynamic	-68.98	-60.21	8.77	0.044	In	In	over corrected

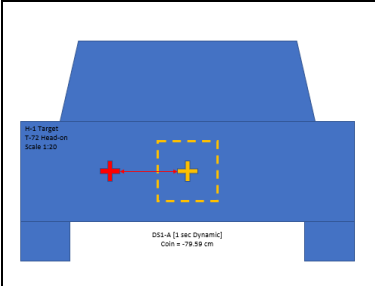
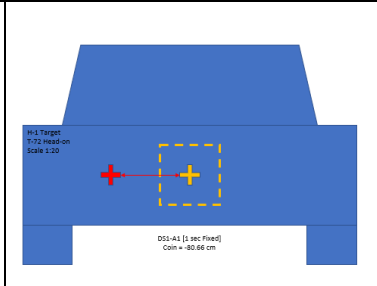
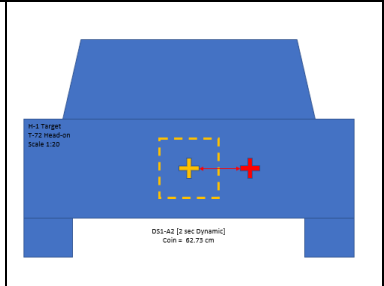
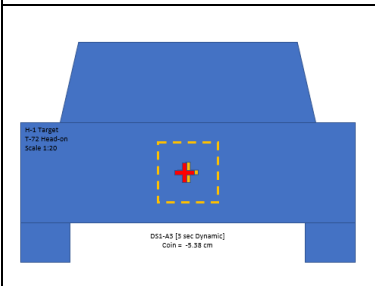
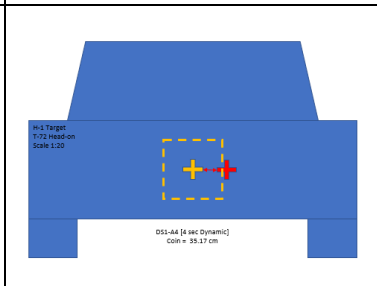
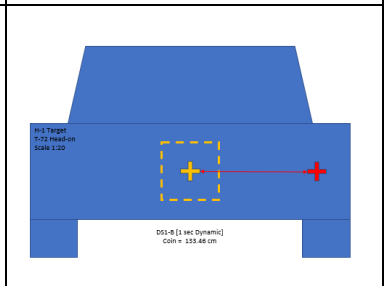
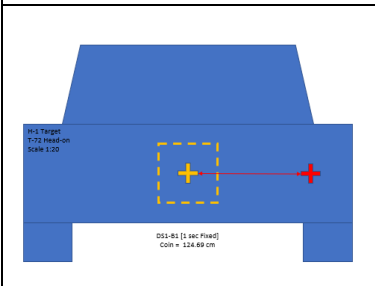
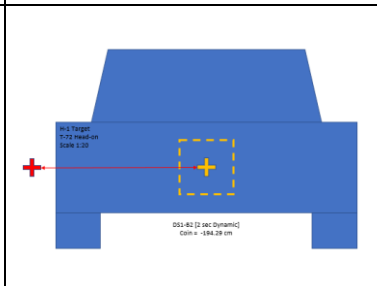
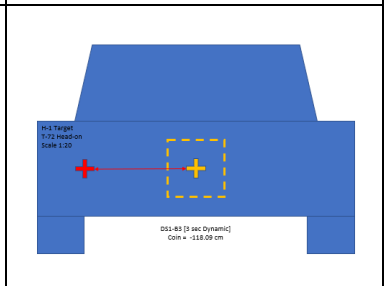
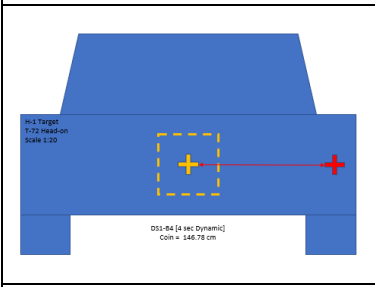
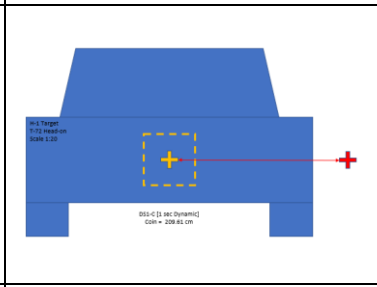
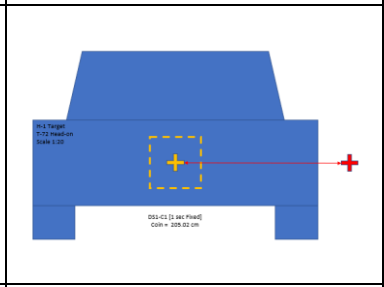
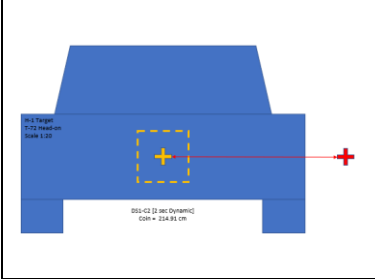
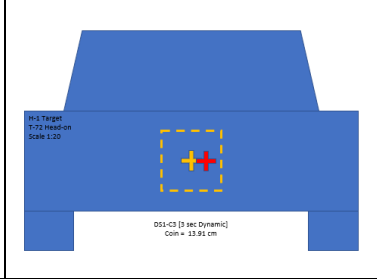
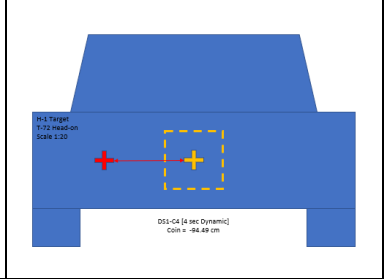
Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrad	0.15 mrad	0.30 mrad	FCC correction
49	18_Sep_22_DS49-E	1 Sec Dynamic	-285.39	-314.65	-29.26	-0.146	In	In	under corrected
49	18_Sep_22_DS49-E1	1 Sec Fixed	-280.17	-314.65	-34.48	-0.172	Out	In	under corrected
49	06_Feb_23_DS49-E4	4 Sec Dynamic	-268.13	-314.65	-46.52	-0.233	Out	In	under corrected
50	18_Sep_22_DS50-A	1 Sec Dynamic	-81.86	-228.47	-146.61	-0.733	Out	Out	under corrected
50	18_Sep_22_DS50-A1	1 Sec Fixed	-71.80	-228.47	-156.67	-0.783	Out	Out	under corrected
50	24_Sep_22_DS50-A2	2 Sec Dynamic	-114.27	-228.47	-114.20	-0.571	Out	Out	under corrected
50	24_Sep_22_DS50-A3	3 Sec Dynamic	-187.40	-228.47	-41.07	-0.205	Out	In	under corrected
50	24_Sep_22_DS50-A4	4 Sec Dynamic	-201.88	-228.47	-26.59	-0.133	In	In	under corrected
50	18_Sep_22_DS50-B	1 Sec Dynamic	-254.60	-254.13	0.45	0.002	In	In	over corrected
50	18_Sep_22_DS50-B1	1 Sec Fixed	-234.65	-254.15	-19.49	-0.097	In	In	under corrected
50	24_Sep_22_DS50-B2	2 Sec Dynamic	-274.58	-254.15	20.43	0.102	In	In	over corrected
50	24_Sep_22_DS50-B3	3 Sec Dynamic	-330.31	-254.15	76.16	0.381	Out	Out	over corrected
50	24_Sep_22_DS50-B4	4 Sec Dynamic	-300.52	-254.15	46.37	0.232	Out	In	over corrected
50	18_Sep_22_DS50-C	1 Sec Dynamic	-205.42	-120.06	85.36	0.427	Out	Out	over corrected
50	18_Sep_22_DS50-C1	1 Sec Fixed	-197.98	-120.06	77.92	0.390	Out	Out	over corrected
50	19_Sep_22_DS50-C2	2 Sec Dynamic	-141.93	-120.06	21.87	0.109	In	In	over corrected
50	19_Sep_22_DS50-C3	3 Sec Dynamic	-149.50	-120.06	29.44	0.147	In	In	over corrected
50	19_Sep_22_DS50-C4	4 Sec Dynamic	-146.16	-120.06	26.10	0.131	In	In	over corrected
50	18_Sep_22_DS50-D	1 Sec Dynamic	-114.68	-133.82	-19.14	-0.096	In	In	under corrected
50	18_Sep_22_DS50-D1	1 Sec Fixed	-119.26	-133.82	-14.56	-0.073	In	In	under corrected
50	19_Sep_22_DS50-D2	2 Sec Dynamic	-98.62	-133.82	-35.20	-0.176	Out	In	under corrected
50	19_Sep_22_DS50-D3	3 Sec Dynamic	-60.79	-133.82	-73.03	-0.365	Out	Out	under corrected
50	19_Sep_22_DS50-D4	4 Sec Dynamic	-119.55	-133.82	-14.27	-0.071	In	In	under corrected
50	18_Sep_22_DS50-E	1 Sec Dynamic	-26.77	-99.84	-73.57	-0.368	Out	Out	under corrected

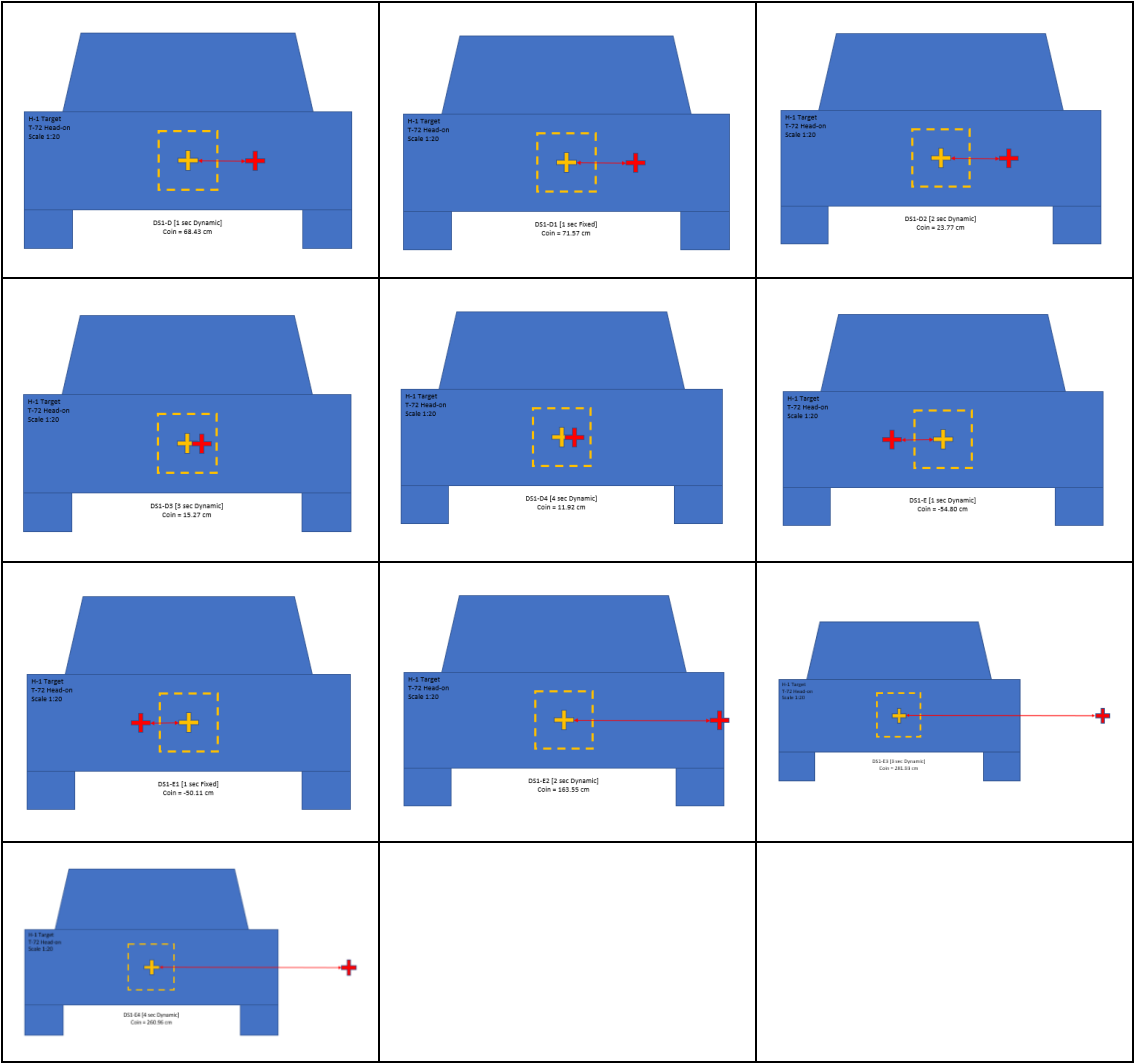
Data Set	File Name	Test	Hit_L [cm]	Hit_F [cm]	Diff [cm]	mrاد	0.15 mrاد	0.30 mrاد	FCC correction
50	18_Sep_22_DS50-E1	1 Sec Fixed	-22.34	-99.84	-77.50	-0.388	Out	Out	under corrected
50	18_Sep_22_DS50-E2	4 Sec Dynamic	-90.59	-99.84	-9.25	-0.046	In	In	under corrected
50	18_Sep_22_DS50-E3	4 Sec Fixed	-77.23	-99.84	-22.61	-0.113	In	In	under corrected
50	18_Sep_22_DS50-E4	All Fixed (2.5 m)	-22.34	-98.97	-76.62	-0.383	Out	Out	under corrected
50	19_Sep_22_DS50-E5	2 Sec Dynamic	29.22	-99.84	-129.07	-0.645	Out	Out	under corrected
50	19_Sep_22_DS50-E6	3 Sec Dynamic	51.71	-99.84	-151.56	-0.758	Out	Out	under corrected
50	19_Sep_22_DS50-E8	2 Sec Fixed	24.37	-99.84	-124.22	-0.621	Out	Out	under corrected
50	19_Sep_22_DS50-E9	3 Sec Fixed	43.99	-99.84	-143.84	-0.719	Out	Out	under corrected

Appendix E Target Hit Silhouettes

E.1 Data Set 01 Results

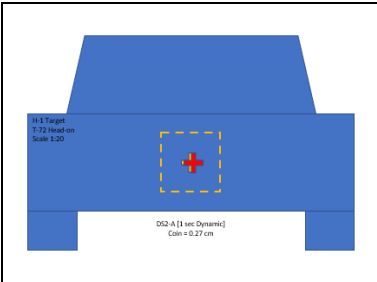
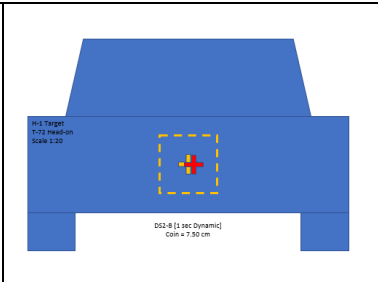
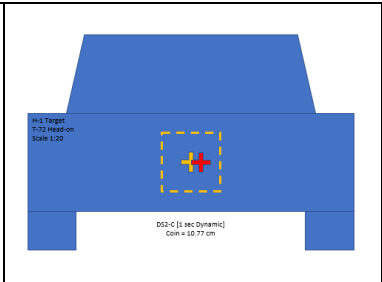
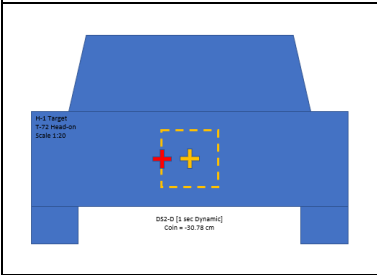
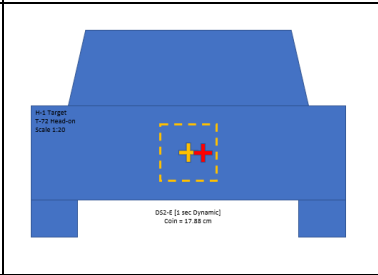
Table E-1 – Data Set 01 – Target Results in order

 DS1-A1 [1 sec Dynamic] Coin = -79.59 cm	 DS1-A1 [1 sec Fixed] Coin = -80.66 cm	 DS1-A2 [2 sec Dynamic] Coin = 62.73 cm
 DS1-A3 [3 sec Dynamic] Coin = -5.38 cm	 DS1-A4 [6 sec Dynamic] Coin = 35.17 cm	 DS1-B [1 sec Dynamic] Coin = 153.48 cm
 DS1-B1 [1 sec Fixed] Coin = 124.69 cm	 DS1-B2 [2 sec Dynamic] Coin = -184.38 cm	 DS1-B3 [3 sec Dynamic] Coin = -118.09 cm
 DS1-B4 [4 sec Dynamic] Coin = 146.78 cm	 DS1-C1 [1 sec Dynamic] Coin = 208.61 cm	 DS1-C2 [2 sec Fixed] Coin = 205.02 cm
 DS1-C2 [2 sec Dynamic] Coin = 234.91 cm	 DS1-C3 [3 sec Dynamic] Coin = 23.91 cm	 DS1-C4 [4 sec Dynamic] Coin = -64.48 cm



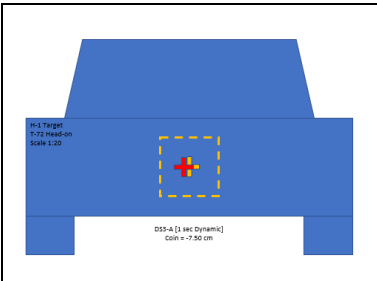
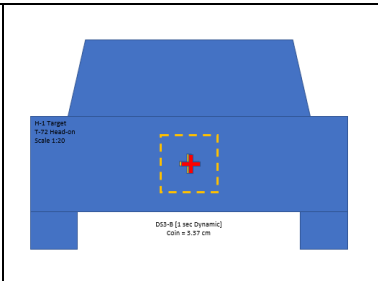
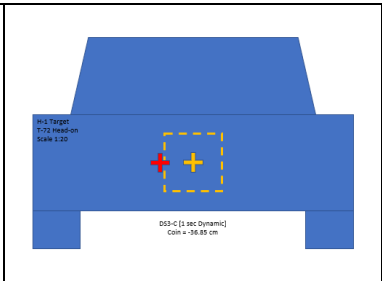
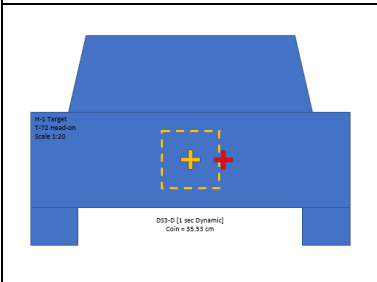
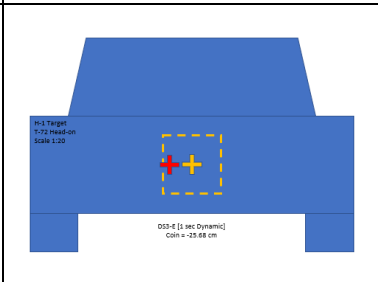
E.2 Data Set 02 Results

Table E-2 – Data Set 02 – Target Results in order

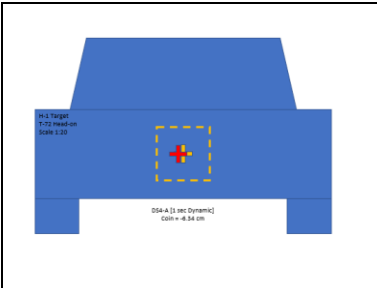
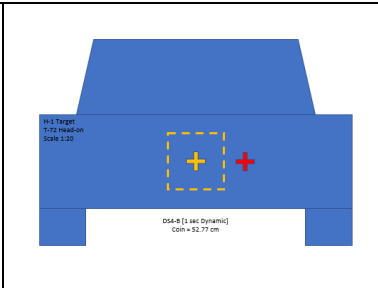
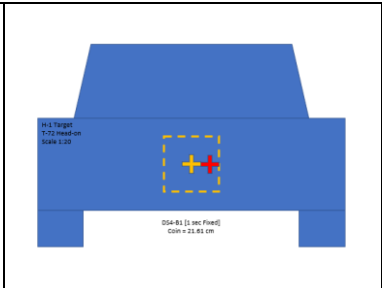
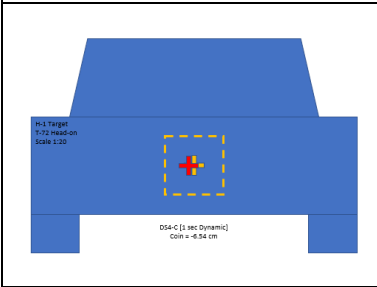
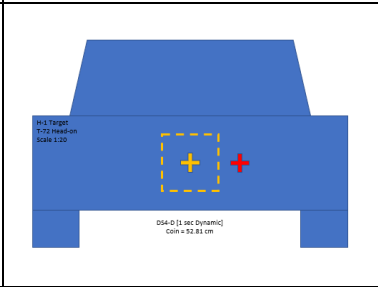
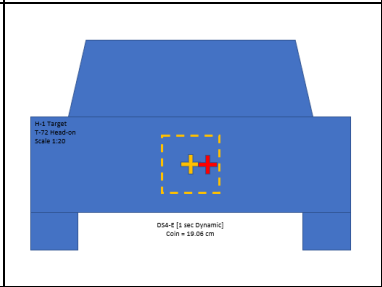
E.3 Data Set 03 Results

Table E-3 – Data Set 03 – Target Results in order

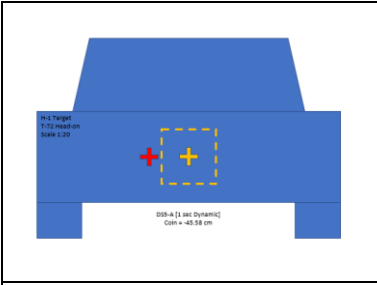
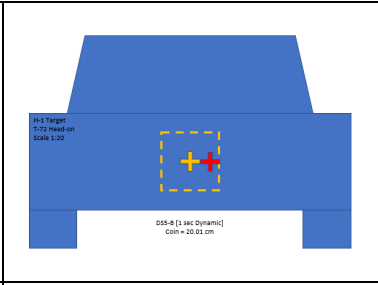
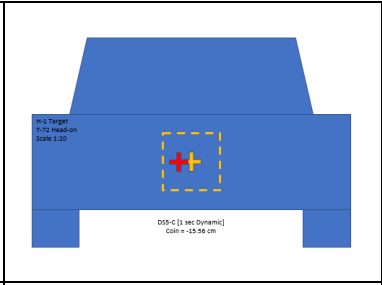
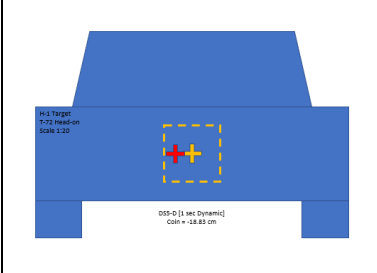
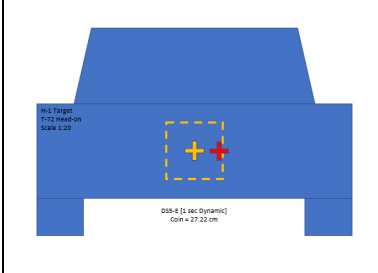
E.4 Data Set 04 Results

Table E-4 – Data Set 04 – Target Results in order

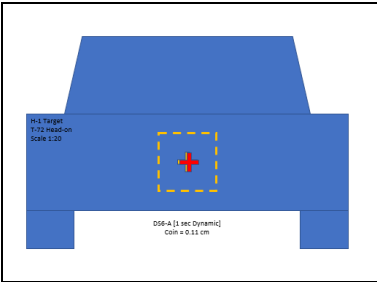
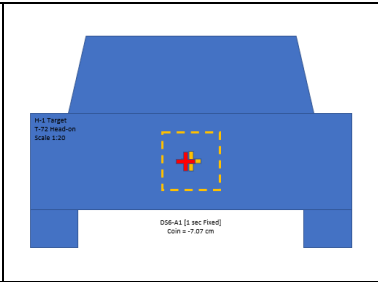
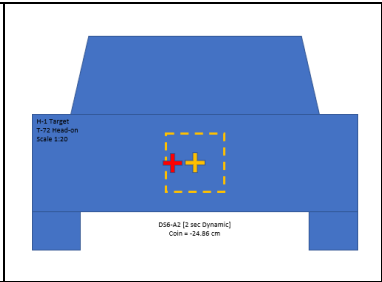
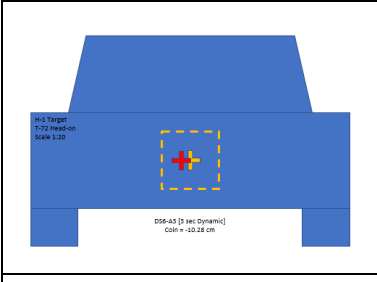
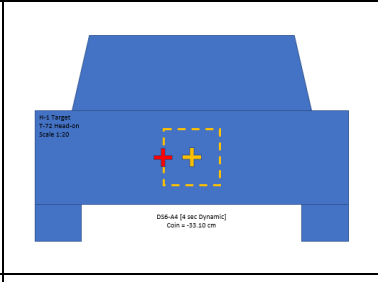
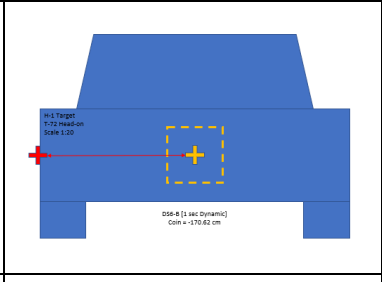
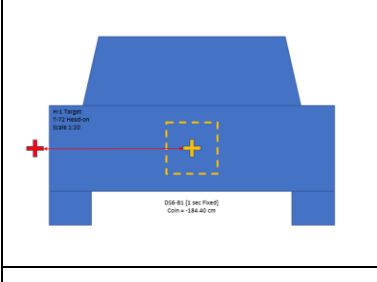
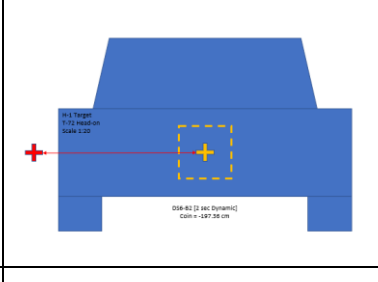
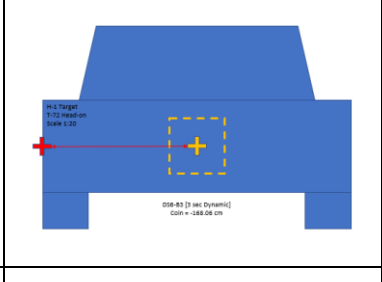
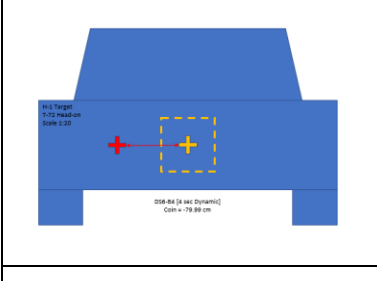
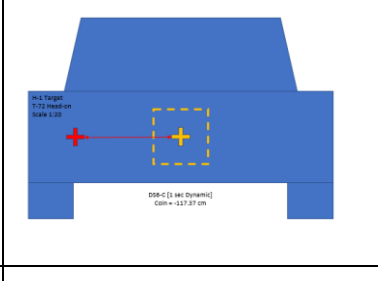
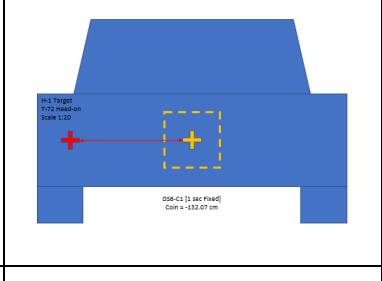
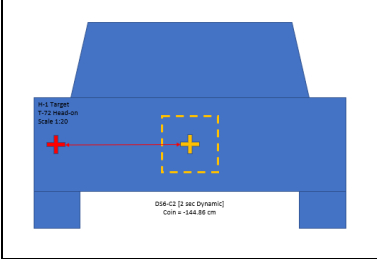
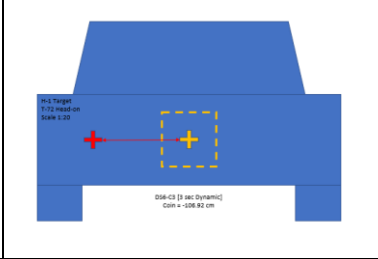
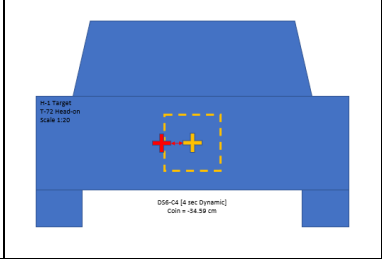
E.5 Data Set 05 Results

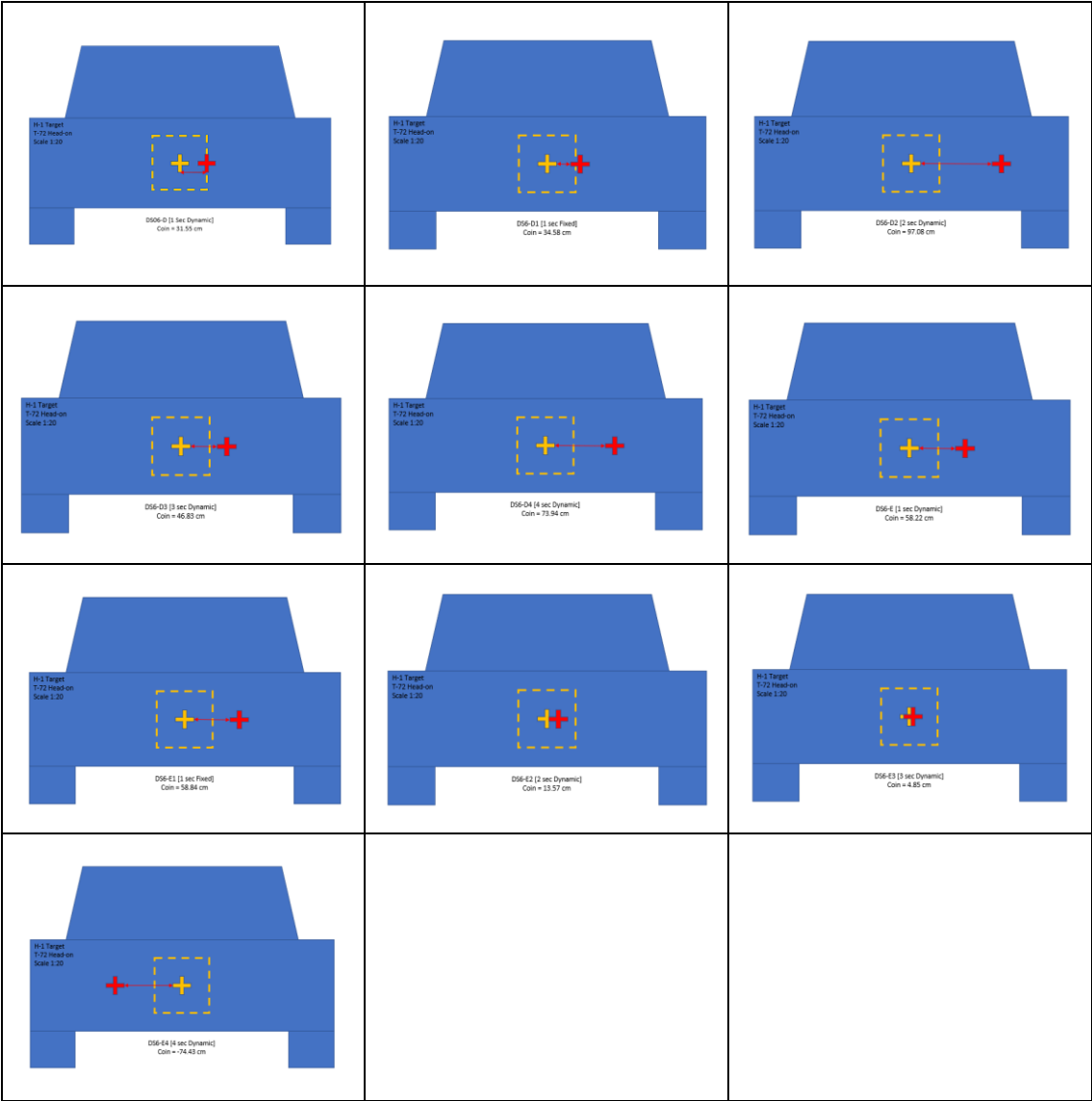
Table E-5 – Data Set 05 – Target Results in order

E.6 Data Set 06 Results

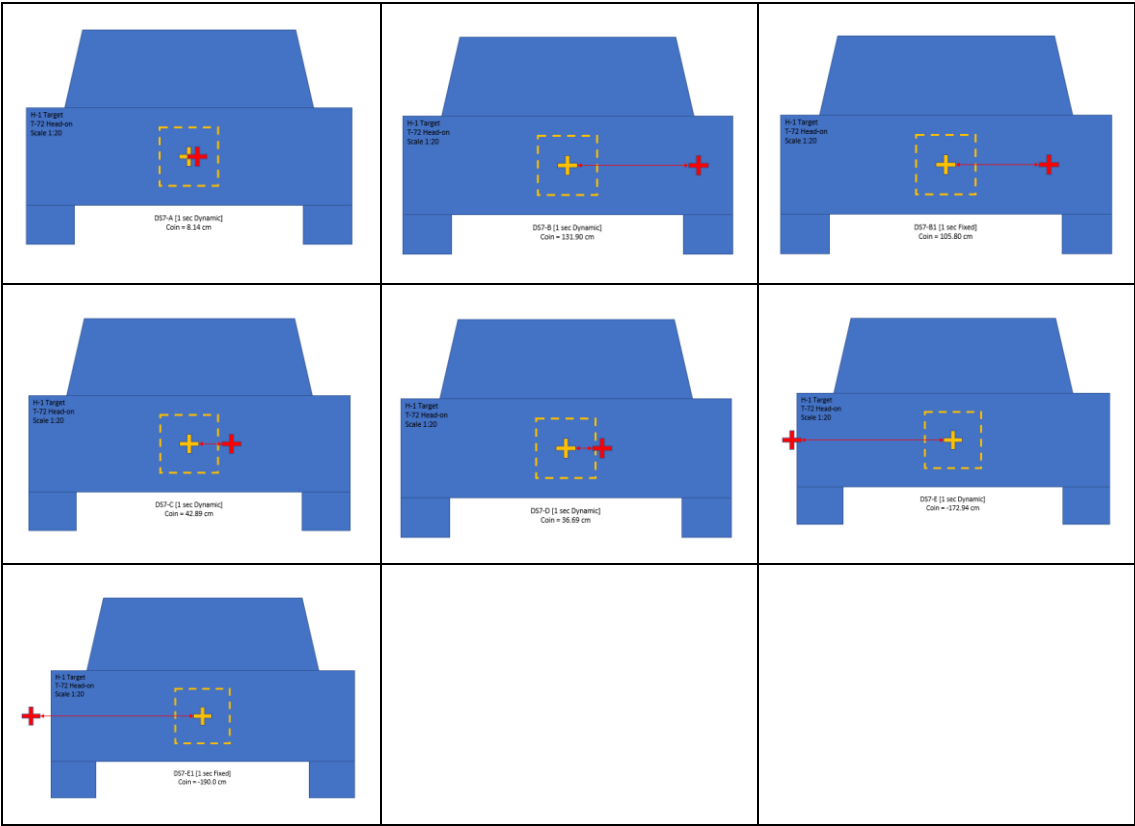
Table E-6 – Data Set 06 – Target Results in order

 H-1 Target 1-12 Head-on Scale 1:20 D56-A [1 sec Dynamic] Coin = 0.11 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-A1 [1 sec Fixed] Coin = -7.07 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-A2 [2 sec Dynamic] Coin = -14.86 cm
 H-1 Target 1-12 Head-on Scale 1:20 D56-B [3 sec Dynamic] Coin = -10.28 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-A4 [4 sec Dynamic] Coin = -10.10 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-B [1 sec Dynamic] Coin = -170.62 cm
 H-1 Target 1-12 Head-on Scale 1:20 D56-B1 [1 sec Fixed] Coin = -154.40 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-B2 [2 sec Dynamic] Coin = -197.35 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-B3 [3 sec Dynamic] Coin = -189.06 cm
 H-1 Target 1-12 Head-on Scale 1:20 D56-B4 [4 sec Dynamic] Coin = -79.89 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-C [1 sec Dynamic] Coin = -117.37 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-C1 [1 sec Fixed] Coin = -132.07 cm
 H-1 Target 1-12 Head-on Scale 1:20 D56-C2 [2 sec Dynamic] Coin = -144.88 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-C3 [3 sec Dynamic] Coin = -106.92 cm	 H-1 Target 1-12 Head-on Scale 1:20 D56-C4 [4 sec Dynamic] Coin = -14.59 cm



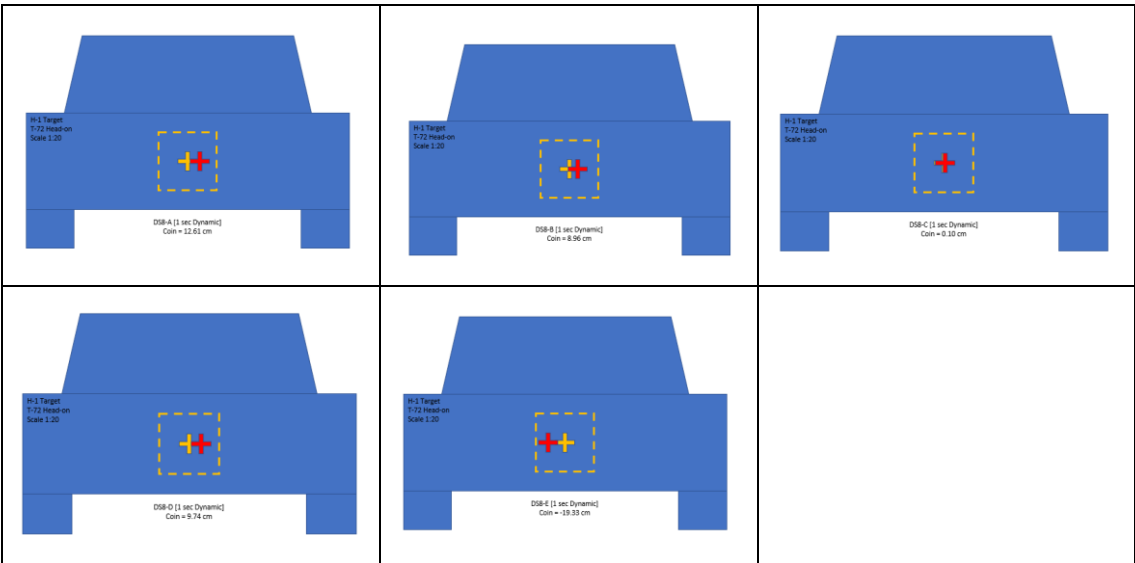
E.7 Data Set 07 Results

Table E-7 – Data Set 07 – Target Results in order



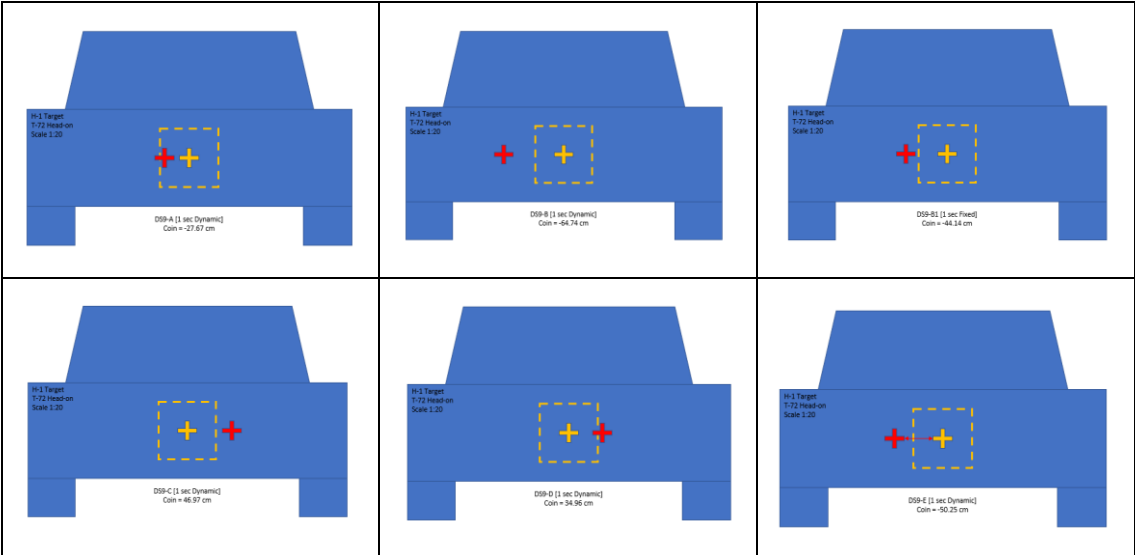
E.8 Data Set 08 Results

Table E-8 – Data Set 08 – Target Results in order



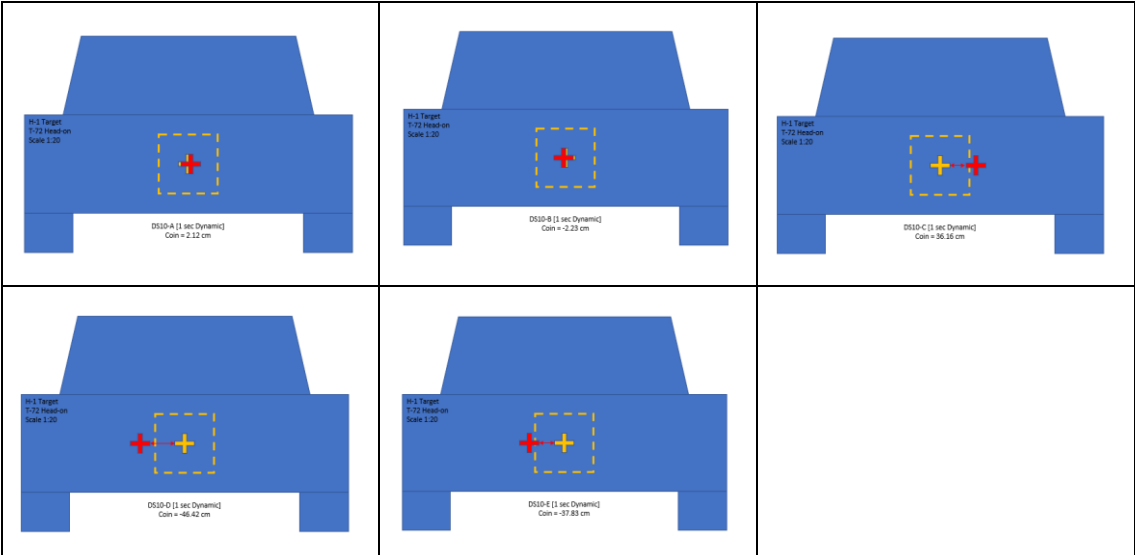
E.9 Data Set 09 Results

Table E-9 – Data Set 09 – Target Results in order



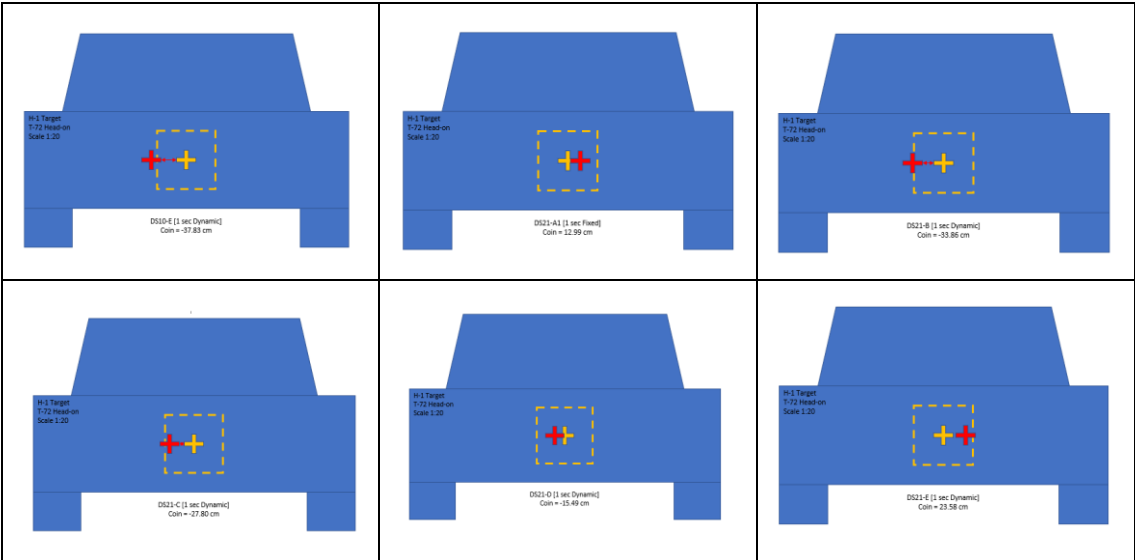
E.10 Data Set 10 Results

Table E-10 – Data Set 10 – Target Results in order



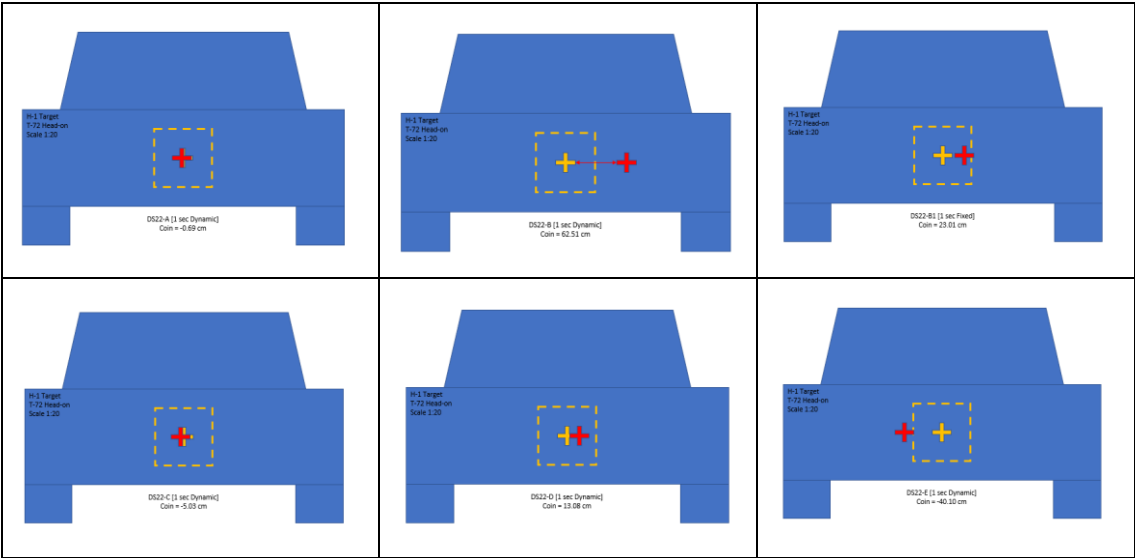
E.11 Data Set 21 Results

Table E-11 – Data Set 21 – Target Results in order



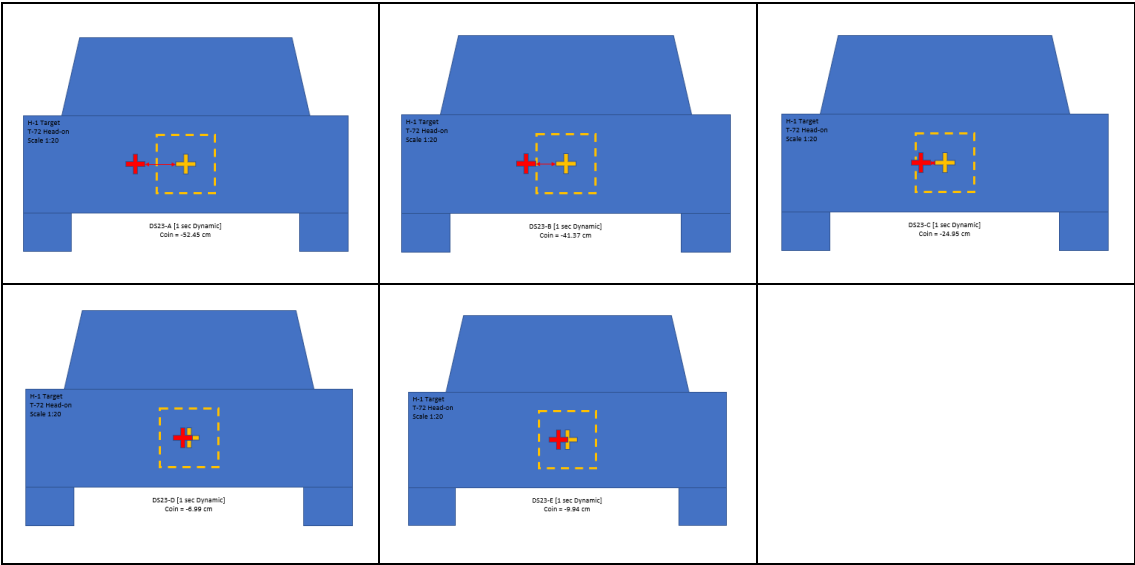
E.12 Data Set 22 Results

Table E-12 – Data Set 22 – Target Results in order



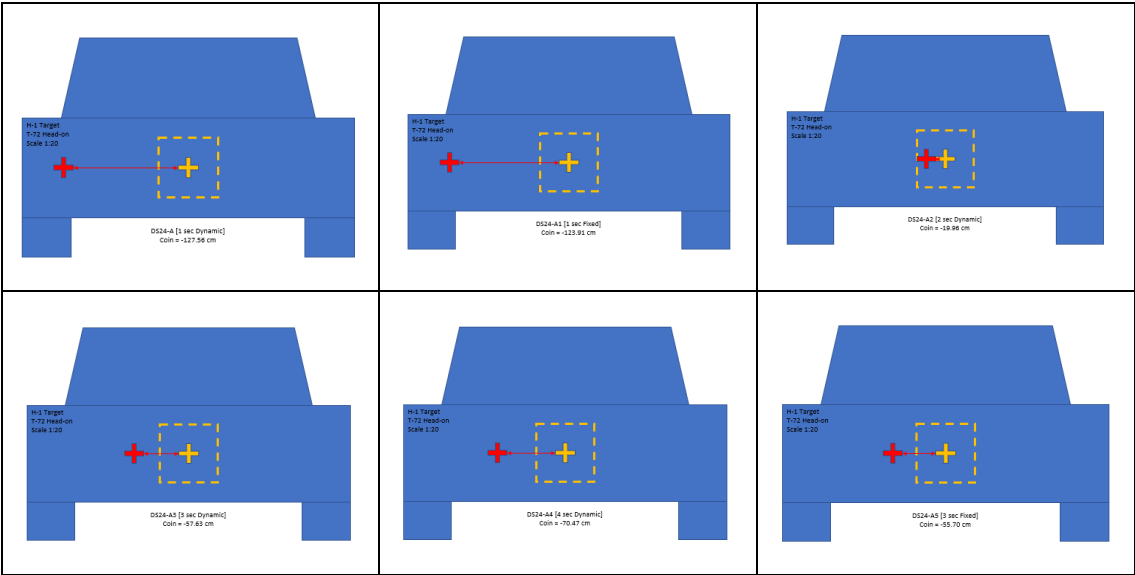
E.13 Data Set 23 Results

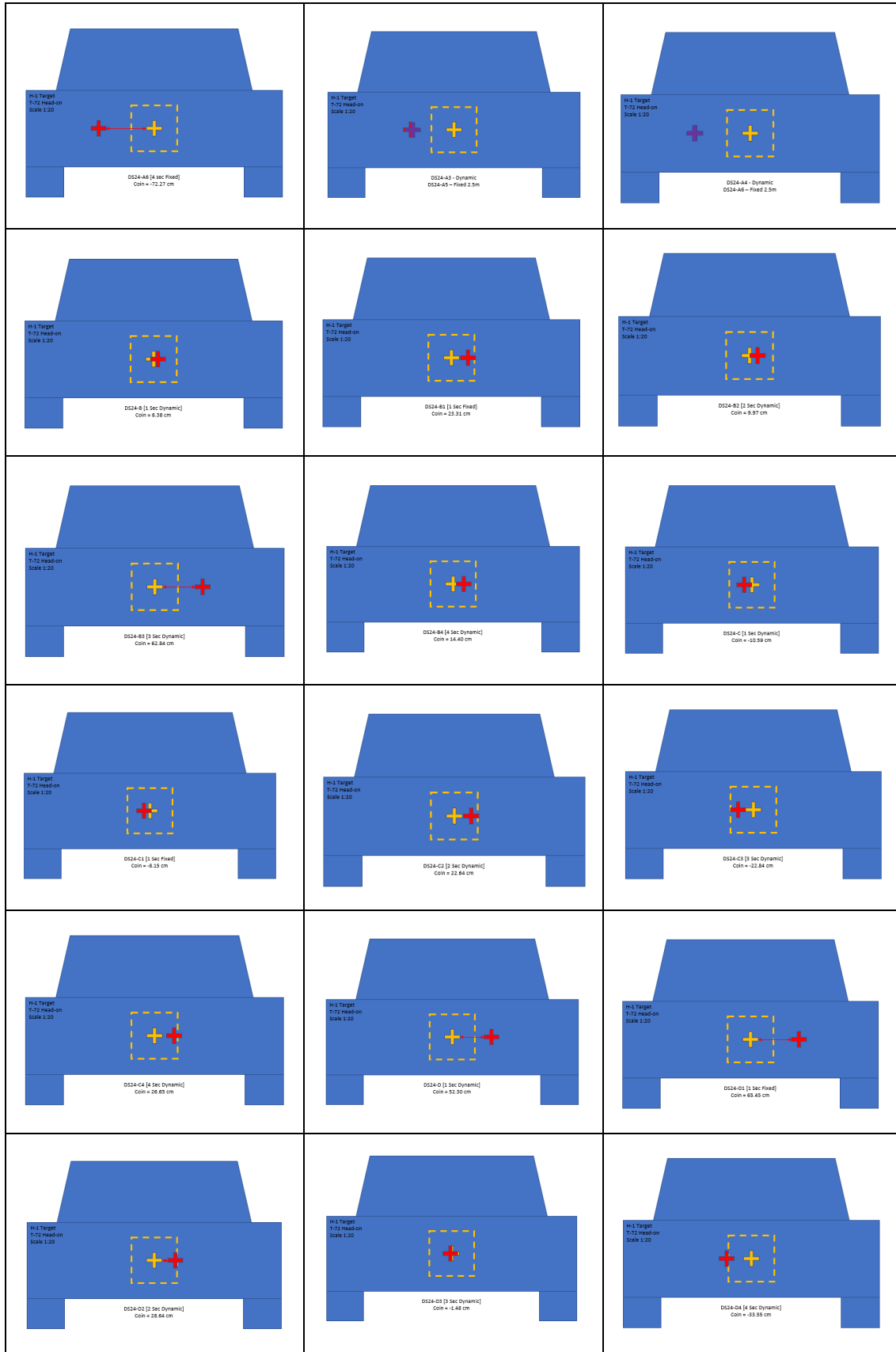
Table E-13 – Data Set 23 – Target Results in order

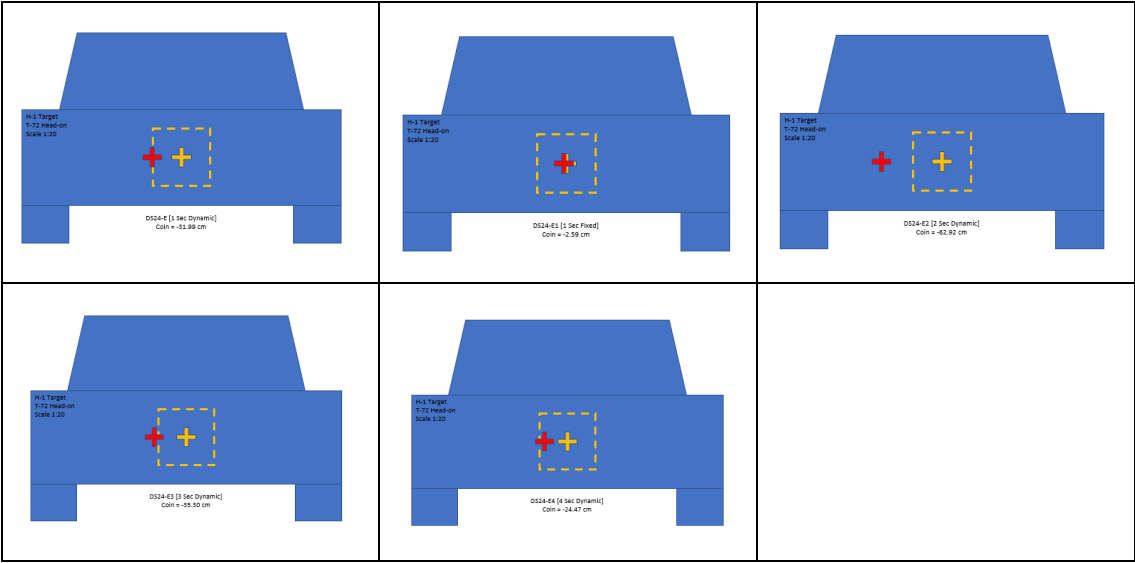


E.14 Data Set 24 Results

Table E-14 – Data Set 24 – Target Results in order

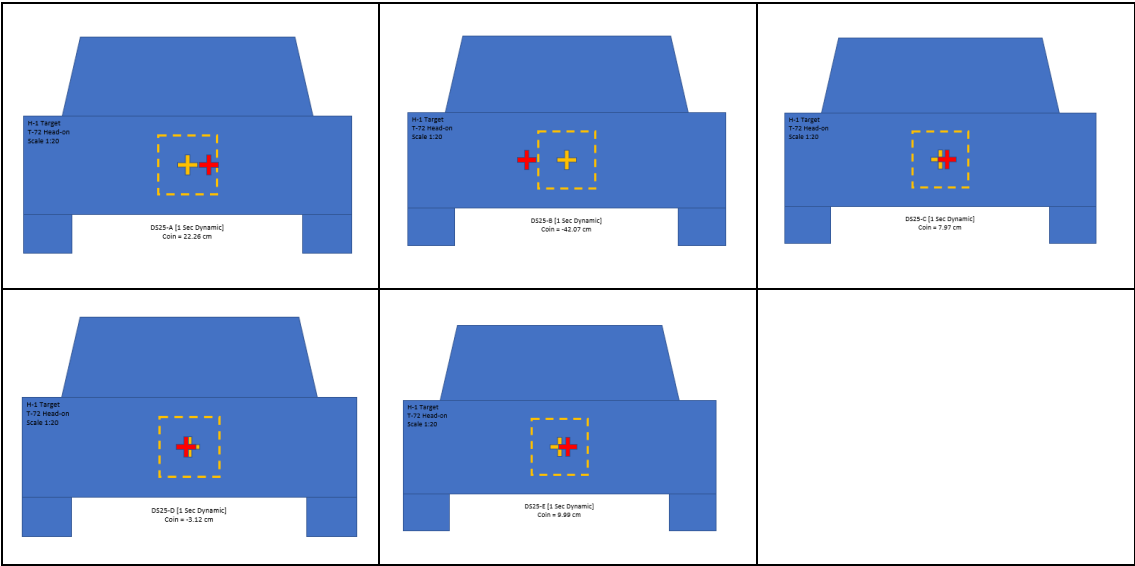






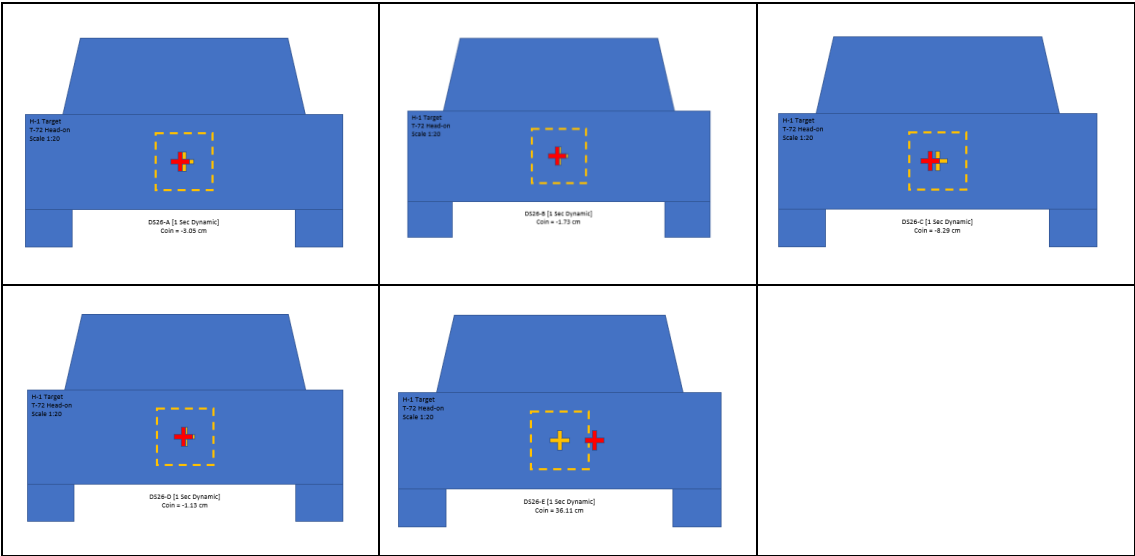
E.15 Data Set 25 Results

Table E-15 – Data Set 25 – Target Results in order



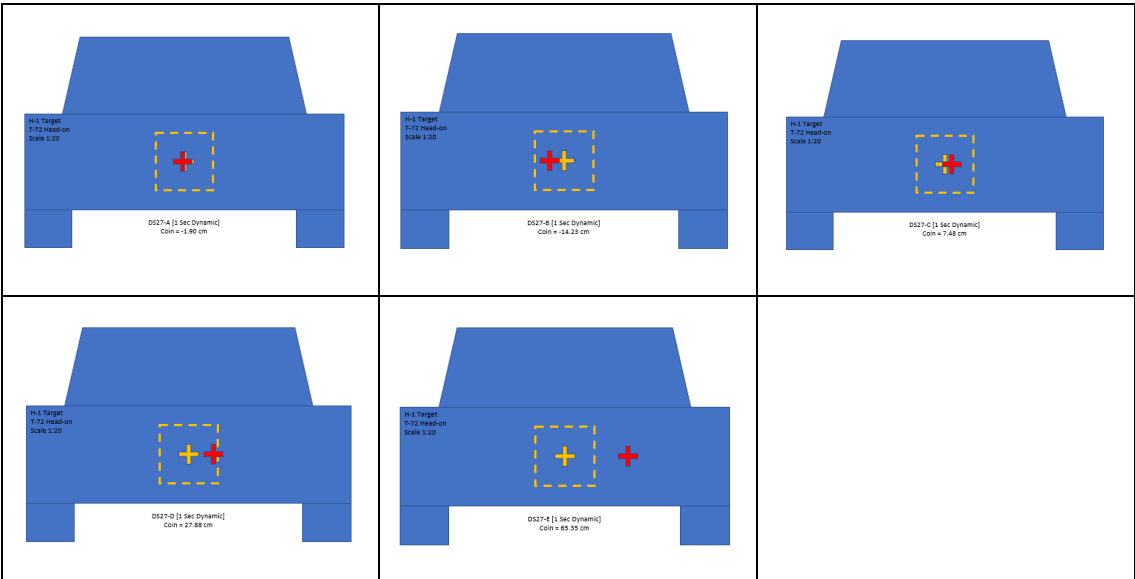
E.16 Data Set 26 Results

Table E-16 – Data Set 26 – Target Results in order



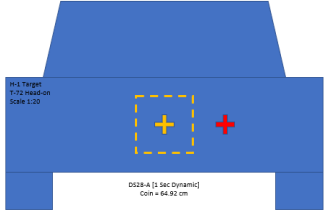
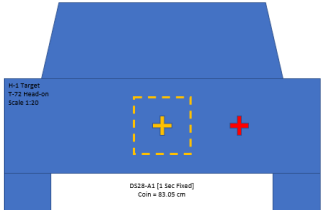
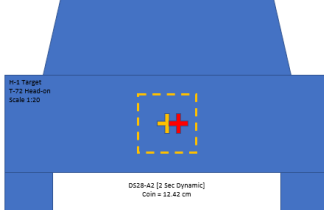
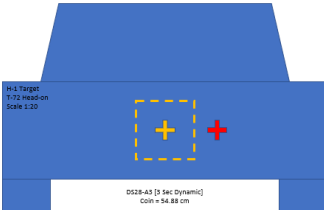
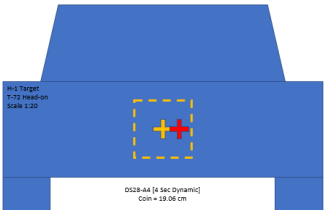
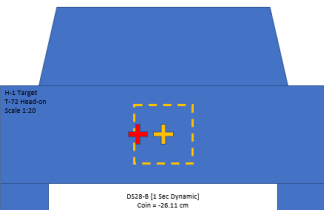
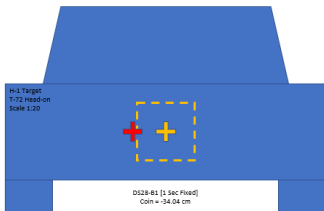
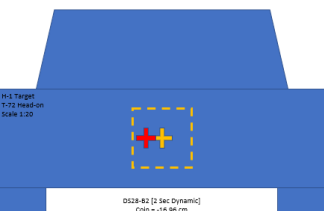
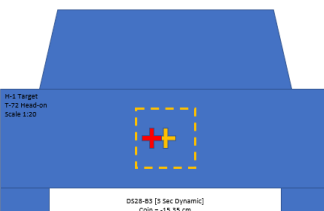
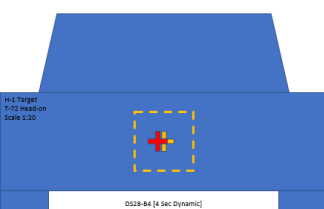
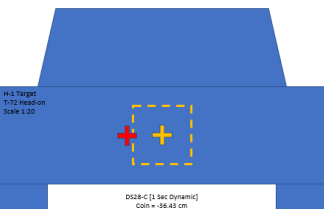
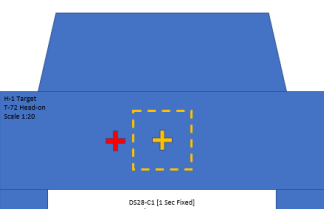
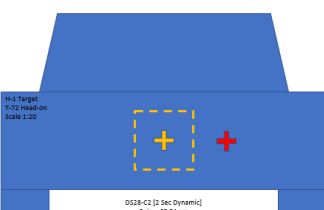
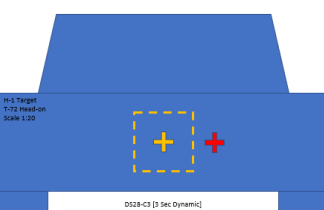
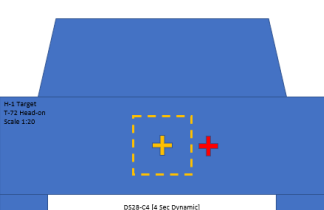
E.17 Data Set 27 Results

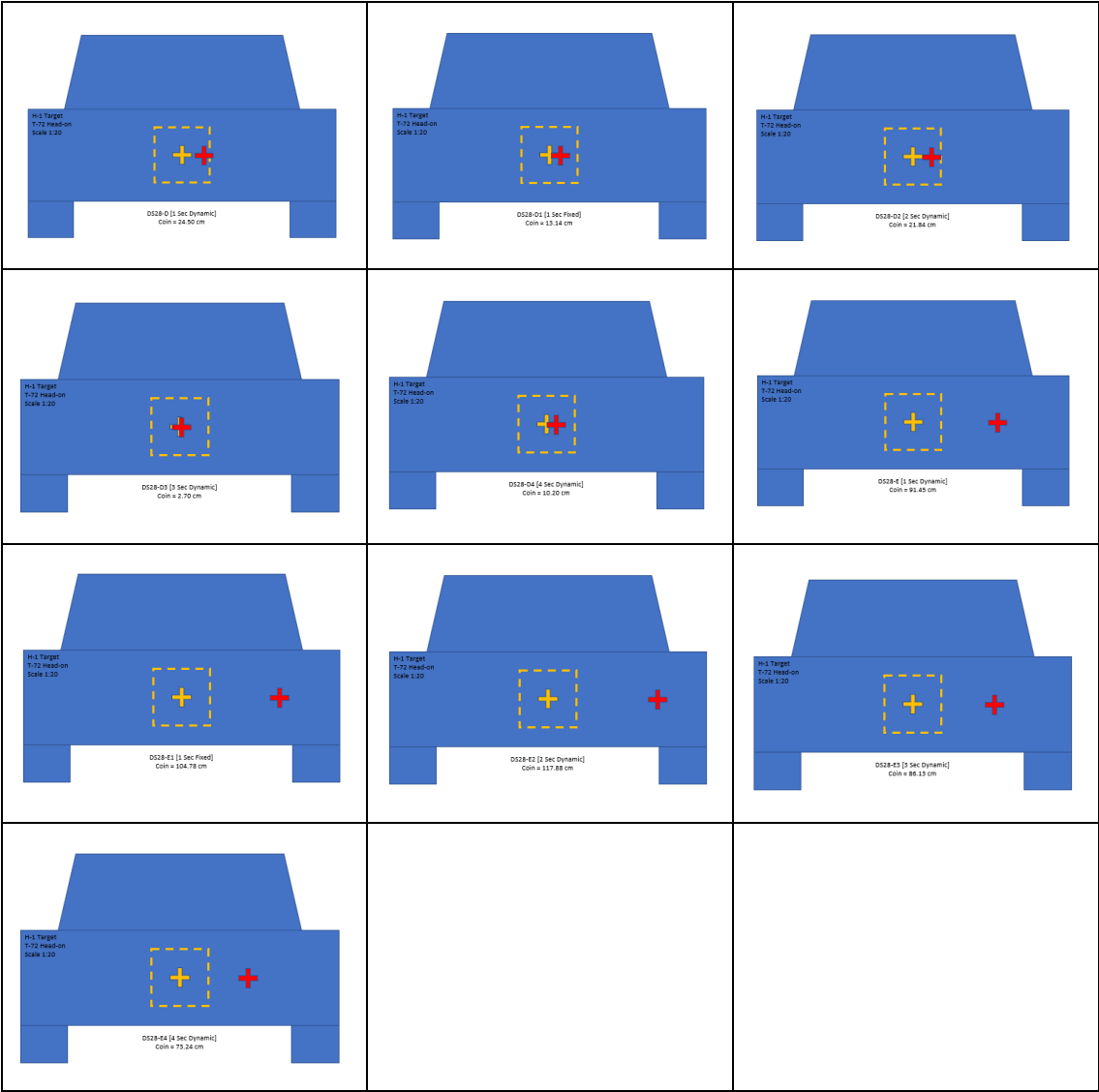
Table E-17 – Data Set 27 – Target Results in order



E.18 Data Set 28 Results

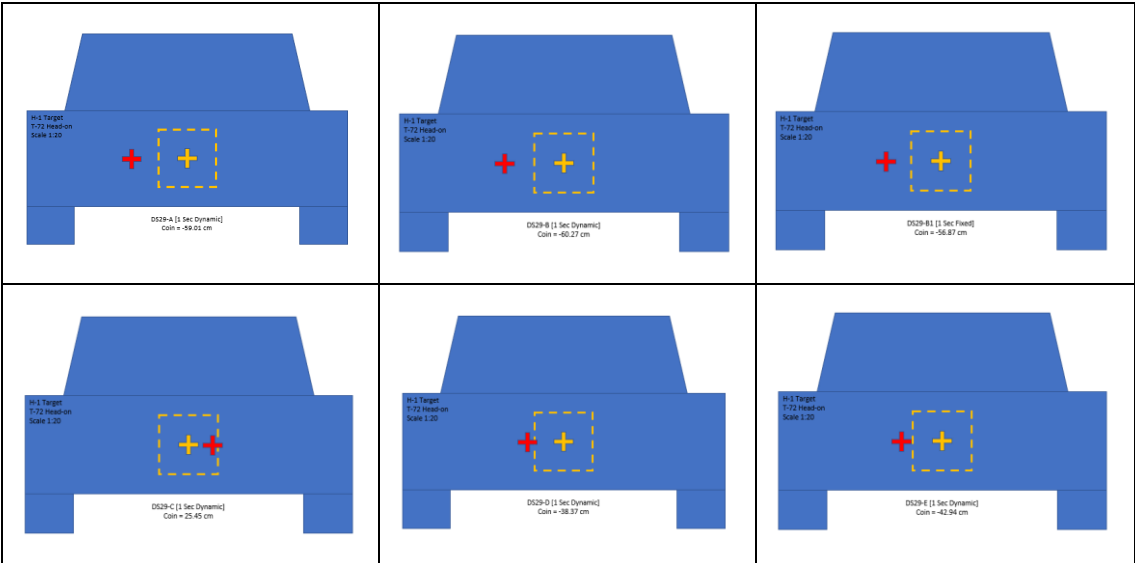
Table E-18 – Data Set 28 – Target Results in order

 H-1 Target 1-72 Head-on Scale 1:20 D528-A [1 Sec Dynamic] Coin = 64.92 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-A1 [1 Sec Fixed] Coin = 93.09 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-A2 [2 Sec Dynamic] Coin = 22.42 cm
 H-1 Target 1-72 Head-on Scale 1:20 D528-A3 [3 Sec Dynamic] Coin = 54.89 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-A4 [4 Sec Dynamic] Coin = 19.06 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-B [1 Sec Dynamic] Coin = 28.11 cm
 H-1 Target 1-72 Head-on Scale 1:20 D528-B1 [1 Sec Fixed] Coin = 34.04 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-B2 [2 Sec Dynamic] Coin = 16.96 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-B3 [3 Sec Dynamic] Coin = 15.55 cm
 H-1 Target 1-72 Head-on Scale 1:20 D528-B4 [4 Sec Dynamic] Coin = 42.44 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-C [1 Sec Dynamic] Coin = 36.43 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-C1 [1 Sec Fixed] Coin = 48.41 cm
 H-1 Target 1-72 Head-on Scale 1:20 D528-C2 [2 Sec Dynamic] Coin = 65.31 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-C3 [3 Sec Dynamic] Coin = 93.21 cm	 H-1 Target 1-72 Head-on Scale 1:20 D528-C4 [4 Sec Dynamic] Coin = 47.84 cm



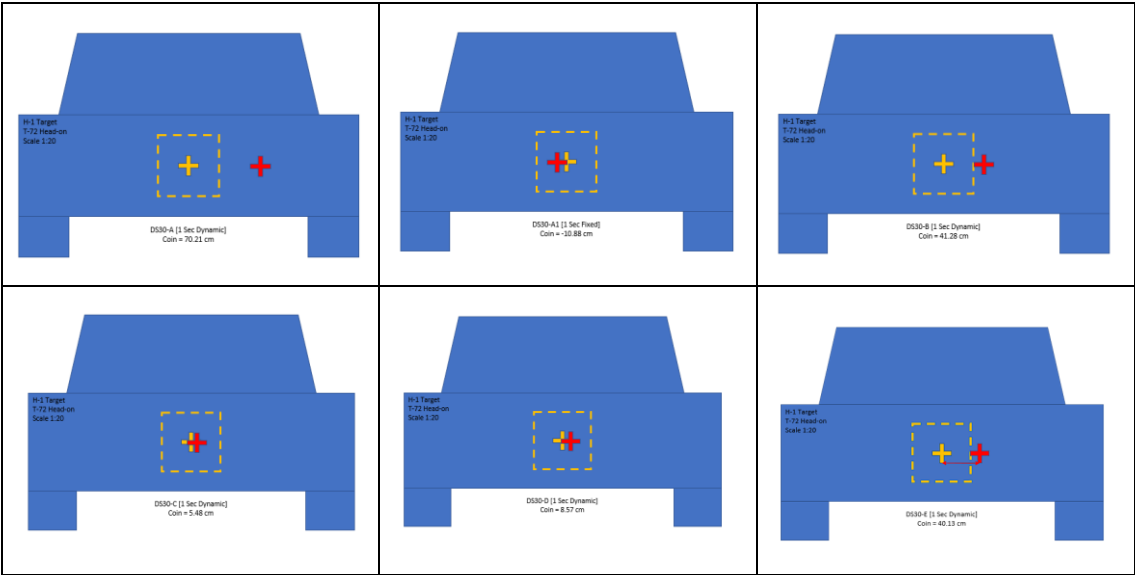
E.19 Data Set 29 Results

Table E-19 – Data Set 29 – Target Results in order



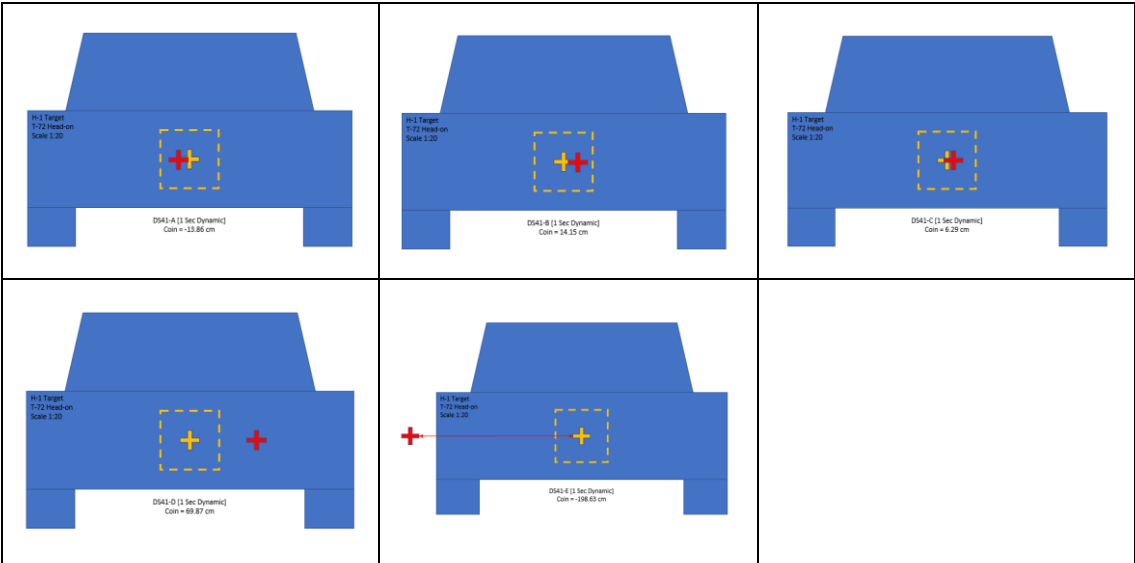
E.20 Data Set 30 Results

Table E-20 – Data Set 30 – Target Results in order



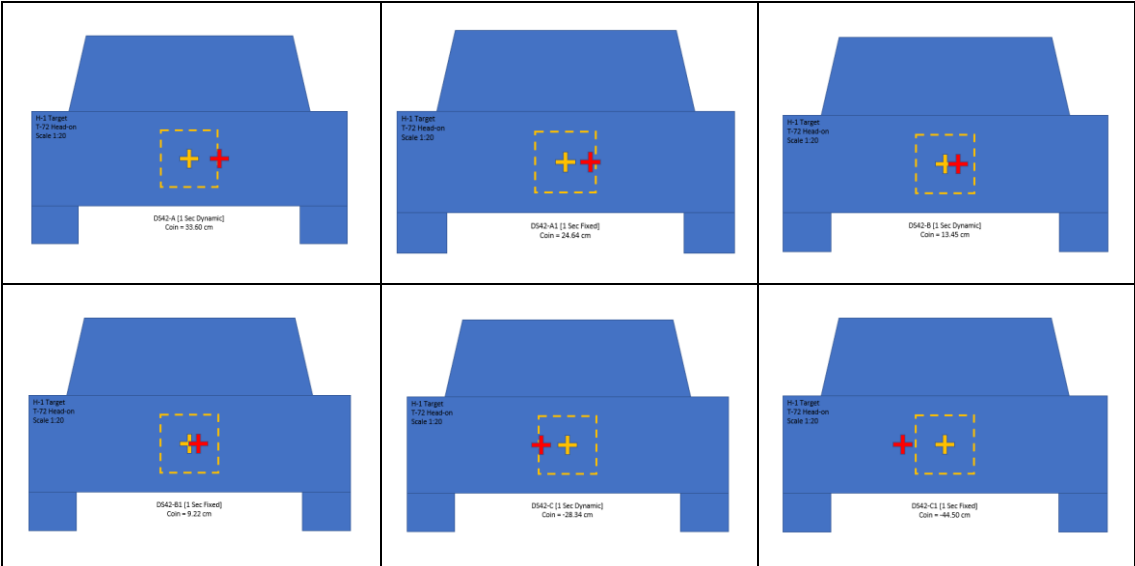
E.21 Data Set 41 Results

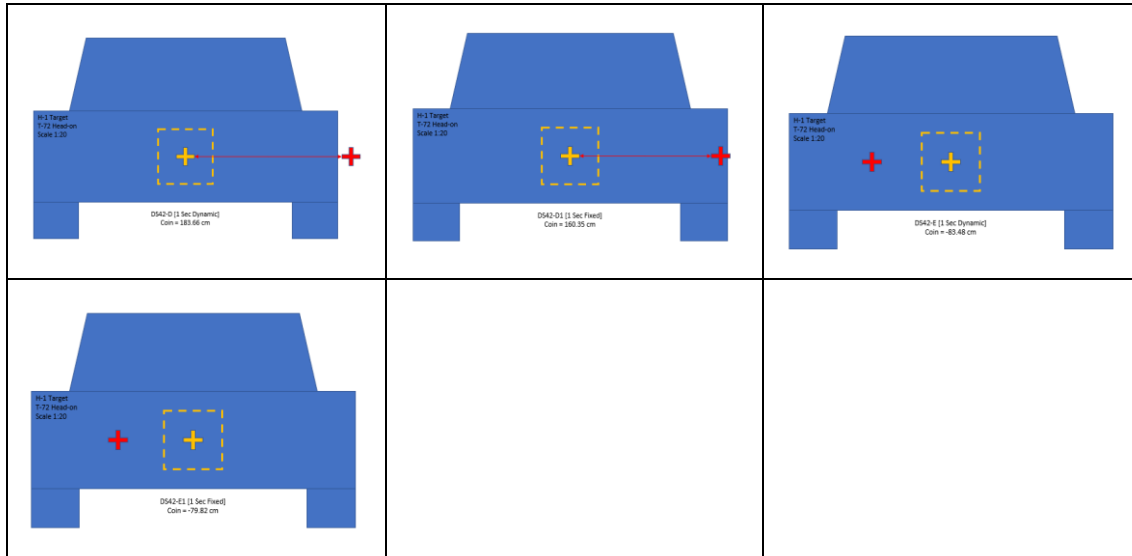
Table E-21 – Data Set 41 – Target Results in order



E.22 Data Set 42 Results

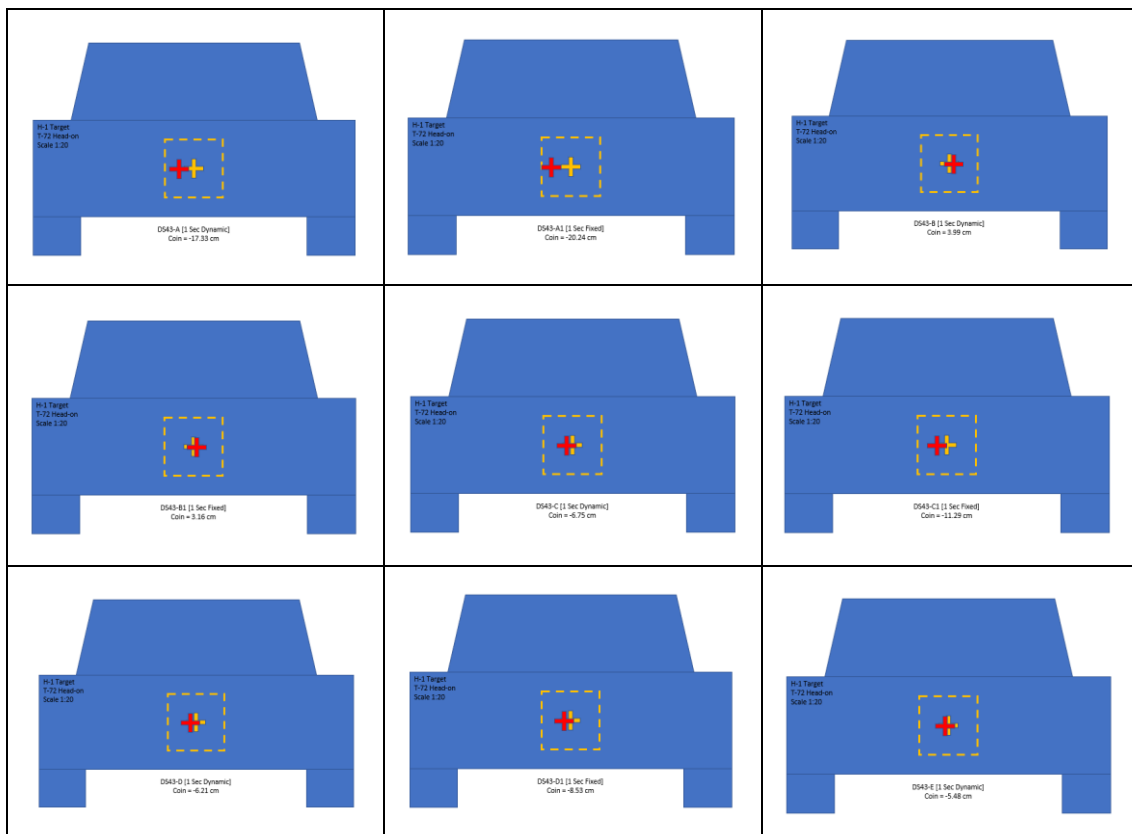
Table E-22 – Data Set 42 – Target Results in order

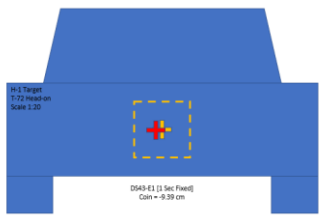




E.23 Data Set 43 Results

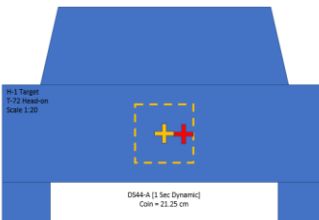
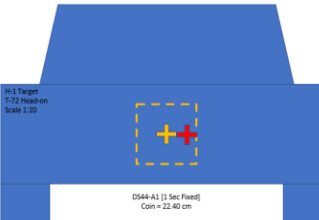
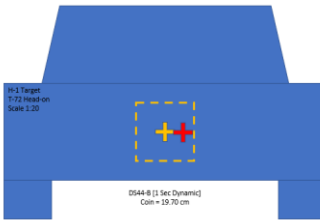
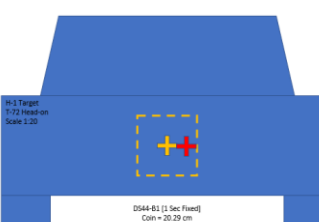
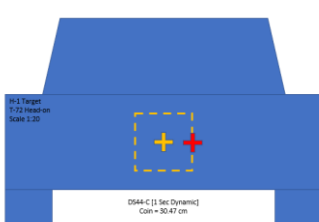
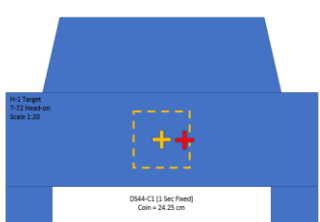
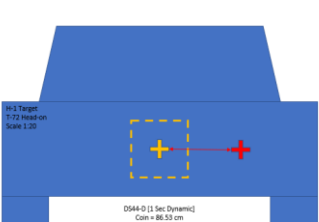
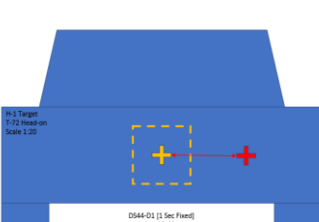
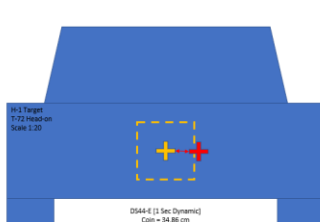
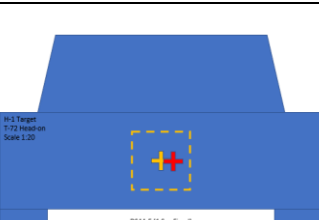
Table E-23 – Data Set 43 – Target Results in order



 H-3 Target 7.72 Head-on Scale 1.20 D543-E1 (1 Sec Fixed) Coin = 9.39 cm		
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E.24 Data Set 44 Results

Table E-24 – Data Set 44 – Target Results in order

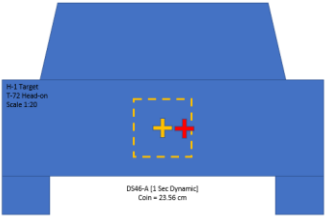
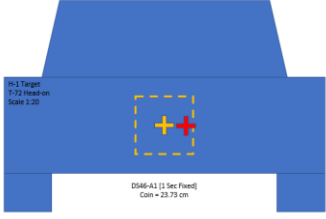
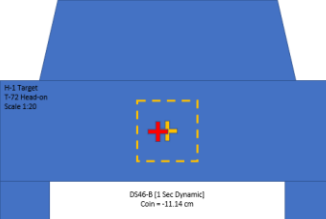
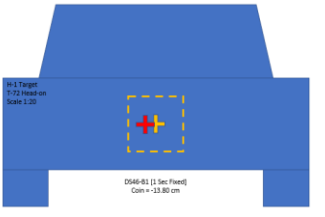
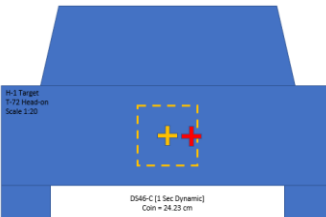
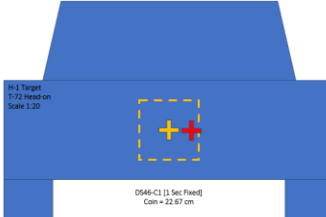
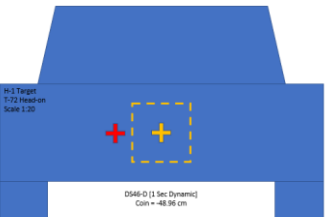
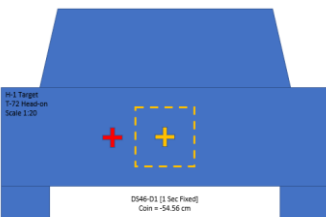
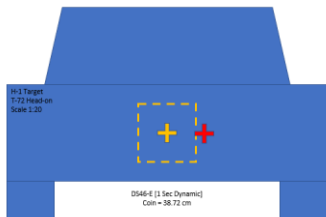
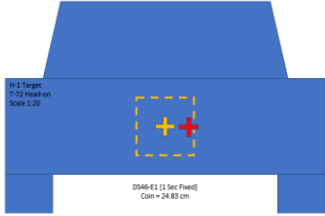
 H-3 Target 7.72 Head-on Scale 1.20 D544-A (1 Sec Dynamic) Coin = 21.25 cm	 H-3 Target 7.72 Head-on Scale 1.20 D544-A1 (1 Sec Fixed) Coin = 22.40 cm	 H-3 Target 7.72 Head-on Scale 1.20 D544-B (1 Sec Dynamic) Coin = 19.70 cm
 H-3 Target 7.72 Head-on Scale 1.20 D544-B1 (1 Sec Fixed) Coin = 20.20 cm	 H-3 Target 7.72 Head-on Scale 1.20 D544-C (1 Sec Dynamic) Coin = 30.47 cm	 H-3 Target 7.72 Head-on Scale 1.20 D544-C1 (1 Sec Fixed) Coin = 24.25 cm
 H-3 Target 7.72 Head-on Scale 1.20 D544-D (1 Sec Dynamic) Coin = 86.53 cm	 H-3 Target 7.72 Head-on Scale 1.20 D544-D1 (1 Sec Fixed) Coin = 88.72 cm	 H-3 Target 7.72 Head-on Scale 1.20 D544-E (1 Sec Dynamic) Coin = 94.86 cm
 H-3 Target 7.72 Head-on Scale 1.20 D544-E1 (1 Sec Fixed) Coin = 13.89 cm		

E.25 Data Set 45 Results

Table E-25 – Data Set 45 – Target Results in order

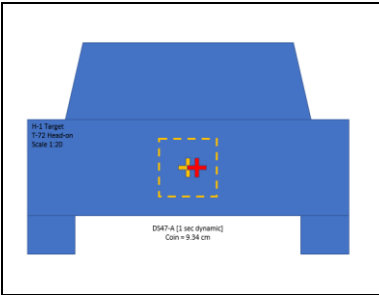
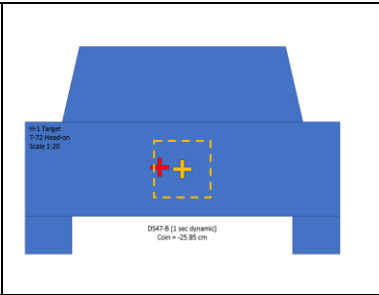
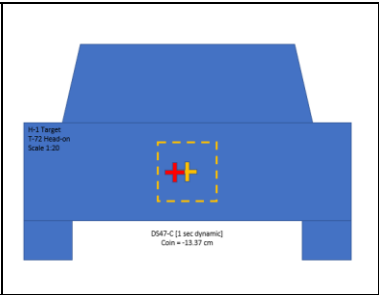
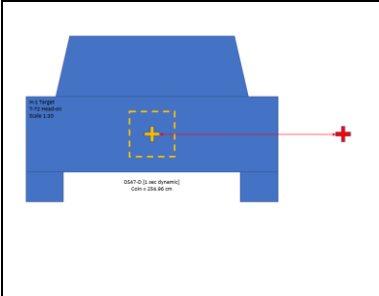
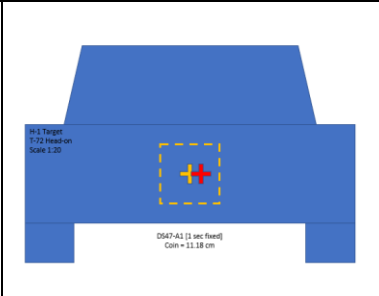
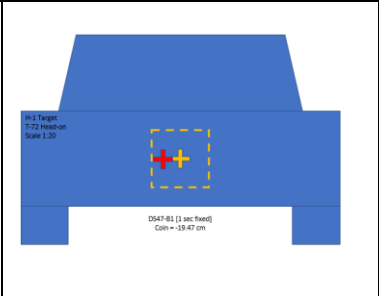
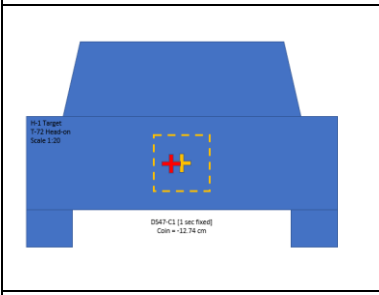
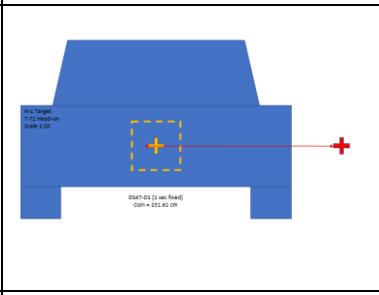
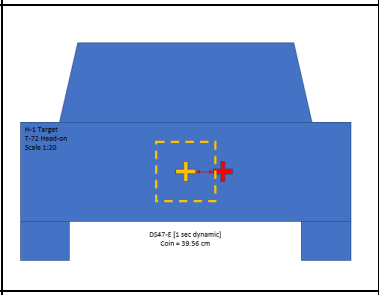
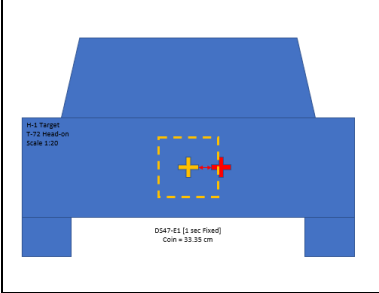
E.26 Data Set 46 Results

Table E-26 – Data Set 46 – Target Results in order

 DS46-A [1 Sec Dynamic] Coin = 23.56 cm	 DS46-A1 [1 Sec Fixed] Coin = 23.79 cm	 DS46-B [1 Sec Dynamic] Coin = -11.14 cm
 DS46-B1 [1 Sec Fixed] Coin = -13.80 cm	 DS46-C [1 Sec Dynamic] Coin = 24.23 cm	 DS46-C1 [1 Sec Fixed] Coin = -22.67 cm
 DS46-D [1 Sec Dynamic] Coin = -48.96 cm	 DS46-D1 [1 Sec Fixed] Coin = -54.56 cm	 DS46-E [1 Sec Dynamic] Coin = 38.72 cm
 DS46-E1 [1 Sec Fixed] Coin = 24.89 cm		

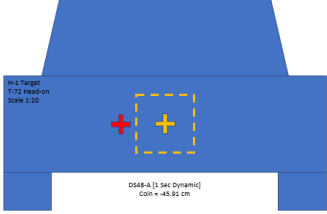
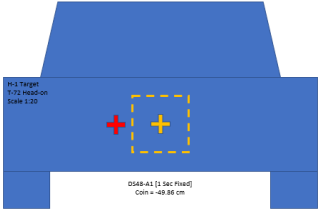
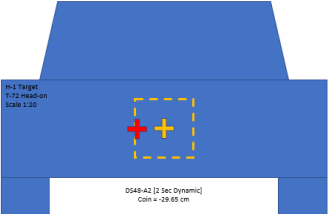
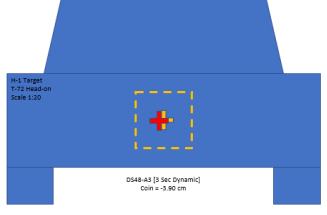
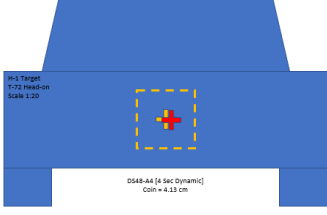
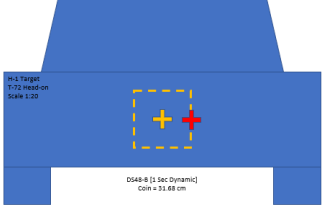
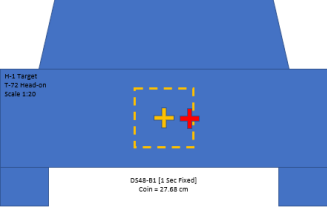
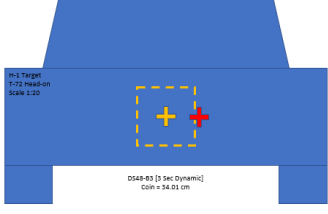
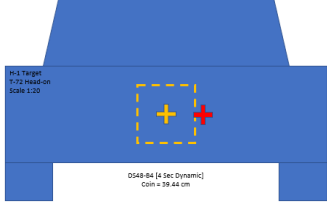
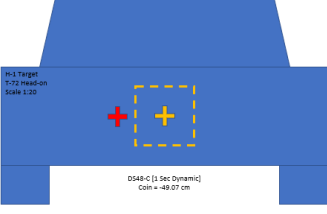
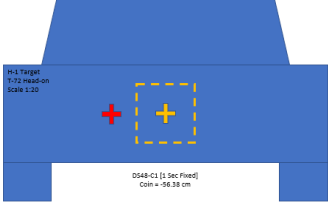
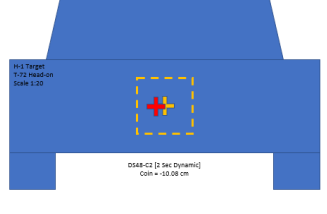
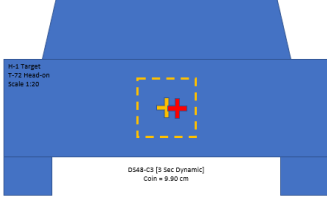
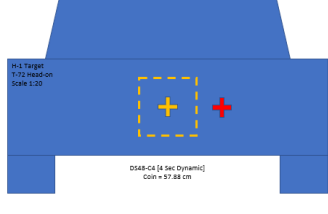
E.27 Data Set 47 Results

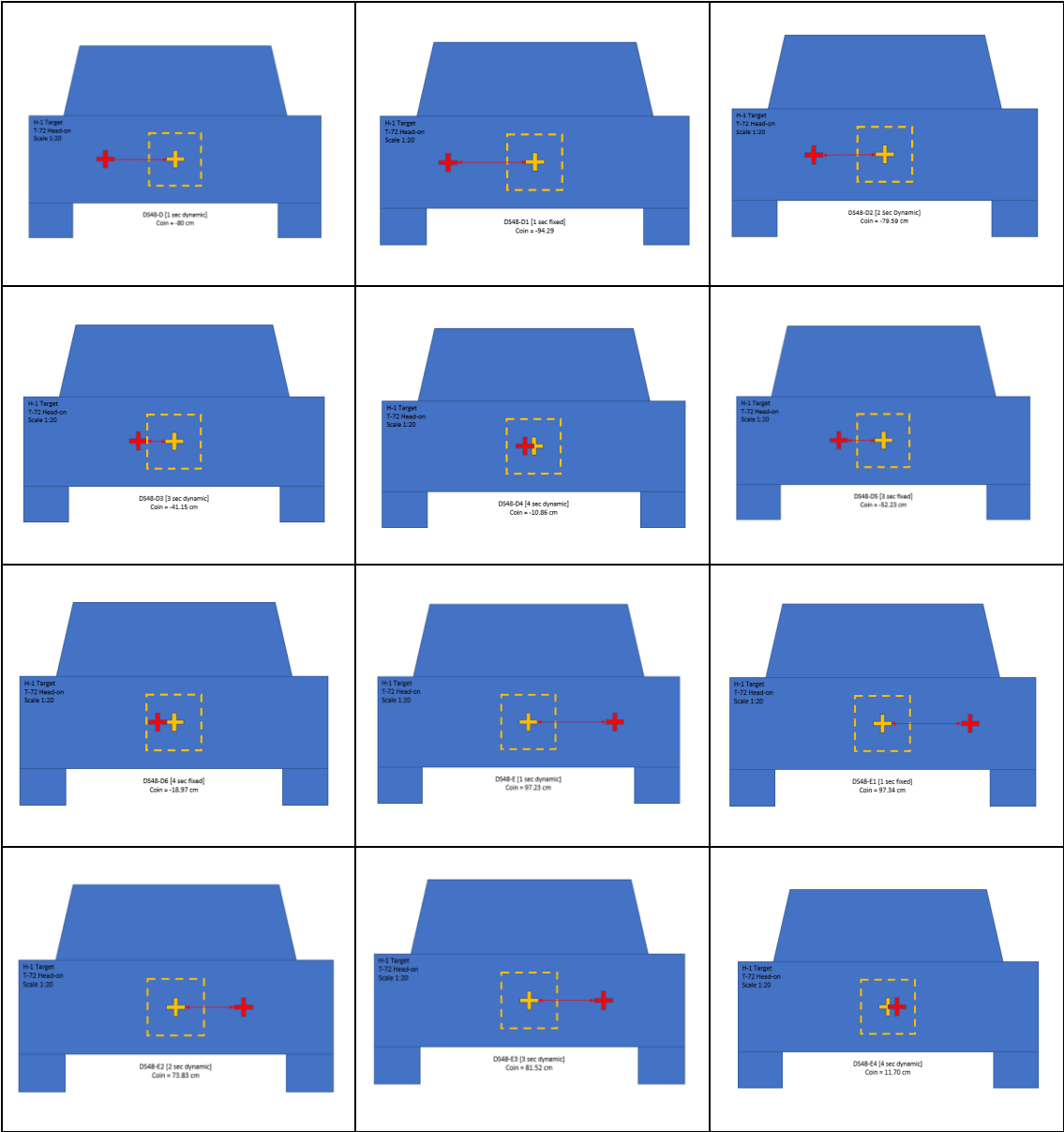
Table E-27 – Data Set 47 – Target Results in order

E.28 Data Set 48 Results

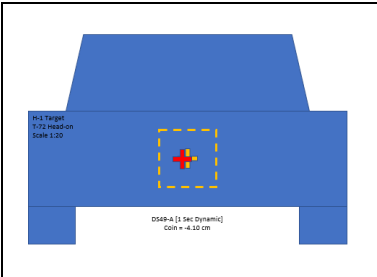
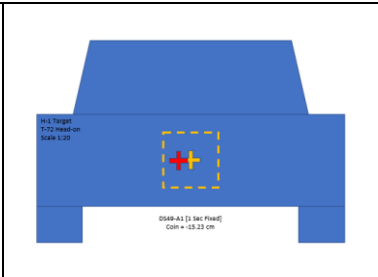
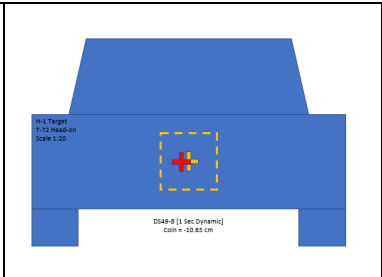
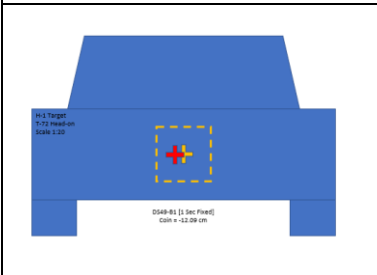
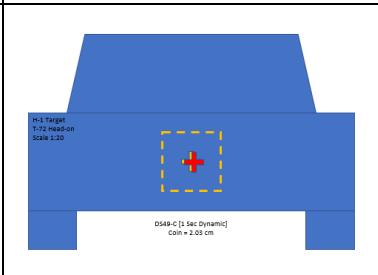
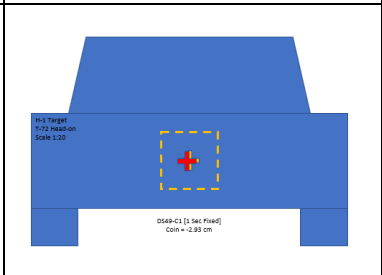
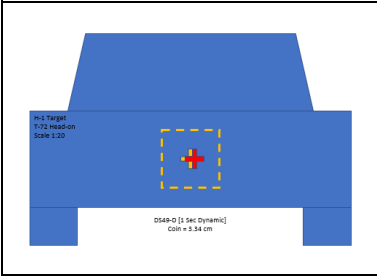
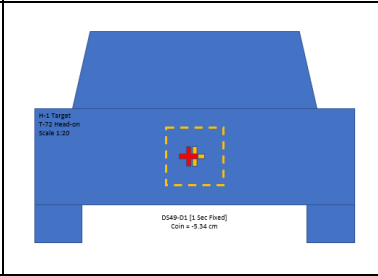
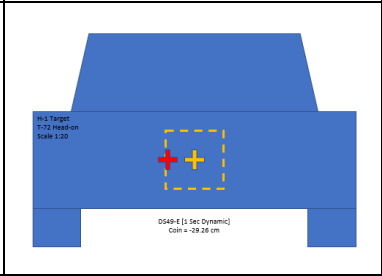
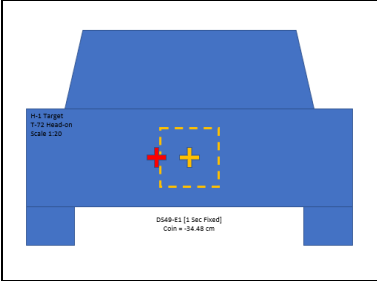
Table E-28 – Data Set 48 – Target Results in order

 H-1 Target 1-72 Head-on Scale 1:20 D548-A [1 Sec Dynamic] Coin = +43.91 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-A1 [1 Sec Fixed] Coin = +49.66 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-A2 [2 Sec Dynamic] Coin = +29.65 cm
 H-1 Target 1-72 Head-on Scale 1:20 D548-B [3 Sec Dynamic] Coin = -3.90 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-A4 [4 Sec Dynamic] Coin = +1.15 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-B [3 Sec Dynamic] Coin = +31.68 cm
 H-1 Target 1-72 Head-on Scale 1:20 D548-B1 [1 Sec Fixed] Coin = +27.68 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-B2 [2 Sec Dynamic] Coin = +30.24 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-B3 [3 Sec Dynamic] Coin = +34.01 cm
 H-1 Target 1-72 Head-on Scale 1:20 D548-B4 [4 Sec Dynamic] Coin = +39.44 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-C [1 Sec Dynamic] Coin = +49.07 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-C1 [1 Sec Fixed] Coin = +56.38 cm
 H-1 Target 1-72 Head-on Scale 1:20 D548-C2 [2 Sec Dynamic] Coin = +10.08 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-C3 [3 Sec Dynamic] Coin = +9.90 cm	 H-1 Target 1-72 Head-on Scale 1:20 D548-C4 [4 Sec Dynamic] Coin = +57.86 cm



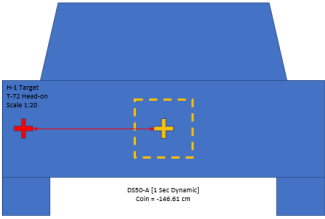
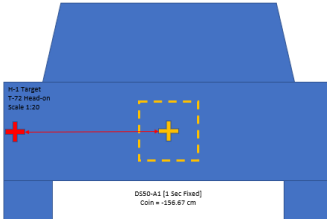
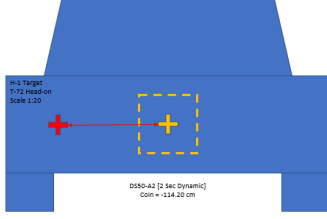
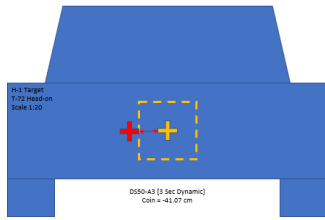
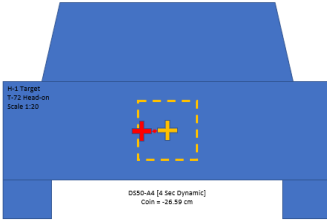
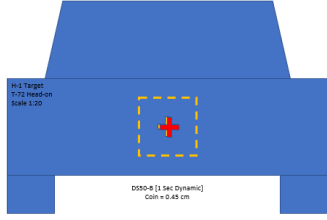
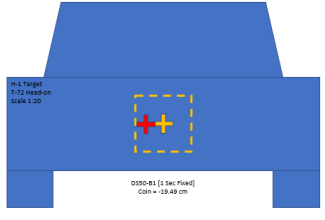
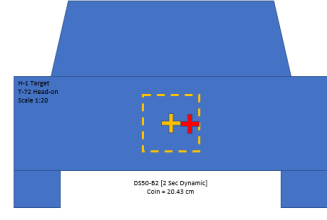
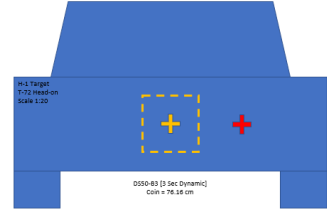
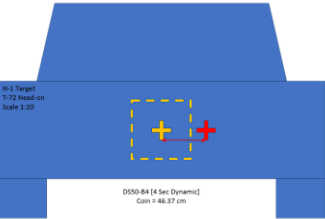
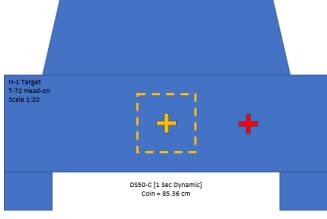
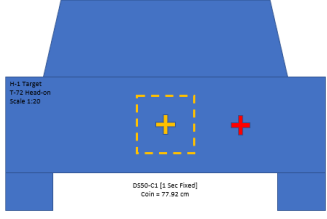
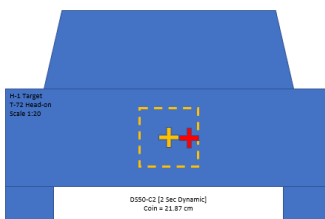
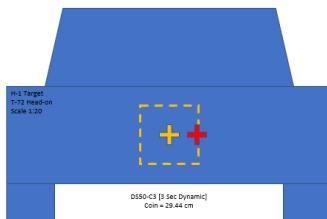
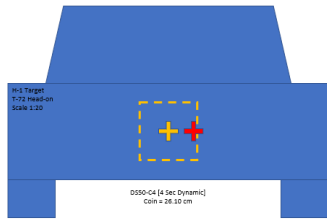
E.29 Data Set 49 Results

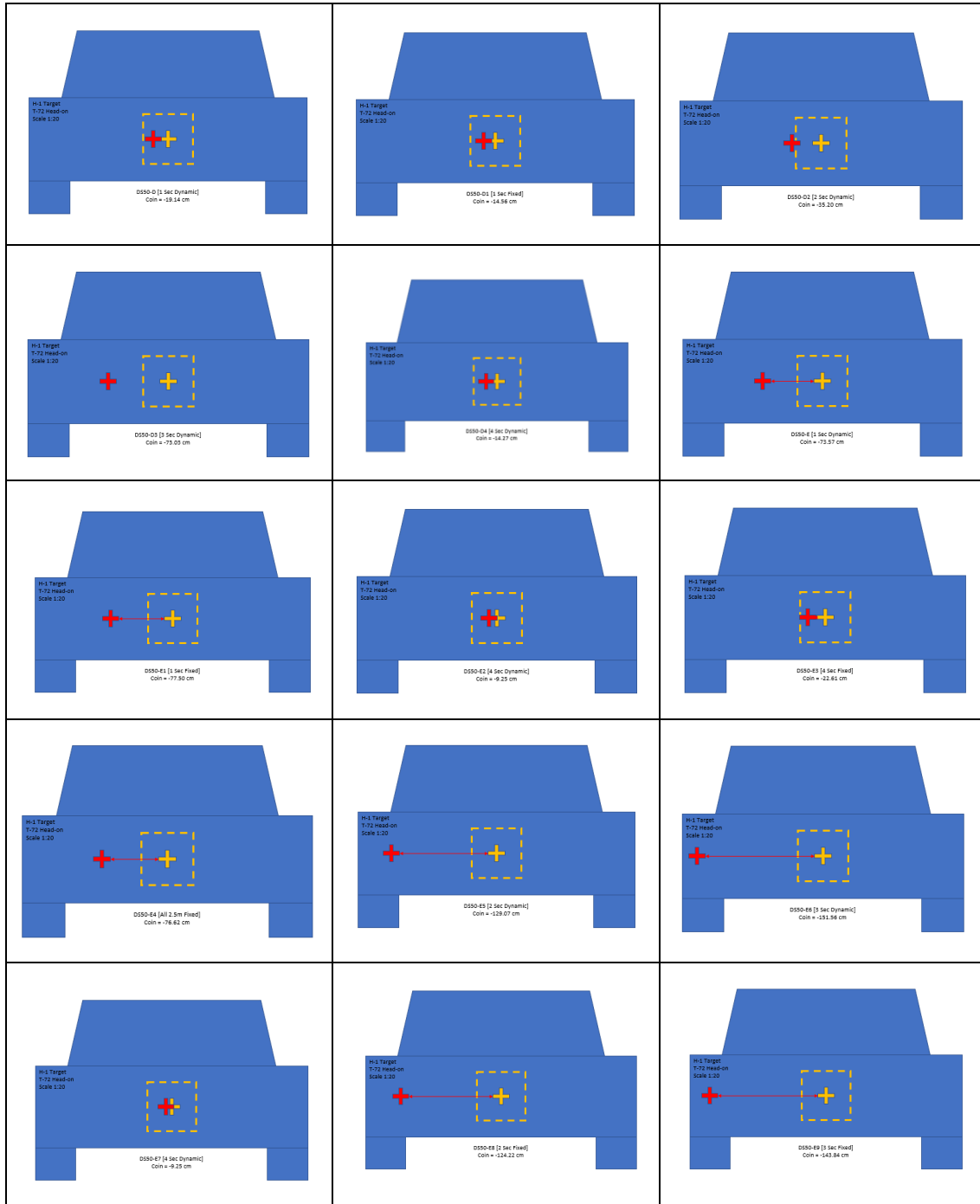
Table E-29 – Data Set 49 – Target Results in order

E.30 Data Set 50 Results

Table E-30 – Data Set 50 – Target Results in order

 H-1 Target 1-72 Head-on Scale 1:20 D550-A1 (1 Sec Dynamic) Coin = -146.61 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-A1 (1 Sec Fixed) Coin = -156.67 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-A2 (2 Sec Dynamic) Coin = -114.20 cm
 H-1 Target 1-72 Head-on Scale 1:20 D550-A3 (3 Sec Dynamic) Coin = -43.07 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-A4 (4 Sec Dynamic) Coin = -28.59 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-B (1 Sec Dynamic) Coin = 0.45 cm
 H-1 Target 1-72 Head-on Scale 1:20 D550-B1 (1 Sec Fixed) Coin = -32.49 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-B2 (2 Sec Dynamic) Coin = -10.41 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-B3 (3 Sec Dynamic) Coin = 76.16 cm
 H-1 Target 1-72 Head-on Scale 1:20 D550-B4 (4 Sec Dynamic) Coin = 66.37 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-C (1 Sec Dynamic) Coin = 83.36 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-C1 (1 Sec Fixed) Coin = 77.82 cm
 H-1 Target 1-72 Head-on Scale 1:20 D550-C2 (2 Sec Dynamic) Coin = 21.87 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-C3 (3 Sec Dynamic) Coin = 29.44 cm	 H-1 Target 1-72 Head-on Scale 1:20 D550-C4 (4 Sec Dynamic) Coin = 26.10 cm



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