MISSILE DEFENCE: AN OVERVIEW

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Missile Defence: An Overview

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CONTENTS

ACRONYMS

ABL	Airborne Laser
ABT	Air Breathing Threat
ACC	Air Control Centre
ACCS	Air Command and Control System
ADCF	Air Defence and Command Frigate
AMRAAM	Advanced Medium-Range Air-to-Air Missile
ARS	Active Ranging System
ASIP	Arrow System Improvement Program
ASM	Air-to-Surface guided Missile
AWS	Arrow Weapon System
BM	Ballistic Missile
BMC2	Battle Management, Command and Control
BMC4I	Battle Management, Command and Control, Communications, Computers and Intelligence
BMD	Ballistic Missile Defence
BSRBM	Battlefield Short Range Ballistic Missile
C2BMC	Command & Control, Battle Management and Communications
CAOC	Combined Air Operations Centre
CAP	Combat Air Patrol
CBRN	Chemical, Biological, Radiological, Nuclear
CCFO	Conventional Counter Force Operations
CEP	Circular Error Probable
CM	Cruise Missile
COCOM	Combatant Commander
COIL	Chemical Oxygen Iodine Laser
DAC	Deployable ACCS Component
DSP	Defense Support Programme
EAD	Extended Air Defence
ECM	Electronic Counter Measures
ECS	Engagement Control Station
EKV	Exo-atmospheric Kill Vehicle
EMP	Electromagnetic Pulse
ER	Extended Range
EW	Early Warning
GEO	Geo-stationary Earth Orbit
GMD	Groundbased Midcourse Defense
GPS	Global Positioning System
HE	High Explosive
HEO	High Earth Orbit

ICBM	Inter Continental Ballistic Missile
ICC	Information Coordination Central
IOC	Initial Operational Capability
IPB	Intelligence Preparation of the Battle Space
IR	Infra-Red
IRBM	Intermediate Range Ballistic Missile
IRST	Infrared Search and Track
JSTARS	Joint Surveillance and Target Attack System
KEI	Kinetic Energy Interceptor
LEO	Low Earth Orbit
LS	Launching Stations
MD	Missile Defence
MDA	Missile Defense Agency
MEADS	Medium Extended Air Defence System
MIRVs	Multiple Independently targetable Re-entry Vehicles
MIVD	Military Intelligence and Security Agency (Netherlands)
MRBM	Medium Range Ballistic Missile
MTCR	Missile Technology Control Regime
NATO	North Atlantic Treaty Organisation
NMD	National Missile Defense
NORAD	North American Aerospace Defense Command
NTW	Navy Theatre Wide
PAC-3	PATRIOT Advanced Capability-3
PATRIOT	Phased Array Tracking Radar Intercept On Target
PTIR	Precision Track and Illumination Radar
RAM	Radar-Absorbing Material
RAP	Recognised Air Picture
RPC	Recognised Air Picture Production Centre
RS	Radar Set
RV	Re-entry Vehicle
SAMP-T	Sol-Air Moyenne Portée/Terrestre
SBIRS	Space Based Infrared System
SBX	Sea-based X-band Radar
SFP	Sensor Fusion Post
SHORAD	Short-Range Air Defence
SLBM	Submarine Launched Ballistic Missile
SMD	Sea-based Midcourse Defence
SM-3	Standard Missile-3
SRBM	Short Range Ballistic Missile
STRATCOM	Strategic Command
TBM	Theatre Ballistic Missile
TBMD	Theatre Ballistic Missile Defence
TCS	Tactical Command System

TEL	Transporter-Erector-Launcher
TELAR	Transporter-Erector-Launcher-And-Radar
THAAD	Terminal High Altitude Area Defence
TM	Theatre Missile or Tactical Missile
TMD	Theatre Missile Defence
TNO	Netherlands Organisation for Applied Scientific Research
TOC	Tactical Operations Centre
UHF	Ultra High Frequency
US	United States
WMD	Weapons of Mass Destruction
WWII	Second World War

1

INTRODUCTION

By means of this book TNO aims at providing an overview of the topics related to Missile Defence and the systems employed for this purpose. It is valuable to people unfamiliar with Missile Defence, and those with detailed knowledge of specific areas of Missile Defence. TNO, the Netherlands Organisation for Applied Scientific Research, conducts extensive research on Missile Defence, on the basis of which this book was largely written.

While traditionally the scope of Missile Defence (MD) covers defence against Ballistic Missiles (BMs), short range surface-to-surface missiles, Cruise Missiles (CMs) and Air-to-Surface guided Missiles (ASMs), within the framework of this book the latter two are omitted in favour of protection against rockets, artillery and mortars (C-RAM). Missile Defence has gained momentum in the last decades, during which an unparalleled number of international actors has obtained, or is seeking to obtain, both weapons of mass destruction and the means to deliver them. If any such actor would possess these capabilities as well as the intention to deploy them, they would pose a significant threat to their opposition and the stability of the region.

The United States Missile Defense Agency (MDA) [1] states the following:
“While the end of the Cold War signalled a reduction in the likelihood of global conflict, the threat from foreign missiles has grown steadily as sophisticated missile technology becomes available on a wider scale. We have already witnessed the willingness of countries to use theatre-class ballistic missiles for military purposes. Since 1980, ballistic missiles have been used in six [by now eight] regional conflicts. Strategic ballistic missiles, including intercontinental and submarine launched ballistic missiles (ICBMs and SLBMs) exist in abundance in the world today.”

The North Atlantic Treaty Organisation, NATO, has also stated that recent events underscore how the missile threat is growing. In response to these continuing changes in the security environment in the North Atlantic Area, NATO has been working to develop protection against this evolving missile threat by means of the Active Layered Theatre Ballistic Missile Defence (ALTBMD) capability. In its 2010 summit declaration NATO states that:

“Our aim remains to provide the Alliance with a NATO operational BMD [Ballistic Missile Defence] that can provide full coverage and protection for all NATO European populations, territory and forces, based on voluntary national contributions, including nationally funded interceptors and sensors, hosting arrangements, and on the expansion of the Active Layered Theatre Ballistic Missile Defence (ALTBMD) capability.”

The Alliance sees Missile Defence as one element in a balanced policy responding to the growing threat of (ballistic) missile proliferation which includes non-proliferation, arms control and diplomacy as well as defence and deterrents [2].

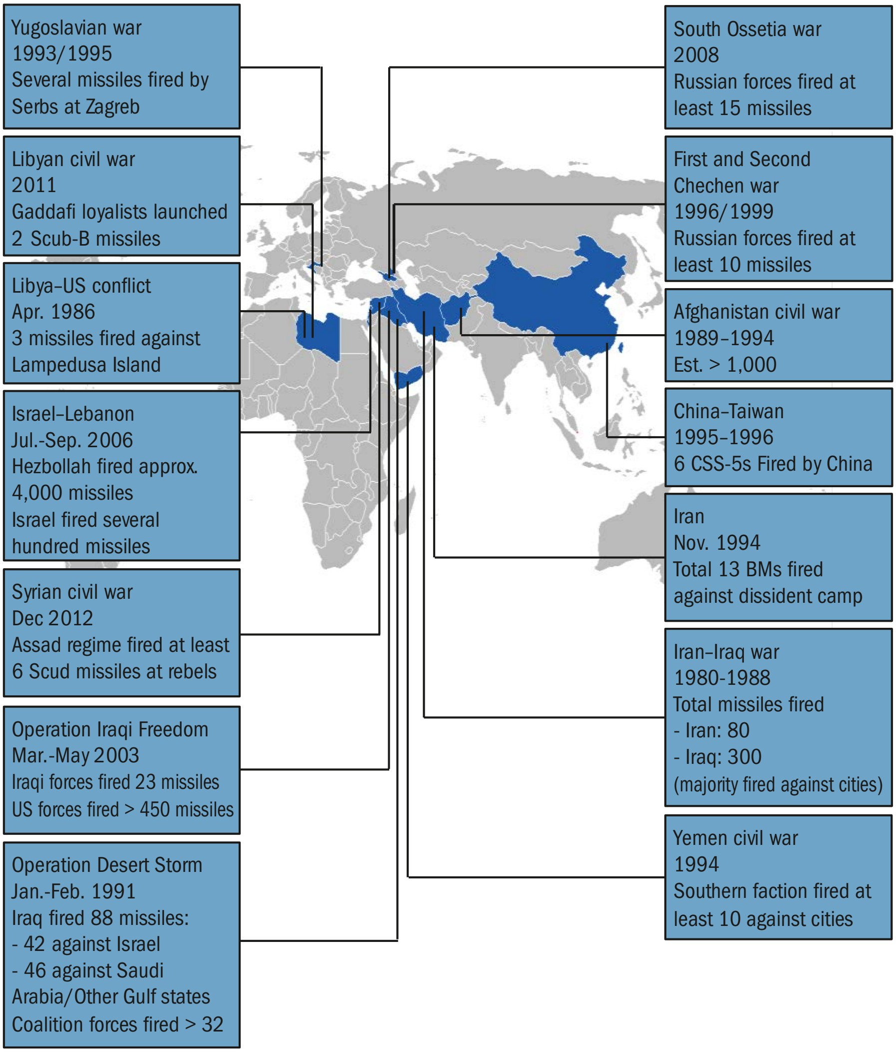


FIGURE 1.1:
Rocket artillery, short range surface-to-surface missiles and ballistic missiles deployed in conflicts around the World (after 1980).

Firstly this book will describe different categories of threats and different categories of defence in order to place Missile Defence in the proper context. While Missile Defence can span many topics the scope of this book has been limited to threats that follow a ballistic trajectory, including the previously mentioned RAM threat. A description of the threat is given in Chapter 2. In this chapter both Ballistic Missiles and short range missile systems will be described with regard to their general characteristics, trajectory, propellants, warheads and countermeasures. Chapter 3 will describe the different pillars of Missile Defence. These pillars are Conventional Counter Force Operations (CCFO), Active Defence, Passive Defence and Battle Management, Command and Control, Communications, Computers and Intelligence (BMC4I) and Early Warning (EW). The book concludes with a summary in Chapter 4.

2

THREAT ANALYSIS

This chapter will provide an overview of the threat emanating from projectiles that follow a ballistic trajectory; these include ballistic missiles, short range artillery rockets, artillery shells and mortars. Special attention is paid to ballistic missiles due their long range and potential for large scale destruction. The first section of this chapter will briefly describe the historical background of these weapon systems. The second section will discuss several aspects common to these systems. The third and final section focusses on the proliferation of such weapon systems.

2.1 General Description

The common feature of all ballistic weapons is their use of a projectile that reaches relatively high velocity by some means of propulsion and follows a ballistic trajectory onto its target. These weapons are often categorized according to their range and means of propulsion.

Gun artillery, for instance, uses an explosive in order to accelerate the projectile. Thus the projectile gains all its speed while inside the barrel and follows a predictable path upon leaving it. The first documented use of gun powder propelled artillery dates back to 1132. Since then this type of weapon has become an intrinsic part of any army. Artillery shells can be fired from various types of weapon platforms varying from deck mounted naval artillery guns to towed howitzers and self-propelled artillery.

FIGURE 2.1:
D-30 towed artillery gun [3], Katyusha rocket launcher [4], and Katyusha volley fire [5].

During World War II a new type of ballistic weapon, the rocket, saw its first large scale use. In contrast to the previously mentioned gun artillery, the rocket accelerates over longer period of time (after leaving the launch platform). This combined with the lack of a guidance system, decreases the predictability of its flight path. The introduction of the Katyusha multiple rocket launcher (called Stalin's organ by German troops) had a profound effect on the eastern front. Compared to traditional artillery, rocket artillery is able to fire a large amount of explosives at a target area and is highly mobile, the downside, however, is its decreased accuracy.

The use of a rocket engine to propel a weapon was, however, not limited to these short range systems. A ballistic missile (BM) uses more powerful rocket engines and a guidance system in order to reach more distant targets. Short range BMs were introduced as a threat in World War II, when German V-2s fell on England and Belgium. Although their accuracy was poor, their value as a weapon of intimidation was clearly demonstrated. After the defeat of Nazi Germany its design was closely studied by both the US and the Soviet Union. Before long an arms race between the US/NATO and the Soviet Union had started. The development of ever more sophisticated ballistic missiles and the space programs of both sides were inherently linked to each other.

FIGURE 2.2:
(Left) V-2 on a launcher [6]. (Middle) Minuteman III ballistic missile in silo [7]. (Right) Delta-class ballistic missile submarine [8].

Four decades of Cold War resulted in a multitude of ballistic missile systems from long range missiles capable of striking other continents to short range tactical systems, from systems launched from missile silos to those launched from trucks or submarines. Ballistic missiles can carry various payloads including chemical, biological, radiological or nuclear (CBRN) warheads.

2.3 Weapon Aspects

This section will focus on certain aspects of ballistic weapon systems. The first subsection will discuss artillery, rockets and mortars, while the second will look at ballistic missile systems. The third subsection deals with the ballistic trajectory, specifically that of a ballistic missile. The fourth subsection will elaborate on the various methods of propulsion and the fifth subsection will provide an overview of the various warheads. Finally the sixth subsection will look at the proliferation of these weapon systems.

2.2.1 Artillery Rockets, Shells and Mortars

Most artillery rockets and artillery shells, lack a guidance system. The reason for treating these systems as a separate category in this book is their (comparatively) short range, lack of inflight guidance, technologically simple design and as a consequence low acquisition cost, which all contributed to the widespread proliferation of these weapons. Especially the last two features combined with their firepower have led these systems to become a common feature in armies, militant factions and insurgent groups around the world.

FIGURE 2.3:
(Left) The Multiple Launch Rocket System (MLRS) [9], (middle) the M109A6 Paladin [10] and (right) the 60mm mortar [11].

These short range systems have a maximum range from a few kilometres to approximately 140 km. Especially this type of short range rockets can pose a threat in future conflicts during expeditionary actions. The rockets are mostly fired in volleys and are easy to transport. This threat category has been mentioned emphatically at several conferences and in specialist literature.

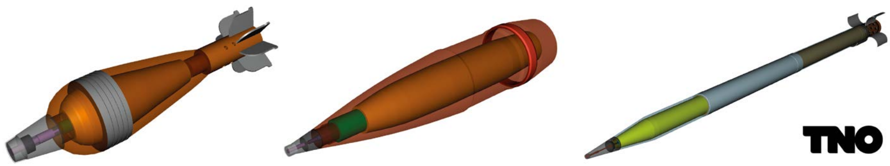


FIGURE 2.4:
Semi-transparent renderings of a mortar round, artillery shell and rocket showing the internal components.

HEZBOLLAH ROCKET ATTACKS

During the Israel-Lebanon conflict in 2006 the Lebanese Hezbollah militia fired approximately 4,000 rockets. About 95% of these were 122 mm Katyusha artillery rockets, which carried warheads up to 30 kg and had a range of up to 30 km. On most occasions, the rocket warheads contained anti-personnel munitions, a mixture of explosives and steel ball bearings or fragments that were lethal to those caught outside, where the majority of fatalities occurred [12].

Six years later under operation "Pillar of Defence" the Israeli forces engaged militants in the Gaza strip. During the eight day operation Hamas launched 1,500 longer-range rockets. By then, however, Israel had developed the Iron Dome missile defence system (which will be discussed in Section 3.5.4) and deployed it during the operation to protect Tel Aviv. The system was able to stop 426 out of the 507 rockets it engaged, giving it a successful interception rate of 84% [13].

2.2.2 *Ballistic Missile Systems*

A BM vehicle consists of a single or multiple-stage rocket. Single-stage BMs have one stage that contains both the warhead and the propellant (see Figure 2.7). Multiple-stage rockets use parts of the rocket sequentially for optimal propulsion with respect to the weight and velocity of the vehicle (see Section 2.2.5).

Multiple-stage missiles, with each stage having its own independent propulsion system, are more efficient for longer-range missions. Inter-Continental Ballistic Missiles (ICBMs) typically have two or three stages. Recent developments in propulsion of BM vehicles show a gradual shift from liquid to solid fuel rockets. The biggest advantage of solid-fuel BMs is their ease of maintenance and the ability to be launched without much preparation (short response time). Liquid fuel needs to be monitored in a controlled or cooled environment [1].

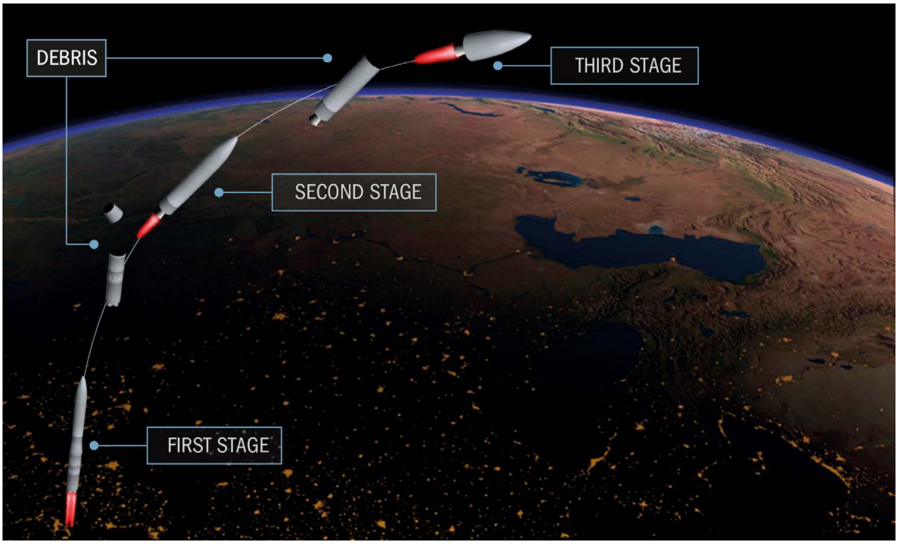


FIGURE 2.5:
Launch of a three stage rocket. Notice the debris caused by the separation of stages.

Table 2.1 shows a classification of BMs which is generally accepted [14][1] and Figure 2.6 shows several examples of currently available BMs from each category.

TABLE 2.1:
BM types and corresponding ranges.

CATEGORY	BM TYPE	RANGE
BSRBM	Battlefield Short Range BM	< 150 km
SRBM	Short Range BM	150 – 800 km
MRBM	Medium Range BM	800 – 2400 km
IRBM	Intermediate Range BM	2400 – 5500 km
ICBM	Inter-Continental BM	> 5500 km

1 US DoD uses different definitions, in which SRBMs have a range of less than 1000 km, MRBMs between 1000 and 3000 km, and IRBMs between 3000 and 5500 km.

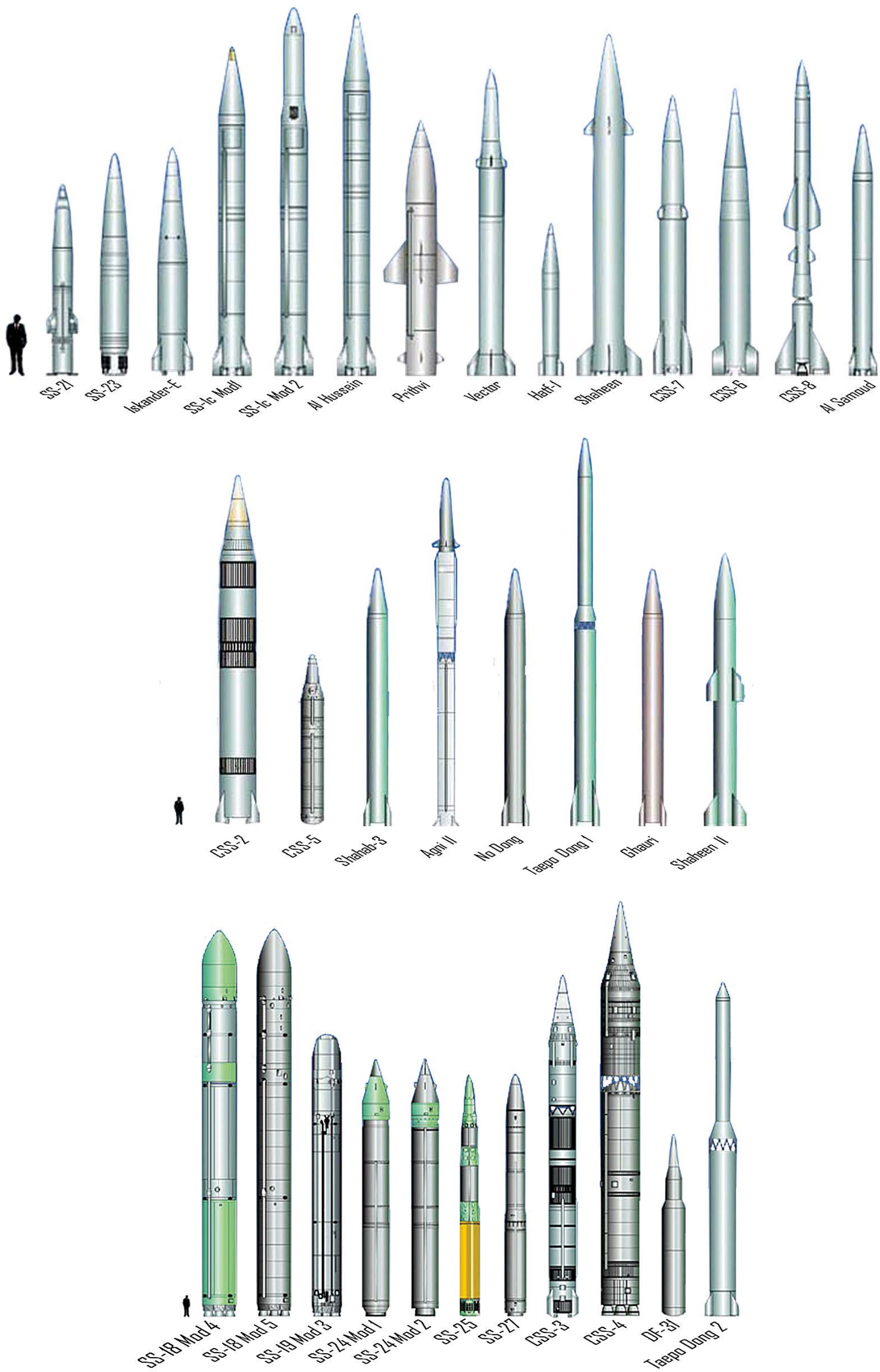


FIGURE 2.6:
Some examples of SRBMs (first figure) [15], MRBMs and IRBMs (second figure) [16], and ICBMs (third figure) [17].

The accuracy of a missile, such as a BM, is expressed by the Circular Error Probable (CEP). The CEP is defined as the radius of a circle, with the target being the centre point, within which the BM will impact with a probability of 50%. The CEP of a BM can differ from several kilometres to approximately 100 m. Due to the (usually limited) accuracy of a BM, its target is usually rather large, e.g. a geopolitical or population centre, air or seaport, a logistics area, or a troop concentration. However, modern (manoeuvring) BMs will have even better accuracy when aided by GPS mid-course guidance and/or terminal radar-aided guidance.

Besides the BM and its launch platform (a fixed site or a Transporter-Erector-Launcher (TEL) for smaller BMs, possibly combined with a radar (TELAR)) the critical support architecture is also worth mentioning. It includes the following elements:
- supporting command and control, and communications,
- logistics, transportation infrastructure (roads, important nodes, bridges, etc.),
- reload areas and hide areas,
- reconnaissance platforms and guidance radars.

FIGURE 2.7:
Transporter-Erector-Launcher (TEL) loaded with a TBM (Scud) [18].

2.2.3 Ballistic Missile trajectory

Generally, a ballistic missile trajectory can be divided into phases and events as shown in Figure 2.8.

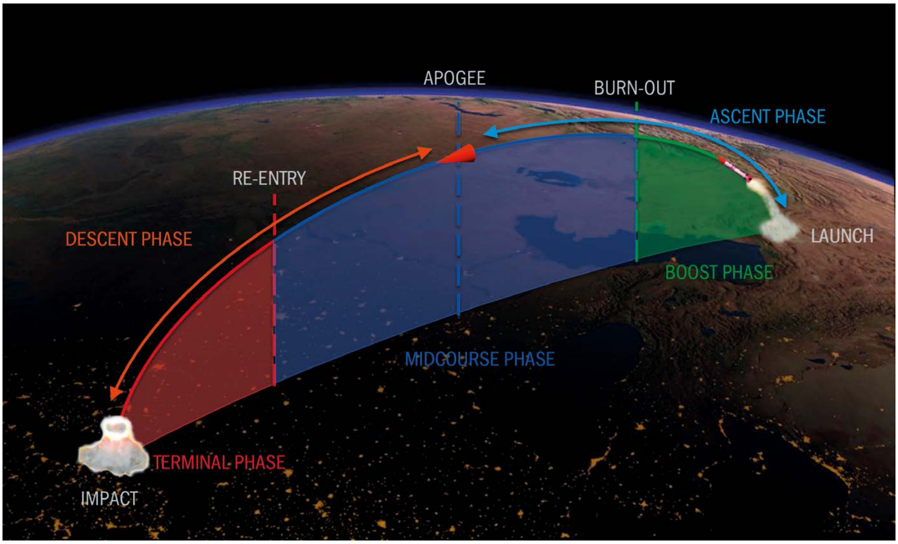


FIGURE 2.8:
BM trajectory in theory

– **BOOST PHASE:** The boost phase begins with ignition of the missile and ends with the burnout event, which occurs when the solid or liquid rocket propellant is depleted or after engine cut-off. In multiple-stage BMs, a booster is ejected and a following stage is ignited. Acceleration during boost can be high with the maximum velocity occurring at burnout (in the order of km/s). During the boost phase, the BM must gain momentum and must align itself for the mid-course phase of its trajectory.

– **MIDCOURSE PHASE:** The midcourse (or ballistic) part of a BM's trajectory is determined by the angle and velocity at burnout and gravity. Roughly 75% of the total duration of the BM's trajectory is spent in the midcourse phase. Maximum altitude is, by definition, reached at apogee (see Figure 2.8), which is approximately one-third to one-fifth of the BM's maximum range, depending on its trajectory.

– **TERMINAL PHASE:** For BMs, the terminal phase (or re-entry phase) has no distinct starting point; it commences when the Earth's atmosphere begins to influence the BM's trajectory (at approximately 100 km altitude). Atmospheric drag causes extreme thermal and mechanical stresses. Deceleration during re-entry can be even more extreme than acceleration during boost. The re-entry phase ends with the impact of the BM warhead, or release of its payload at a certain altitude, if it has not been previously intercepted (see Figure 2.8).

A BM can follow three basic trajectories, as shown in Figure 2.9. Assuming burn-out velocities are equal; these trajectories can be described as:
- Minimum energy: to gain the maximum range (optimal angle at burnout);
- Lofted: to gain a higher altitude and accuracy (steeper than optimal angle at burnout). In general, a BM flying a lofted trajectory can be more easily detected by sensor systems;
- Depressed (lower than optimal angle at burnout): a BM flying a depressed trajectory reaches its target sooner and has a lower altitude (its decreased detection likelihood increases the chances of a surprise attack) and a lower accuracy.

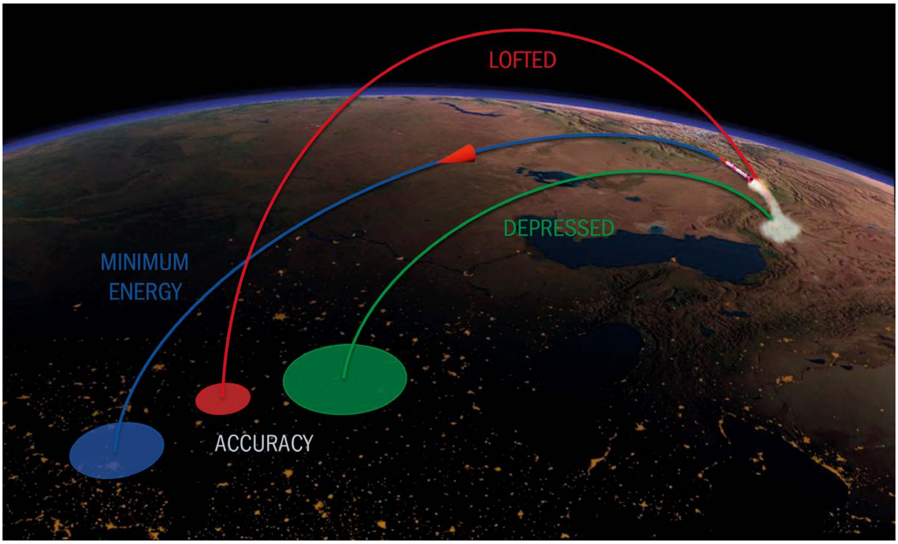


FIGURE 2.9:
Three basic types of BM trajectories.

ISKANDER TBM SYSTEM

Designed as the successor to the infamous SCUD missile system (Figure 2.7), the Iskander TBM offers several significant improvements. The missiles can carry various conventional warheads such as high explosive, cluster or penetrator munitions. But most importantly the actively guided warhead is steerable, allowing it to be retargeted inflight and to avoid missile defence systems.

In addition it reaches its target using a depressed trajectory with an apogee of 50km in order to decrease its detectability [19] and has a range of 400-480 km.

2.2.4 Propellants

Usually the desired range of a missile determines the number of stages for the boost phase. Multi-stage rockets are rockets that use two or more stages, each of which contains its own engines and propellant. The main operating principle for multi-stage rockets is that once the propellant of a stage is burnt, the structure of the stage and rocket motors serve no further purpose and are subsequently released. By discarding the spent stage, the rocket decreases its total weight and the future stages can use their fuel more efficiently. In doing so, the thrust of the total rocket is able to provide more acceleration than if the earlier stage was still attached. This means that it needs less total fuel to reach a given velocity and/or altitude. Therefore, given a certain total mass of propellant, a multistage rocket can significantly increase the missile's range.

In most cases, contemporary missiles are still propelled by liquid propellants, where the fuel and the oxidizer are stored in separate tanks. Before launch, these tanks have to be filled. Solid propellants, on the other hand, where the fuel and the oxidizer are cast into a solid, composite mixture, have tremendous advantages. The propellant can be stored easily, is ready to use and simplifies the design of the rocket motor. Considering this, it is no wonder that an increased use of solid propellants for BMs can be seen in BM proliferating countries [20].

2.2.5 Warheads

Although many currently available missiles are fitted with a conventional High Explosive (HE) warhead, the technology for loading missiles with a Chemical, Biological, Radiological or Nuclear (CBRN) warhead is proliferating rapidly. In general a warhead with a CBR(N) payload can be more lethal than an HE warhead since its CBRN content can be dispersed over a wider area.

Normally a BM with an HE warhead causes no damage when intercepted in flight except for that caused by falling debris. A BM with a CBRN warhead can still have a significant effect on the ground when intercepted in flight, because the biological or chemical agent can be dispersed over a large area. Chemical and biological warheads can be composed of smaller submunitions, see Figure 2.10 (left). Nuclear warheads may be equipped with sensors that detonate the nuclear charge just prior to intercept by a hit-to-kill interceptor, preventing the destruction of the warhead (this is called salvage fusion).

Some nuclear-tipped ballistic missiles are fitted with Multiple Independently targetable Re-entry Vehicles (MIRVs), for example the Peacemaker shown in Figure 2.10. Essentially one BM holds several smaller nuclear warheads within its body. The main advantage of MIRVs is the ability to attack multiple targets with a smaller number of BMs. Terminal defence against a BM with MIRVs is more difficult after the MIRVs have been dispersed [21]. Some long-range ballistic missiles carry up to 10 RVs per missile. RVs re-enter the Earth's atmosphere at very high velocities, on the order of 6-8 km/s for ICBM ranges [1].

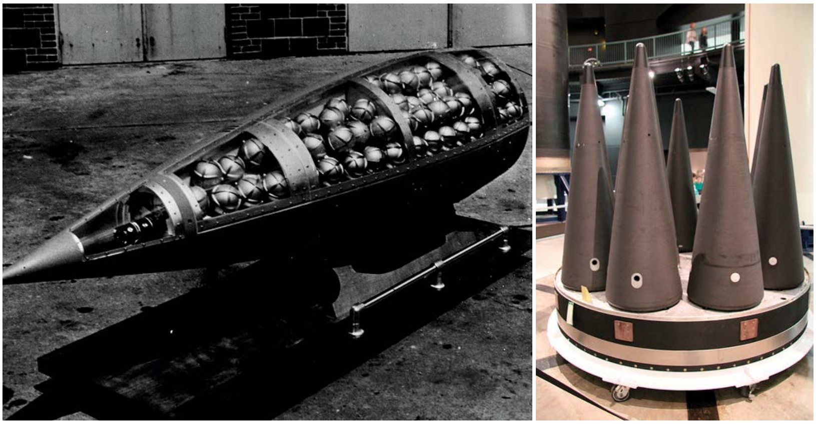
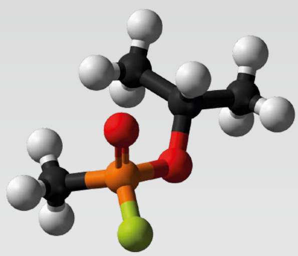


FIGURE 2.10:
(Left) An 'Honest John' missile cutaway, showing chemical (Sarin) submunitions [22].
(Right) Payload of the Peacekeeper ICBM: 10 MIRVs [23].

Chemical agents

A chemical payload can be transported as a bulk load or in the form of submunitions. In the former case, the load is stored in a container. In the case of submunitions, the space is filled with small metal cylinders or spheres, each containing the chemical agent (Figure 2.10). Depending on the size of the container, the number of submunitions is on the order of tens to hundreds. Deadly effects against unprotected personnel can occur within a timeframe ranging from minutes to a few hours after emission. Under optimal conditions (from the aggressor's point of view), the area of distribution on the ground can amount to approximately 10 km2, depending on the type of warhead (for bulk loads tenths of square kilometres, for submunitions several square kilometres).



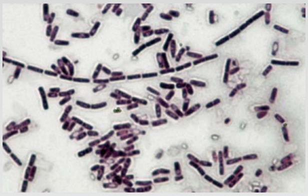
SARIN

Sarin is an example of a colorless, odorless, tasteless, human-made chemical warfare agent. Following the release of sarin into the air, people can be exposed to it through contact with skin or eyes, or can inhale it as a gas. Sarin disrupts the ability of the body to regulate nerve impulses. When this happens, the glands and muscles of the body are continually stimulated, leading to system fatigue. The victim will lose control over his bodily functions. Ultimately, the victim will fall into a coma and suffocate. Iraq used Sarin in the 1980-1988 war with Iran and the Japanese religious sect, Aum Shinrikyo, released Sarin in Matsumoto in 1994 and the Tokyo subway in 1995. Combined, the latter two attacks resulted in 19 deaths and thousands of hospitalizations [22],[25].

Biological agents

A biological payload is transported by the means of submunitions. These submunitions are smaller than submunitions with a chemical payload and can be released with hundreds up to 2000 submunitions at a time. On average, the deadly effects against unprotected personnel occur within days until weeks after emission. The area of distribution ranges from several dozens to hundreds of square kilometres [26].

ANTHRAX



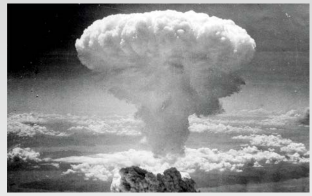
Anthrax is a serious disease caused by the bacteria *Bacillus anthracis*. Anthrax is considered an effective bioterrorism agent because the bacterial spore (dormant form) is highly stable and storable, and because of the disease's relatively high lethality. Humans can become infected with anthrax in three ways: ingestion, inhalation, and skin exposure. Once in the body, anthrax becomes active, multiplies, and releases a three-part protein toxin of which one part is deadly to humans. This lethal part interferes with the normal functioning of the body's immune system cells. In 2001, the United States experienced an anthrax attack in which weaponized anthrax was delivered via the postal system, killing five people and sickening seventeen others. In 1979, accidental release of anthrax from a lab in the Soviet Union killed over 60 individuals [27],[28].

Radiological agents
A weapon equipped with a radiological warhead is more commonly known as a “dirty bomb”. Simply put, the weapon contains a conventional explosive lined with radiological material, such as waste material from nuclear reactors or hospitals. Depending on the size of the material, the human body can be contaminated by external radiation or by breathing in the aerosols formed by the radiological material (fallout). The deadly effects resulting from a typical contamination can occur years after exposure.

Nuclear effects
The effects of a nuclear explosion can be divided into three groups: heat, pressure and radiation. An explosion within the atmosphere directly causes deadly effects from severe heat and pressure. On a longer timeline the exposure to nuclear radiation will also cause casualties. The area of effect around the point of detonation is on the order of several dozens of kilometres, depending on the altitude of detonation and the yield of the warhead.

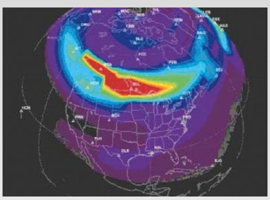
An explosion at high altitude creates a completely different effect, the so-called electromagnetic pulse (EMP). The EMP threat arises from the ability, whether by terrorists or states, to launch relatively unsophisticated missiles and to subsequently detonate them at an altitude between 40 and 400 kilometres above the Earth’s surface.

HIROSHIMA & NAGASAKI



The atomic bombs dropped on Hiroshima and Nagasaki in Japan at the end of WWII instantly killed 90,000 people in Hiroshima and 70,000 people in Nagasaki. In the following months, approximately 50,000 and 10,000 more people died due to their injuries and radiation poisoning [29].

A single nuclear weapon exploded at high altitude will interact with the Earth's atmosphere, ionosphere, and magnetic field to produce an electromagnetic pulse radiating down to Earth creating additional electrical currents [30]. Within nano-seconds after the explosion, exposed electronic components burn out or are temporarily disabled. The area of effect in which electronic components are (permanently) disabled, depends on the explosion altitude and the yield of the nuclear warhead, and can amount to a radius of thousands of kilometres from the explosion epicentre.



ELECTROMAGNETIC PULSE

High altitude nuclear weapon tests by the U.S. and the Soviet Union in 1962 had unintended consequences and the effects were felt as far away as 1400 km. Damage to overhead and underground cables was reported, together with surge arrester burnout, spark-gap breakdown, blown fuses, and power supply breakdowns. Additional effects consisted of failure of street lighting systems, tripping of circuit breakers, triggering of burglar alarms, and damage to a telecommunications relay facility [31].

An EMP attack would represent a highly successful asymmetric strategy against a society heavily dependent on electronics, energy, telecommunications networks, transportation systems and distribution capabilities. The destruction and mayhem caused by an EMP explosion would be far more substantial today given the ubiquity of electronics and society's increased reliance on them to run critical infrastructures.

Countermeasures and debris

Two phenomena can make it harder for defence systems to destroy the missile warhead or RV: countermeasures and debris. Examples of countermeasures are the dispersion of chaff and/or dummy warheads or (balloon) decoys during the mid-course phase of the missile. Other countermeasures include RV reorientation, radar-absorbing material (RAM), booster fragmentation, low-power jammers [32] and manoeuvring RVs.

Debris is formed from parts of the missile that separated during flight, including intentional and unintentional debris (but excluding countermeasures as discussed above). One of the most difficult tasks of the defence system is to discriminate between the re-entry vehicle, debris and countermeasures, this is called debris discrimination.

Intentional debris refers to the stages that are separated from a multiple-stage BM. When the separation is manipulated such that the separated stage follows the same trajectory as the warhead, it can also be considered as a countermeasure (as discussed above). Unintentional debris can be the result of the break-up of a single-stage BM re-entering the atmosphere.

FIGURE 2.11:
Debris may still be CBRN-contaminated.

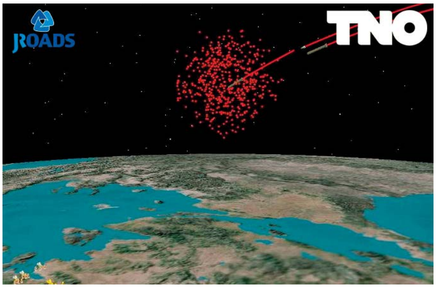


FIGURE 2.12:
Simulated debris caused by an intercepted BM.

Re-entry creates a combination of enormous aerodynamic and thermal stresses, which can result in break-up of the unstable BM. If such a BM is carrying a CBRN-load, its debris may still be dangerous, see Figure 2.11.
Debris can also be the result of a successful hit of an incoming missile by an interceptor, see Figure 2.12. This type of debris may also continue to be hazardous, even lethal, when it falls down. This will be elaborated on in Section 3.6.

2.3 Proliferation

The manufacture and distribution of CBRN weapons and delivery vehicles such as BMs will remain a concern in the near future. To stop proliferation, the Missile Technology Control Regime (MTCR), a non-proliferation treaty, has been initiated. However, non-proliferation treaties alone do not provide an adequate defence. Countries interested in BM capability continuously find new ways to acquire resources and materials for their programmes, and additional measures are therefore needed [14]. Despite international agreements with respect to BMs, some nations continue to trade technology and materials concerning BMs and their warheads.

An unprecedented number of international actors have now acquired – or are seeking to acquire – ballistic missiles. Apart from countries non-state groups are also interested in obtaining missiles with nuclear or other payloads. A total of 31 countries possess BMs of some type [33]; fourteen of these countries have the capability to produce and/or export BMs, and two of which had BM whose whereabouts are unknown. Furthermore, there are eight countries that possess nuclear weapons deliverable by BMs [34]. The BM capabilities of various countries are displayed in Figure 2.13.

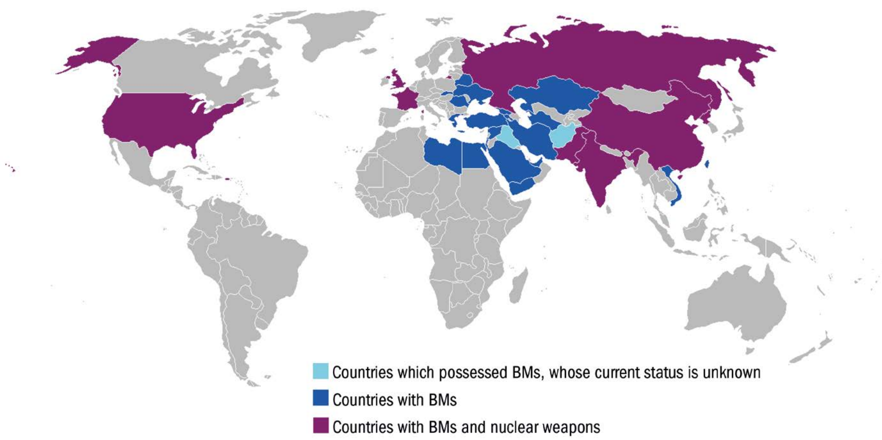


FIGURE 2.13:
BM and capabilities of various countries [33], [34].

A further development in the spread of BMs is the so-called "second-tier proliferation". This form of proliferation sees nations with lesser BM capabilities (BMs of lower technological complexity) trade among themselves in order to further each other's BM programs. The best known example of this practice came to light after the arrest of A.Q. Kahn, who confessed to selling components and providing technical assistance to Libya, Iran and North Korea. Design schematics for a nuclear bomb were also found on the computers of several members of his network [35].

2.3.1 Asymmetric threats

The dangers posed by rogue states and strategic competitors have been compounded by a series of asymmetric threats.

Terrorism

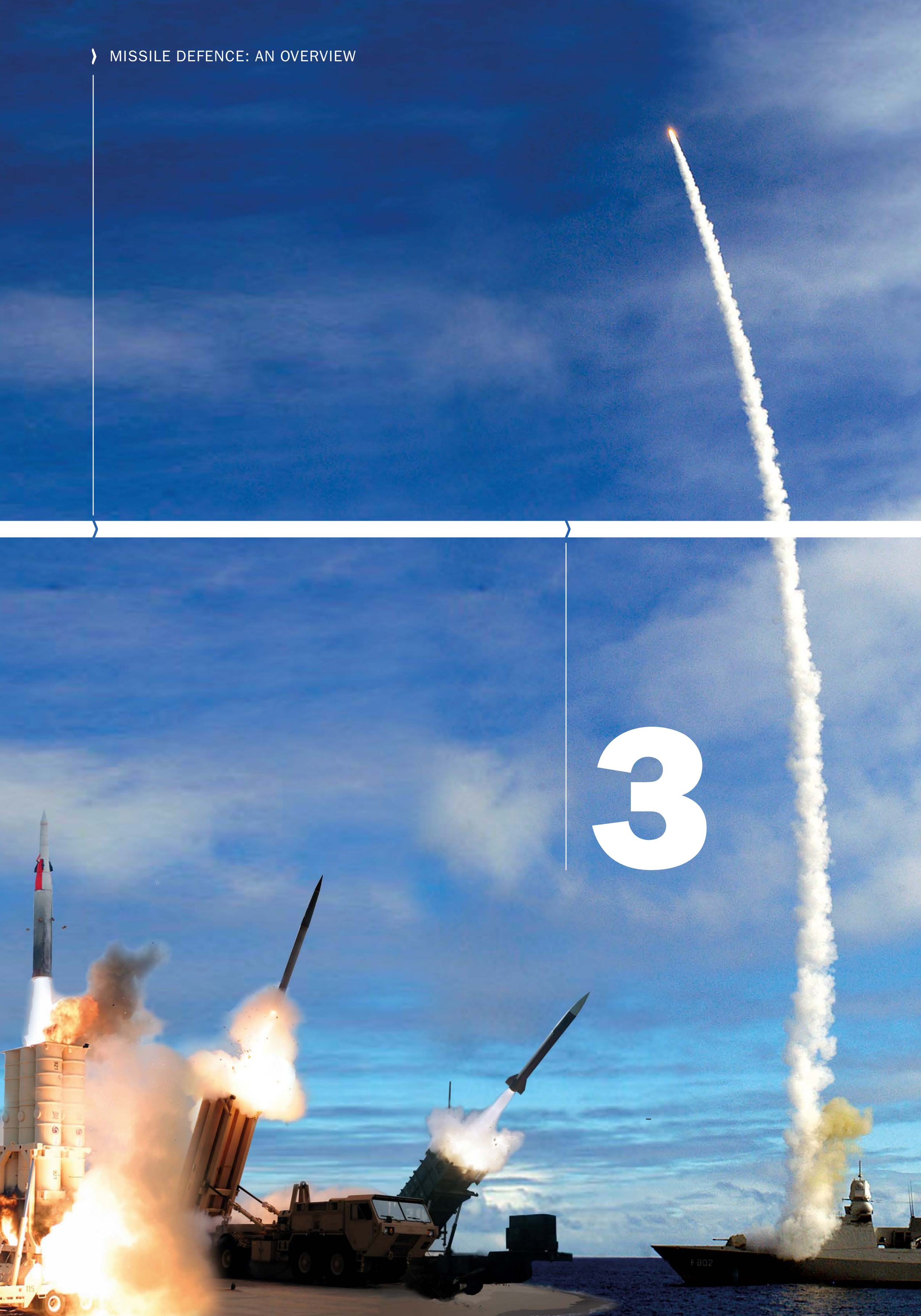
A growing number of terrorist groups have made concerted efforts to acquire CBRM weaponry. During the 1945-98 period, at least twelve terrorist groups or individuals sought to acquire or use chemical or biological agents [36]. As recent as 1994, terrorists affiliated with Iran's Islamic Jihad Organisation made a serious bid to buy an atomic bomb or fissile material from Russia [37].

Lebanon's Hezbollah now possesses some 12,000 rockets capable of striking targets within Israel. They have even shown to enforce their threat and to use their arsenal during the 2006 Israel-Lebanon conflict, in which they fired approximately 4,000 rockets [38]. The Palestinian militant group Hamas possess several members of the Iranian Fajr-family of rockets which it used during the Gaza conflict in 2012. It also claims to produce similar rockets itself [13].

The ship-borne missile threat

Container ships, tankers or freighters close to the shoreline can also pose a significant threat. A hostile state or group can easily take a short-range missile, such as a Scud missile, put it on a transport-erector launcher, take the vessel out onto the seas, peel back the top, erect it, fire it, lower it and cover it back without leaving much of trace. Al Qaeda is believed to possess 15 cargo vessels [39].

FIGURE 2.14:
Example of a container launch pad at a seaport terminal and on a container ship [40].



3

DEFENCE AGAINST MISSILES

This chapter will discuss the measures that can be taken to defend against the threat from missiles and other ballistic projectiles. The first section will outline in broad strokes the four pillars of missile defence. The second section will then present an alternative classification based on the chain of events in missile defence. Regardless of which classification is used, four distinct components stand out; conventional counter force operations, active defence, passive defence and BMC4I, which are discussed in the subsequent sections.

3.1 Missile Defence pillars

Missile Defence (MD) consists of Ballistic Missile Defence (BMD), Cruise Missile Defence (CMD), Air-to-Surface guided Missile Defence and Counter Rocket Artillery and Missile (C-RAM). The Missile threat can be among others countered by MD; this is illustrated in Figure 3.1. The first two measures, proliferation prevention and deterrence, are not part of MD in the military context and are carried out at a more political level. The possession of BMs and CBRN weaponry is prevented by non-proliferation regimes such as the Missile Technology Control Regime, the Proliferation Security Initiative, the Chemical Weapons Convention (CWC), the Biological and Toxin Weapons Convention (BTWC), the Convention on Physical Protection of Nuclear Material and the Nuclear Non- Proliferation Treaty (NPT). Political sanctions can sway sovereign nations to abandon weapon programs and possibly even dismantle their current CBRN stock piles and weapon systems (as was the case in Libya when in 2003 its leader Moammar Gaddafi announced the abandonment of his country's chemical and nuclear weapons programs and its long range missile systems). A country can be deterred from its intention of launching missiles, for example, by threatening the enemy with military retaliation (see text box at the end of this section).

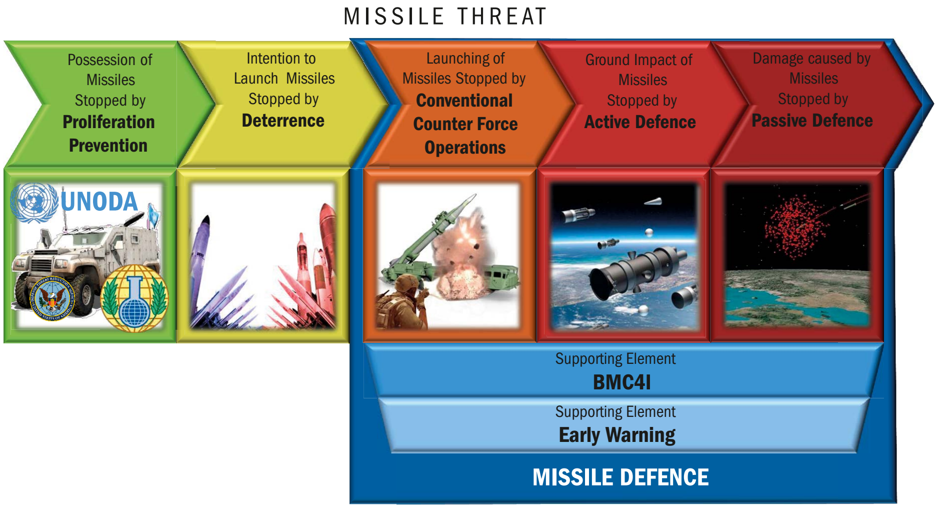


FIGURE 3.1:
The concept of countering the threat of ballistic missiles.

MD consists of the following components:

1. **CONVENTIONAL COUNTER FORCE OPERATIONS** (**CCFO**) or **ATTACK OPERATIONS** are initiated to destroy, disrupt or neutralise (i.e., suppress) enemy missile capabilities and infrastructure. In other words this prevents the launch of missiles.
2. **ACTIVE DEFENCE** measures are actions taken to destroy or mitigate the effectiveness of an enemy attack by intercepting missiles in flight.
3. **PASSIVE DEFENCE** measures reduce vulnerability of friendly assets and minimise the effects or damage to friendly assets or population caused by a missile.
4. **BATTLE MANAGEMENT, COMMAND AND CONTROL, COMMUNICATIONS, COMPUTERS AND INTELLIGENCE AND EARLY WARNING** (**BMC4I AND EW**) consists of the capabilities, processes, procedures and information for co-ordinating and synchronising both offensive and defensive measures. A BMC4I and EW system supports Passive and Active Defence as well as CCFO.

MUTUALLY ASSURED DESTRUCTION

Mutually Assured Destruction (MAD) is both a military strategy and a national security policy. The concept hinges on the principle of deterrence whereby the threat of using weapons that can annihilate an enemy prevents that enemy from initiating a conflict. When both sides are equipped with such weapons an equilibrium is reached whereby neither side has any incentive to attack the other. This equilibrium, however, also hampers any attempts at disarmament, especially unilateral disarmament.

During the Cold War the weapon of choice to achieve this equilibrium was the nuclear bomb delivered by various means. In this type of warfare the weapon can be employed against two types of targets; counterforce (against the military, and especially the nuclear component thereof) and countervalue (the civilian targets). The main focus of MAD lay on countervalue warfare for which nuclear weapons with relatively large CEPs and area of effect launched from platforms which are difficult to detect are a particularly good fit. The recognition of MAD as a countervalue doctrine by the US and the Soviet Union was made explicit by the Anti-Ballistic Missile Treaty, which was signed in 1972. It prohibited the development and deployment of any system capable of defending against “strategic ballistic missiles”, which would be capable of disturbing the equilibrium. The US policy in the words of President Carter:

“To continue to deter in an era of strategic nuclear equivalence, it is necessary to have nuclear (as well as conventional) forces such that in considering aggression against our interests any adversary would recognize that no plausible outcome would represent a victory or any plausible definition of victory. To this end and so as to preserve the possibility of bargaining effectively to terminate the war on acceptable terms that are as favorable as practical, if deterrence fails initially, we must be capable of fighting successfully so that the adversary would not achieve his war aims and would suffer costs that are unacceptable, or in any event greater than his gains, from having initiated an attack.”

On June 14th 2002 the US unilaterally withdrew from the treaty in order to test its limited national missile defense system (aimed at defending against BM launches from “rogue states”. The following day the Russian Federation withdrew from the START II treaty aimed at reducing the nuclear stockpiles of both countries and banning the use of MIRVs.

3.2 Missile Defence Chain of Events

In the previous section, MD was divided into four pillars. Another way to divide MD as a whole, and to divide the pillars CCFO, Active Defence and Passive Defence into parts, is the chain of events shown in Figure 3.2.

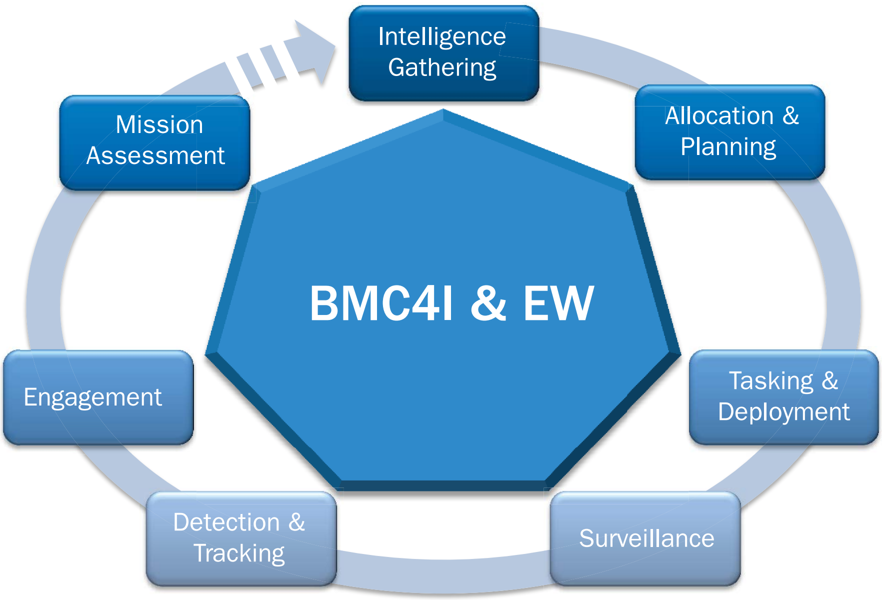


FIGURE 3.2:
MD chain of events.

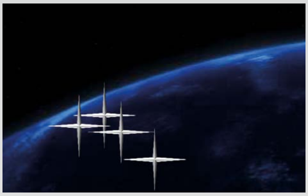
The chain of events starts with intelligence gathering. This includes assessment of the threat by identifying enemy capabilities, activities and intentions in order to obtain indications of the location(s) from which missiles will be launched, towards which targets they will be launched, what kinds of warheads can be expected, etc.

This information can be used in Allocation & Planning and Tasking & Deployment to determine which platforms will be deployed, to which location(s) they will be deployed and what tasks they must execute. This applies to all MD pillars.

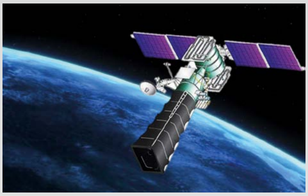
After deployment, missiles and missile infrastructure must be detected during the Surveillance and Detection & Tracking phases. Based on intelligence, the missile infrastructure can be detected before any missiles have been launched; this allows proactive CCFO. For BMs, based on the track of the missile, the launch position can be estimated which allows reactive CCFO. Furthermore, the track of a BM allows prediction of the trajectory of the BM which is needed for Active Defence and for Passive Defence (Passive Defence needs the prediction of the impact position of the BM).

The mission is assessed by determining the performance of all elements in the chain. Based on this assessment, it is possible that choices made in one or more elements of the chain need to be reconsidered. For example, the positioning of CCFO platforms can be adjusted based on estimations of the missile launch positions.

BMC4I and EW support most elements in the chain. In order to clearly illustrate the interdependencies between the three main components of MD the next section will discuss Early Warning systems and platforms first, as information from this component is often the trigger for further action and is required throughout the process. BMC4I will be discussed at the end of this chapter as it represents the nervous system that links all the various components of MD.



FALSE LAUNCH ALERTS



On October 5th 1960 the US Ballistic Missile Early Warning System detected a massive missile attack with a 99.9% certainty. NATO forces went on alert and planned their retaliation. Fortunately, before any irreversible measures had been taken, the military realized that rather than detecting a missile launch the system had detected the rising moon. The consequence of such a false alert would have been far more devastating had it occurred two years later, in the middle of the Cuban Missile Crisis [41].

More false alerts of the US' early warning system would follow during the 80's when, for instance, a defective integrated circuit chip let the system to "detect" a volley of Soviet land and sea-based missile launches. Or when a test program was accidently loaded into the early warning system [42].

The Soviet early warning system was also not impervious to such errors. On September 26th 1983, in the Soviet early warning command center Oko sirens began ringing. The early warning satellites had detected the launch of a ballistic missile in the US. The commanding officer dismissed it as an error, since a true first strike would consist of hundreds of launches. The system detected a total of four launches but throughout the night the officer in charge remained convinced that these were erroneous alerts and did not act upon them. This was most fortunate since Soviet doctrine dictated that an immediate counter-attack would be launched upon launch detection (launch-on-warning doctrine). A later investigation concluded that a rare sunlight reflection off of high altitude clouds was the cause for the erroneous missile launch alerts [43].

3.3 Early Warning

Early Warning is the generation of information about the trajectory of BMs in flight. This includes estimation of the launch point which is important for CCFO, prediction of the trajectory for Active Defence and prediction of the impact point for Active Defence and for Passive Defence.

Cueing is a hint from one sensor to another sensor about the position or trajectory of a threat such as a BM. This information can be used to search for the threat in a specified volume of space resulting in higher probabilities of detection and longer engagement ranges for instance when engagement modes such as Launch-on-Remote or Engage-on-Remote are used (these will be discussed in Section 3.5). Alerting provides unspecified information about an incoming threat.

3.3.1 Sea-Based Early Warning

Since ships offer a large platform which is both mobile and generates large amounts of power for its systems they are ideally suited for the early warning task. They can be deployed to areas as the threat emerges and can remain on station for extended periods of time.

SMART-L

The SMART-L (Signal Multibeam Acquisition Radar for Tracking, L-band) radar has been mounted on Dutch, German, Danish and South Korean frigates. It was the Netherlands, however, who first committed to software modifications that allowed the radar to track objects in space. In 2006 the Dutch frigate HNLMS Tromp demonstrated the ability to detect and track uncued targets. Normally at least a general direction has to be known from which a launch is expected such that radars only need to search a limited amount of the sky for targets.

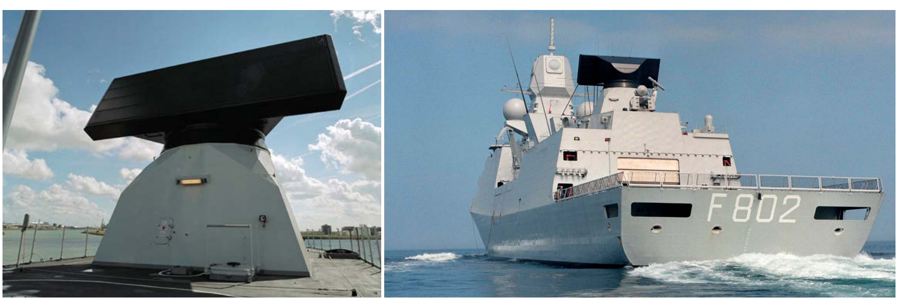


FIGURE 3.2:
SMART-L radar [44].

The SMART-L can track over 1000 targets at ranges over 400km [44]. An upgrade of the radar, the SMART-L Early Warning Capability (EWC), increases the range of the radar to over 1000 km, further enhancing its BMD capabilities.

SPY-1

The SPY-1 radar is a long-range air- and surface radar, which lies at the heart of the Aegis combat system (as will be described in Section 3.5). It is capable of tracking multiple targets (supposedly up to 100 [45]) at long ranges (>250km for ballistic missiles [46]). 360 degree coverage of the airspace around the ship is accomplished by four fixed antennas rather than one mechanically rotated one. This allows the radar to provide continuous coverage of the airspace. As with the SMART-L radar its BMD capability was added later on through upgrades. Of the five countries that operate the SPY-1 radar two have implemented the upgrades (US and Japan) though others might follow [47].

FIGURE 3.3:
Four panels of the SPY-1 radar on board the Kongō-class destroyers [48], [49].

3.3.2 *Ground-Based Early Warning*

When a likely path of incoming BMs is known in advance or a large stationary area has to be protected ground-based EW sensors can be used. These systems are also freed from size and available power constraints.

RAF Fylingdales

Royal Air Force (RAF) Fylingdales is a base in North Yorkshire Moors (UK) and is unique in its ability to provide 360 degrees ballistic missile early warning. The site first opened in 1963 but has been updated between 1989 and 1993 with new three sided phased array radar, called Solid State Phased Array Radar (SSPAR) in order to improve tracking accuracy and resolution. The 28m diameter SSPAR array can detect incoming BMs at a range of up to 3000nm and simultaneous tracking of several hundred targets, due to its large size and power output [50].

FIGURE 3.4:
SSPAR and its coverage [50].

TPY-2
The TPY-2 is an advanced mobile radar which is able to detect, classify and identify targets in order to categorize them according the threat they pose [51]. By placing it close to suspected launch zones (called the "forward based mode") it can be used in a similar fashion as the naval SPY-1 radar; for early warning and cueing purposes of interceptor platforms [52].

FIGURE 3.5:
Forward based TPY-2 radar [53].

Voronezh-DM
The first of these Russian radars was built in 2005 at Lekhtusi near St Petersburg and became operational in 2009 [54]. This radar is the first of six new radars that will provide EW of BM launches to the Russian Federation. The latest site, in the Kaliningrad enclave, became operational in 2011 [55]. With a range of 6000km it is able to cover all of Europe and the Atlantic, according to the Russian military [56]. The new radars are meant to restore the EW capability of the Russian military, which has been compromised after the fall of the Soviet-Union resulting in, for instance, the Norwegian Rocket Incident (see text box at the end of this section).

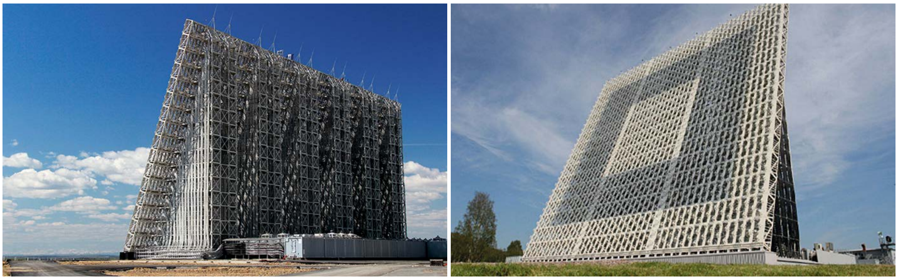


FIGURE 3.6:
Voronezh DM early warning radar [57].

3.3.3 *Airborne Early Warning*

The strict constraints (size, weight, power) imposed on radars placed on board of aircraft are often compensated for by the high mobility of the platform and increased range of the radar.

FIGURE 3.7:
E-8 Joint STARS [58].

E-8 Joint STARS

The E-8 Joint Surveillance Target Attack Radar System (Joint STARS, initially known as JSTARS) is a long-range, air-to-ground surveillance system designed to locate, classify and track ground targets in all weather conditions. While flying in friendly airspace, Joint STARS can look deep behind hostile borders to detect and track ground movements. The radar has a range of more than 250 km. Although still under development, two aircraft were deployed in 1991 to participate in Desert Storm. Joint STARS was praised for tracking mobile Iraqi forces, including tanks and Scud missiles [59]. This example shows that Joint STARS can support conventional counter force operations.

3.3.4 Space-Based Early Warning

Finally EW sensors can also be placed in space on board of satellites. Depending on the satellite constellation, certain areas can be continuously surveyed from space; these systems therefore offer indefinite persistence.

DSP

The Defence Support Program (DSP) satellites are operated by the US Air Force Space Command. DSP satellites operate in geo-synchronous orbits at 35,780 km altitude. They use an IR sensor to detect heat from missile and booster plumes against the Earth's background, providing 24 hours a day, world-wide surveillance. The satellite Early Warning system consists of five satellites, three providing front-line operational service with two as backup. Each satellite has the capability of viewing almost an entire hemisphere of the Earth and can detect missile launches from any location within its field of view. Each telescope is pointed towards the Earth and rotates at six revolutions per minute.

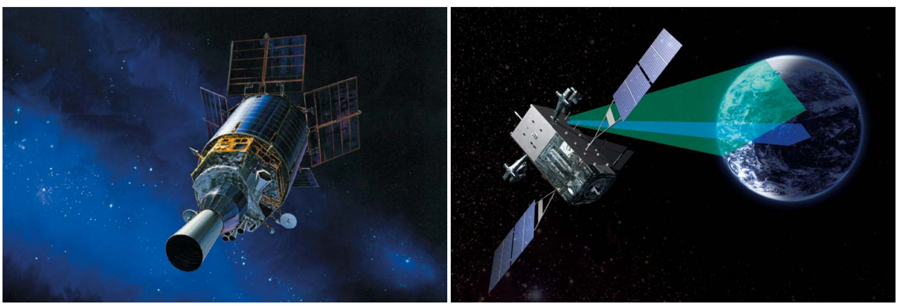


FIGURE 3.8:
(Left) Forward looking SPY-1 antennas [48], (right) rearward looking SPY-1 antennas [49].

A launch warning is reported to the North American Aerospace Defence Command (NORAD) Early Warning centre. This centre immediately forwards data to various agencies and areas of operation around the world.

SBIRS

The Space-Based Infrared System (SBIRS) program is the follow-on capability to the Defence Support Program (DSP) described above. It will have to provide timely and accurate missile warning/defence information and will be critical for protection against global and theatre ballistic missile attacks against the U.S., its deployed forces and its allies. Currently the SBIRS program consists of two Geosynchronous Earth Orbit (GEO) satellites, two Highly Elliptical Orbit (HEO) payloads riding on classified host satellites, and associated world-wide deployed ground systems. The assembly of the third and fourth GEO satellites is already under way at present date, and the procurement of a fifth and sixth GEO satellite has commenced in 2012 as well [62].

The SBIRS GEO spacecraft is a 3-axis stabilized platform with a scanning sensor and a staring sensor. Sensor pointing is accomplished with pointing mirrors within the telescopes. The GEO scanning sensor provides a shorter revisit time than DSP over its full field of view, while the staring sensor is used for step-stare or dedicated stare operations over smaller areas. SBIRS GEO and HEO unprocessed sensor data is down-linked to the ground, thereby making the same data observed in space available to units on the ground. The first SBIRS HEO payload was delivered in August 2004 for integration and the second HEO payload was delivered in September 2005. The first GEO satellite was launched in 2011 and the second GEO satellite is expected to be launched in 2013 [62].

The SBIRS architecture has been allocated four missions:
- missile warning: detection of missiles during launch and boost,
- missile defence: support to missile defence by tracking targets from initial boost phase to re-entry; the data will be relayed to missile defence platforms,
- technical intelligence: valuable data for missile characterisation, phenomenology and other target data will be provided,
- battle space characterisation: assessment of battle damage and tracking IR-intensive events to improve battle field situational awareness.

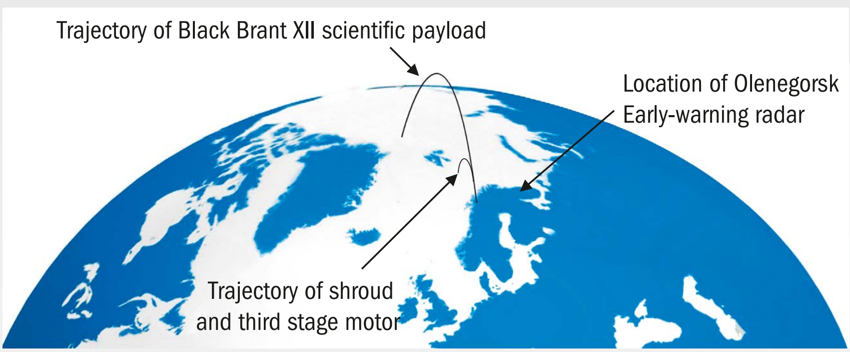
FIGURE 3.9:
(Left) SBIRS GEO satellite and (right) SBIRS LEO satellite [63].

SBIRS will provide a much more accurate prediction of the trajectory of a missile than DSP, including more accurate launch point estimation and more accurate impact point prediction. Furthermore, the missile warning time from SBIRS will be much shorter than the one obtained from DSP.

NORWEGIAN ROCKET INCIDENT

On the morning of January 25th, 1995 the Russian early warning radars detected a missile launched from a northern region of Norway. The officer in charge of the outpost, wanting to avoid blamed for a false alarm or failure to act in the event of an actual SLBM launch, passed the decision up the chain of command until several minutes later the nuclear suitcase (or Cheget) was brought into President Boris Yeltin's office. The region from which the launch had originated matched the expected patrol zone of American submarines. Furthermore, as the rocket climbed and ejected its first stage, the flight profile matched that of Trident SLBM, putting Moscow well within its range.

The Russian electronic command-and-control network, Kazbek, had been activated, by means of which President Yeltzin was able to communicate with the other two suitcase holders and follow the missile's track. The Kazbek network was operating in combat mode and an alert was sent to the strategic forces putting them on alert. Confusion about the origin of the threat and the response continued until the missile disappeared into the arctic sea.



The apparent missile threat was actually the Black Brant III rocket carrying a scientific payload to study the aurora borealis. It was flying on a northern heading, not south towards Moscow. To add insult to injury the Russian government had been informed of the intended launch months in advance. In the chaos of the post-Soviet era government the document had gone missing. Adding to the chaos was the decrepit state of the Russian early warning system. Many of the Soviet-era radar sites were now located in foreign countries, its military was severely underfunded and its equipment ill-maintained [64].

3.4 Conventional Counter Force Operations (CCFO)

CCFO is initiated to prevent enemy missile launches by conventionally searching for and destruction, disruption or neutralization (i.e. suppression) of enemy missile capabilities and infrastructure. Destroying enemy missile capabilities and infrastructure can be accomplished by destroying one or more of the key elements necessary for a missile launch. Disrupting, neutralising (i.e., suppressing) enemy missile capabilities and infrastructure makes it impossible for the enemy to launch missiles. An example is the suppression of missile launchers coming out of their hide areas.

CCFO can be carried out reactively (if a launch has been detected, try to find and destroy capabilities and infrastructure to prevent additional launches) or proactively (try to find and destroy capabilities and infrastructure before missiles have been launched) both approaches have been employed by coalition forces with a varying degree of success during operation Desert Storm in 1991. The remaining part of this section is based on [38, 65, and 66].

Counterforce is viewed as the preferred method of defeating the missile threat because of its potential efficiency. In addition to destroying the missile before its launch, the destruction of the launcher has the additional benefit of denying the enemy the opportunity to launch other missiles that could be stored nearby. In the future it is therefore desirable to monitor mobile launch facilities during peacetime around the clock in order to detect the activities associated with missile units transitioning to a wartime footing. Only by adopting such an approach will CCFO improve.

OPERATION IRAQI FREEDOM

At the end of March 2003, during Operation Iraqi Freedom, 6 TBMs were launched at Kuwait from somewhere between Basra and Al Amarah in Southeastern Iraq. Numerous missions were coordinated by the U.S. Army which resulted in the destruction of two launchers (post-launch). This may have been a first in the history of counter-TBM operations (during operation Desert Storm the use of air power for CCFO proved disappointing, out of 48 sighted targets ordnance was released against only eight [67]). The enemy's launch pattern had been analyzed using Aegis tracking data, based on which potential launch sites were derived along with the sites suitable for the enemy to hide their equipment between missions. A Predator Unmanned Aerial Vehicle (UAV) subsequently patrolled the area and engaged the TEL's on sight with Hellfire missiles. After disrupting and destroying the first two night launches the Iraqis never fired again at night and the launch tempo was diminished [68].

3.5 Active Defence

Active Defence measures are actions taken to destroy or mitigate the effectiveness of an enemy attack by intercepting missiles (or a RAM threat) in flight in order to defend an area or assets on the ground. A defence system must first detect the target using its sensor before it can proceed with the intercept. After initial detection, the target must then be tracked, once a track has been established, the warhead must be engaged, for example, by launching a defensive missile or by deploying a directed energy weapon.

Even if the warhead is intercepted before reaching its target, it is possible that the missile or projectile will cause damage on the ground. To minimise this damage, the missile should preferably be intercepted above a certain altitude, called the ‘keep out’ altitude. This altitude depends among other factors on the type of warhead: conventional, nuclear, biological or chemical [59].

The Active Defence systems can be grouped according to the flight phase during which the missile will be intercepted:
- boost phase,
- mid-course or ballistic phase,
- terminal- or re-entry phase.

A way to group the terminal phase systems corresponds to the maximum altitude of the interceptors:
- lower-tier systems: systems that can intercept missiles up to an altitude of 30-50 km; the interceptor’s manoeuvrability is mainly dependent on aerodynamics requiring a relatively dense atmosphere,
- upper-tier systems: systems with interceptors that do not require aerodynamics to manoeuvre, or have sensors that operate outside the dense atmosphere.

The reader will notice that the two most prominent components of any BMD system are the sensor that detects and tracks targets (most often radar) and a means to kill the threat (usually the missile itself).

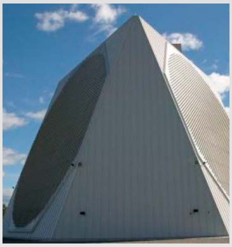
Intercept sequence
The chain of events from launch to intercept remains the same regardless of phase during which a BM is intercepted. The various active defence systems are therefore remarkably similar in terms of their design. This chain of events will be illustrated below.

1. BM Launch

A ballistic threat is launched and quickly accelerates to high velocity and altitude. The rocket motor produces a bright flame, whose signature can be detected by IR-sensors.

2. Early Warning

Space-based sensors or long range radars positioned in such a fashion as to provide the best coverage of the most likely flight paths towards the area that is to be protected, detect the incoming ballistic missile and begin tracking it. Their cueing information is send to the command & control network.



3. Activation of Protocols

The emergency procedures are now activated, the appropriate units are alerted and key decision makers are informed of the threat. The resulting commands are disseminated to the missile defence units along with the information obtained from the early warning sensors.

4. Target Acquisition & Tracking

After detection, and partially in parallel with the previous step, information from the early warning systems can be used by shorter range radars to determine the target's position and flight path more precisely (the missile track). Using it both the launch and impact point can be calculated. This track is then fed to the interceptor.

5. Interceptor Launch

An interceptor is launched from its canister and guided towards the threat using the missile track information. An interceptor missile can consist of more than one stage and/or a specially designed kill vehicle (KV). Such a KV will autonomously guide itself onto the threat in the last phase of the intercept, the so-called end-game.

Engagement modes

Several aspects of step 4 and 5 merit further discussion due to the variety of available setups and techniques. This first aspect is the engagement mode. Classic (or organic) missile defence uses a radar which is part of the same system as the launcher and is therefore co-located (e.g. on board the same ship, or at relatively the same location on the ground). This is illustrated by Figure 3.10 where an incoming warhead is intercepted due to the information provided by the radar of the air-defence system itself.

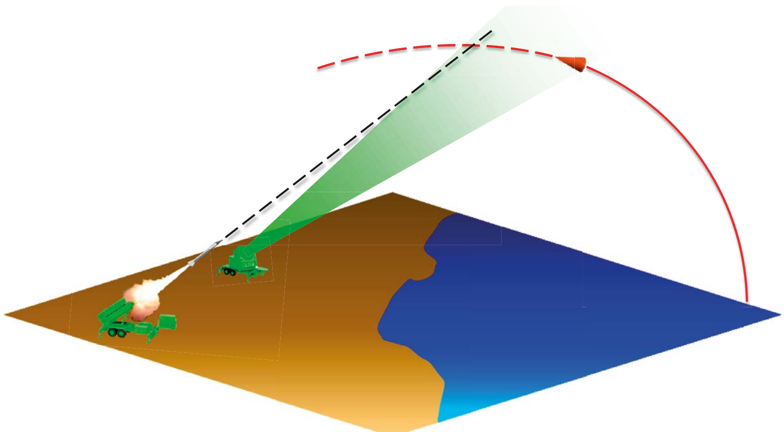


FIGURE 3.10:
Classic missile defence setup.

However, in order to intercept the target at an earlier time, providing the defender with more time to assess the situation, an alternative engagement mode has been developed called Launch-on-Remote (LoR). Here a different platform, located closer to the launch zone, provides the track using its own acquisition radar which is communicated to the interceptor system using a Tactical Data Link (TDL). TDLs will be discussed in more detail in Chapter 3.6.

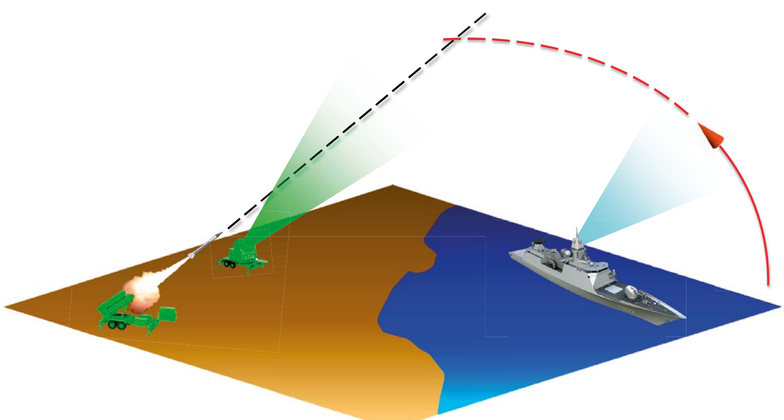


FIGURE 3.11:
Launch-on-remote engagement mode.

The interceptor can consequently be launched before the target becomes visible to its own radar (see Figure 3.11). The intercept, however, still has to occur within the field of view of its own radar. An even more advanced variant is the Engage-on-Remote (EoR) mode. It uses a track generated by one platform and an interceptor from another platform to perform the intercept as illustrated in Figure 3.12. Obviously these more advanced engagement modes require a high degree of inter-platform coordination and communication which Chapter 3.6 will discuss.

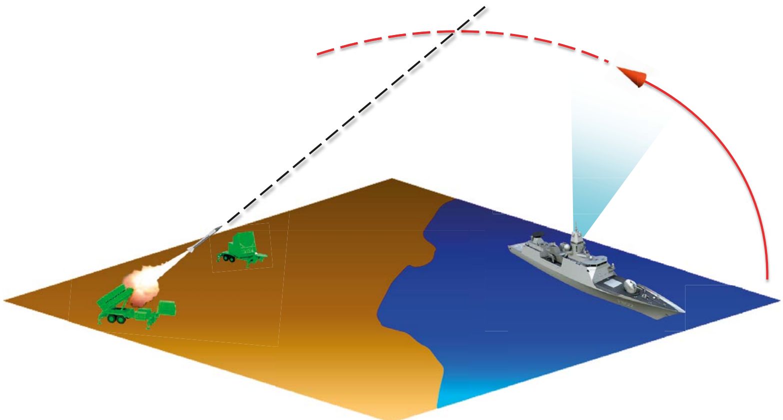


FIGURE 3.12:
Engage-on-remote mode.

Shooting doctrine

The likelihood of a successful intercept for a single interceptor will, however, never be 100%. Tracking inaccuracies, hardware failure and proximity fuse (see text box) malfunctions all decrease the probability of a successful kill. Therefore shooting doctrines have been developed that increase the likelihood of success. All of them rely, however, on the possibility to launch multiple interceptors at the same target.

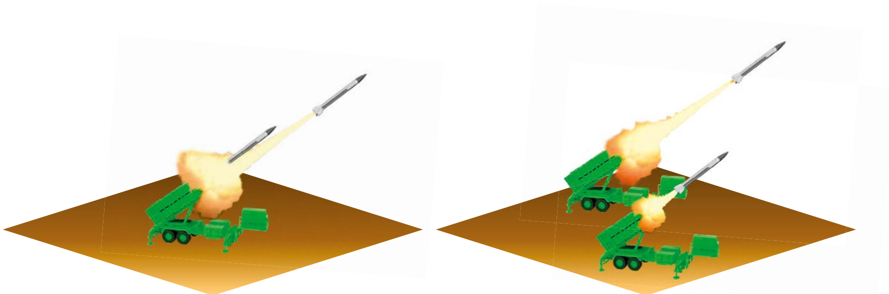
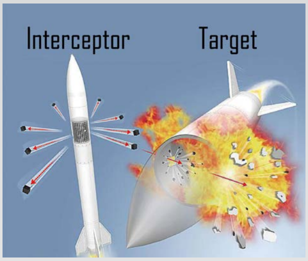
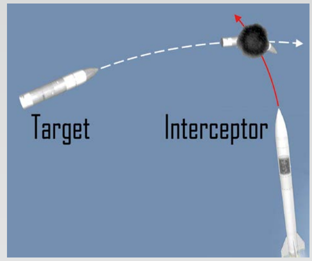


FIGURE 3.13:
(Left) Salvo fire, and (right) ripple fire.

Two distinct shooting doctrines will be discussed here; Shoot-Look-Shoot (SLS) and Shoot-Shoot-Look (SSL). The former fires one interceptor then uses its sensor(s) to assess whether or not the intercept was successful and in the event of failure launches another interceptor. While the latter fires two interceptors at one target and then assesses the situation. The firing of multiple interceptors can be accomplished by either salvo fire or ripple fire (Figure 3.13).



INTERCEPT TECHNIQUES



A successful intercept with a missile system can be accomplished by two distinct techniques; proximity fusing and hit-to-kill.

Proximity fuse
This technique uses an intercept vehicle with an explosive warhead which is detonated once the target is within a certain range. The target is consequently destroyed by the shrapnel and blast effect of the warhead. Since the blast radius of the warhead can be quite large the guidance system of such an interceptor does not need to be very precise in order to score a hit. In fact interceptors can even be equipped with nuclear warheads such as those deployed around Moscow since the 70's.

Hit-to-Kill
Interceptors need not be equipped with an explosive warhead, provided their targeting system is accurate enough. In such a case the target is destroyed by the force of impact of an inert warhead, ergo the term hit-to-kill. The required precision of the tracking and guidance systems raises the level of technical sophistication needed in order to achieve a successful intercept.

Overview
In section 3.5.1, a number of boost-phase systems that have been proposed over the years are discussed and in section 3.5.2 a description of several mid-course phase systems is given. Terminal-phase systems are subsequently described in section 3.5.3 and finally short-range C-RAM systems are discussed in section 3.5.4.

The descriptions in the following subparagraphs are mostly based on [24, 71, 72, 73 and 74].

3.5.1 Boost-phase intercept systems

Airborne Laser

Both the Soviet Union and the US investigated the usefulness of airborne platforms carrying directed energy weapons, while the Russian program was abandoned soon after the collapse of the Soviet Union, the US' AirBorne Laser (ABL) program was continued until recently.

FIGURE 3.14:
Beriev A-60 [75].

The ABL project aimed at delivering a weapons platform that would allow for the destruction of ballistic missiles during the boost phase of their flight. For this purpose the ABL used a Chemical Oxygen-Iodine Laser (COIL) weapon placed in a converted 747-400F freighter designated the YAL-1. A chemical reaction provides the laser with several megawatts of power.

The ABL concept envisioned one or more YAL-1s flying an elongated figure-8 pattern at an altitude of about 12km near the launch site of threat missiles while continuously scanning for possible BM launches. The ABL used six IR Search and Track (IRST) sensors to cover 360 degrees in azimuth for the detection and initial tracking of a BM. When a BM is detected, the Active Ranging System (ARS) with a CO2 laser was used to obtain an accurate 3D track of the BM.

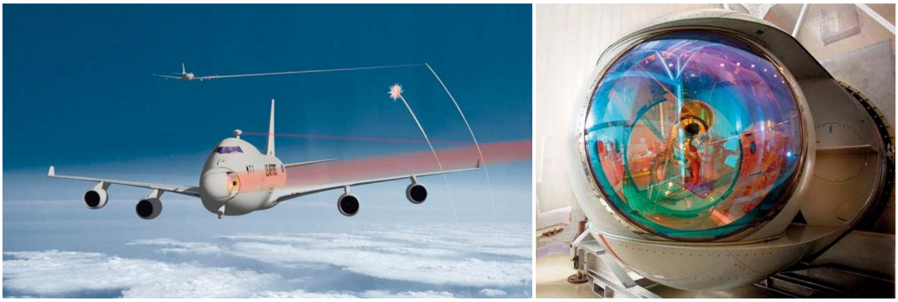


FIGURE 3.15:
(Right) The YAL-1 airborne laser platform [75] and (left) its laser turret [76].

Based on the 3D track of the BM provided by the ARS, the COIL could subsequently be used to destroy the BM. The beam does not burn through the missile, or disintegrate it. It rather heats the missile skin, weakening it and causing failure due to flight stresses. The range of the COIL remains unknown; the US Air Force wanted the ABL to have a lethal range of at least 320 km. The actual effective range depends on atmospheric conditions, the quality of the tracking and guidance systems and the type of BM. It also depends on the geographic arrangement of the BM launch site, the BM target and ABL racetrack for the system to be able to engage and destroy the BM [77].

Since it is unlikely that the exact position of the launch will be known beforehand, the ABL must be able to remain on site for extended periods of time. The concept of operations saw at best two ABLs fly a Combat Air Patrol (CAP), which would be supported by airborne tankers and relieve ABLs. A total of seven aircraft would be needed per location; five flying the CAP while two would be in maintenance. Therefore a considerable amount of ground support would be required [77].

The entire concept of the proposed ABL hinged on the premise that the ABL system would be able to loiter in close proximity to the enemy launch site. Since the ABL itself had only limited defence capabilities the concept thus implicitly depended on the USAF being able to achieve air dominance. The proliferation of integrated, mobile air defence systems, however, casts doubts on the achievability of this premise [77]. The high price tag and limited usefulness of the system eventually caused the program to be cancelled in 2011.

Kinetic Energy Interceptor

Another approach to boost-phase missile defence systems uses the kinetic energy of the interceptor. The Kinetic Energy Interceptor (KEI), as envisioned, would provide land-based and sea-based defence against medium, intermediate, and intercontinental ballistic missiles during the boost and midcourse phases of flight. The proposed land-based KEI capability, developed by Northrop Grumman and Raytheon under a joint contract, was estimated to be deployable in 2014.

At approximately 12 meters in length and 1 meter in diameter, the KEI interceptor was twice the size of the Standard Missile-3 (SM-3). The KEI can reach a maximum speed close to 5.5 km/s in order to destroy ascending targets, which is more than twice the speed of the SM-3 (which will be discussed in the next section). The KEI engages its targets during their most vulnerable stage, before re-entry vehicles or countermeasures can be deployed.

FIGURE 3.16:
(Left) the KEI launcher and (right) the KEI projectile [78].

Kinetic boost phase intercept with an intercepting missile is challenging because the threat missile must be detected and confirmed within a few seconds of its launch. It then becomes a race between an accelerating ballistic missile and the interceptor in which the ballistic missile has a head start. Another technical challenge is designing a kill vehicle that can detect and track the target following missile-staging events and then impact the missile in the presence of a brilliant plume [78]. The kinematic restrictions imposed on the interceptor severely limit the platform's choice of launch positions. Large countries can for instance easily find launch sites for their ballistic missiles which lie beyond the reach of the KEI [77]. The project was cancelled in 2009 because of a perceived mismatch between the capabilities it offered and the performance of ballistic missiles from nations like North Korea and Iran [79].

Net-Centric Airborne Defense Element (NCADE)
NCADE is an airborne BMD system consisting of a launch platform (manned or unmanned), the required fire and targeting systems and the interceptor, currently in development in the US. In this case the interceptor is a modified AIM-120 AMRAAM (Advanced Medium-Range Air-to-Air Missile). Unlike its standard counterpart the NCADE missile uses a passive IR sensor for targeting and is equipped with a second stage in order to increase its range and speed [80].

FIGURE 3.17:
AMRAAM fired from F-15 [81] and breakdown of the NCADE AMRAAM [80].

The program aims at capitalizing on the established reliability of its components by using existing hardware and combining it into a new system. The advantage of using the AMRAAM is its widespread use allowing for the installation of the system on a wide range of platforms. The use of these platforms offers some advantage over a ground based system as the missile is launched at altitude (requiring less energy to reach its target) and has an initial velocity. Furthermore it is considerably easier for airborne platforms to decrease the distance to the launch site than it is for ground based systems [81]. The launching aircraft will, however, still have to be within a 50km range of the launch site. This combined with intercepts having to occur below an altitude of 30km due to the limitations of the missile, still severely limits the opportunity the system will have to achieve a successful boost-phase intercept.

3.5.2 *Mid-course phase intercept systems*

Aegis Ballistic Missile Defence
The mission of Aegis BMD, formerly called Sea-Based Midcourse Defence (SMD) and before that Navy Theater Wide (NTW), is to provide protection against medium to long-range threats by intercepting them between the exo-atmospheric ascent phase and the exo-atmospheric descent phase (thus mid-course).

The Aegis combat system was first installed on board of US Navy ships in the 80's in order to provide integrated defence against air- and surface threats. Since then the system has been exported to four other nations. The addition of BMD capability is, however, a newer development which began in the late 90's. The Ticonderoga class cruisers and Arleigh Burke class destroyers serve as the platforms. Next to the US Navy, the Japanese Navy has also equipped four Kongõ class destroyers (modified versions of the previously mentioned Arleigh Burke class) with the Aegis BMD system [83].

FIGURE 3.18:
USS Hopper conducting BMD test [82].

The Aegis BMD upgrade consists of the Standard Missile-3 (SM-3) and improvements of the Weapon System. The SM-3 missile destroys the incoming BM by physically impacting a kinetic warhead with it (hit-to-kill). Future upgrades of the SM-3 missile (block IIA) will feature a kill warhead with a larger diameter and a greater ability to manoeuvre while in flight in order to increase the defended area [47].

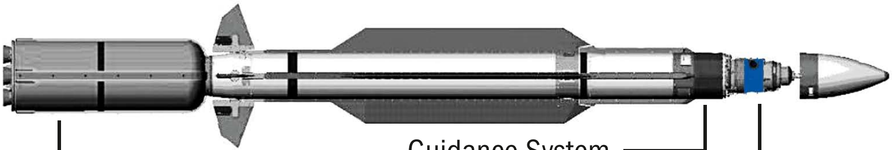


FIGURE 3.19:
SM-3 Block IA missile (based on image from [47]).

The sensor component of the Aegis BMD system consists of the SPY-1 radar used for tracking and initial targeting of the interceptor and an infrared sensor on board of the kinetic warhead for the final intercept. This radar has also been described in the section on Early Warning.

FIGURE 3.20:
(Left) Two of the four SPY-1 arrays of an Arleigh Burke class destroyer [84].
(Top right) Kill warhead with IR seeker of an SM-3 missile [85].

Aegis BMD (as well as a ground-based variant of it) is currently the cornerstone of NATO's European BMD program [86]. An effort is underway, however, to include ships of other member nations in the sea-based BMD system. This is strongly related with the development of the previously discussed Launch-on-Remote and Engage-on-Remote capabilities. Since the launcher is decoupled from the sensor platform other nations can provide the radar track of incoming BMs. Spanish F-100 frigates are, for instance, also equipped with the SPY-1 radar. Dutch ADCF frigates and German F124 frigates carry the SMART-L radar which is, as demonstrated by the Netherlands in 2006, capable of tracking BM targets. Thus, by expanding the number of sensor platforms connected to the Aegis BMD and by using LoR or EoR it is not necessary to equip every ship with interceptors in order to defend large areas.

Ground Based Midcourse Defense

In 2002, National Missile Defense (NMD) was changed to Ground-Based Midcourse Defense (GMD), to differentiate it from other missile defence programs, such as space- and sea-based intercept programs, and missile defence targeting the boost phase or the terminal phase. The mission of the Ground-Based Midcourse Defense program is to counter a limited long-range ballistic missile attack.

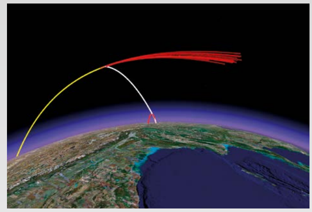
Ground-Based Midcourse Defense uses a variety of sensors and radars to obtain information on missile launches and to track, discriminate, and target an incoming warhead. An example is the Sea-Based X-Band (SBX) radar, which is a midcourse fire control sensor installed on a re-locatable semi-submersible platform for siting flexibility. Fixed radars, like the Upgraded Early Warning Radar (UEWR), provide coverage only for a limited area due to the curvature of the Earth. The primary task of the SBX is discrimination (identification) of enemy warheads from countermeasures like decoys, followed by precision tracking of the identified warheads. The Ground-Based Interceptor is cued to the information from the sensors before launch and during flight to help the interceptor find the incoming ballistic missile and close in on it.

FIGURE 3.21:
(Top left) Upgraded Early Warning Radar. (Bottom left) Sea-based X-band radar. (Middle) GMD Boost Vehicle and (right) the Exo-atmospheric Kill Vehicle [87].

The current Ground-Based Interceptor consists of a three-stage, solid fuel booster and an Exo-atmospheric Kill Vehicle (EKV). When launched, the booster missile carries the kill vehicle toward the target's predicted location in space. Once released from the booster, the 70 kg EKV uses data received in-flight from ground-based radars and its own on-board sensors to close in on and destroy the target using only the force of the impact (thus hit-to-kill).

Fire Control and Communications is the central nervous system of the Ground-Based Midcourse Defense element. It connects all of the hardware, software and communications systems necessary for planning, tasking and controlling Ground-Based Midcourse Defense [88].

CHINESE ASAT AND ABM TESTS



On 11 January 2007 the People's Republic of China launched a ballistic missile with a kinetic kill vehicle that intercepted an obsolete Chinese weather satellite at an altitude of around 850 km. While no official statements have been issued about the specific booster used for the intercept the director of the US Defense Intelligence Agency (DIA) classified it as the SC-19, a modified DC-21 ballistic missile [89], [90]. Exactly three years later the PLA conducted a successful anti-ballistic missile test when either the previously used SC-19 or the civilian counterpart the KT-1 was used to intercept a medium-range ballistic missile during the midcourse phase in the exo-atmosphere.

3.5.3 Terminal-phase intercept systems

PATRIOT

The Phased Array Tracking Radar to Intercept On Target (PATRIOT) is a medium-range air-defence system that can provide defence against TBMs and Air Breathing Threats (ABT) including CMs.

FIGURE 3.22:
PATRIOT Launcher (Photo credit: Royal Netherlands Army Ground-Based Air Defence Command).

A PATRIOT fire unit consists of an Engagement Control Station (ECS) coupled to a Radar Set (RS) and a number of Launching Stations (LS) with Patriot missiles. The ECS initiates and controls the engagements of the Fire Unit. Multiple fire units are controlled by an Information Coordination Central (ICC) and a Tactical Command Station (TCS). The ICC performs target deconfliction between the subordinate ECSs and provides communication linkage with higher echelons. The PATRIOT RS has a search sector of 120 degrees in azimuth. At least three Patriot fire units are needed to cover 360 degrees in azimuth if the threat consists of cruise missiles.

The PAC-2 (Patriot Advanced Capability-2) missile has an approximate range of 160 km with a maximum altitude of 24 km. The PAC-3 missile has a substantially lower range but has an increased lethality against ballistic missiles. PAC-3 has an active radar seeker and uses hit-to-kill to destroy the threat, thereby transferring all its kinetic energy onto the threat. Furthermore, the PAC-3 missile can be launched on remote data allowing intercepts beyond the horizon; this increases its effectiveness against cruise missiles. PATRIOT is in use by a number of NATO countries (USA, Netherlands, Germany, Greece, Spain) and other countries (Israel, Japan, Kuwait, Taiwan, Saudi Arabia).

MEADS

MEADS is an acronym for Medium Extended Air Defence System. The mission of MEADS is to provide area and point defence to fixed high value assets or manoeuvring units against tactical missiles and air breathing threats including CMs. Under development by Germany, Italy and the United States, MEADS is a mobile air defence system designed to replace the aging NATO PATRIOT systems.

FIGURE 3.23:
MEADS launcher and radar [91], [92].

A firing unit consists of one UHF surveillance radar, two X-band multi-function fire control radars and six vertical launchers and three reloaders each with 12 missiles. The interceptor segment consists of hit-to-kill missiles (initially PAC-3 augmented by the Missile Segment Enhancement (MSE) technologies in order to increase their range), controlled by two Tactical Operations Centres (TOC). All elements are truck-mounted. The radars can be either rotating or staring. The potential addition of a second missile system to the baseline system has been studied because for some threats the PAC-3 missile capability might be excessive. Fielding of MEADS, however, now appears unlikely as none of the three partner countries are planning to acquire the system.

SAMP/T

The basic SAMP-T (Sol-Air Moyenne Portée/Terrestre) version with Aster 30 has a capability against aircraft and missiles, including CMs and TBMs. An Aster Extended Range (ER) version is being developed; it will have a range of 150 km and will be able to intercept targets at up to 25-30 km. A typical SAMP-T battery consists of Arabel, a rotating multi-function radar, truck-mounted vertical launchers with eight Aster 30 missiles per launcher and a truck-mounted engagement module. SAMP/T must be integrated into a battle management system including an early-warning system or long-range radar to be able to provide a capability against TBMs.

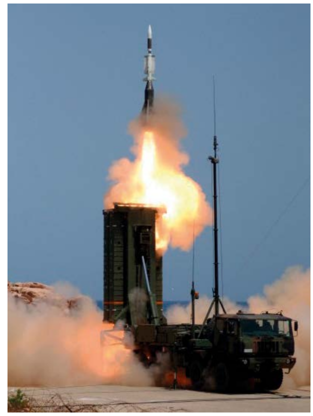


FIGURE 3.24:
Test fire of Aster 30 missile [93].

FIGURE 3.25:
SAMP/T launcher and the Arabel radar [93], [19].

PAAMS

The Principal Anti Air Missile System (PAAMS) is a joint British/French/Italian naval anti-air weapons system, which uses the Aster-15 and the aforementioned Aster-30 missile. As with SAMP/T the Aster-30 will be able to provide some level of terminal-phase BMD capabilities to the navies of these three countries [95].

FIGURE 3.26:
The Horizon-class frigate, and an Aster 30 launch [95], [96].

Specifically for the BMD task, however, a new Aster block 2 is being developed that would be interoperable with current Aster launch systems. The new interceptor will be designed to deal with the new generation of manoeuvring short and medium range ballistic missiles. The engagement would take place endo-atmospherically, whereby the interceptor would be guided by an IR seeker to ensure hit-to-kill [95].

ARROW

ARROW is jointly developed by the U.S. and Israel. ARROW consists of missiles, interceptor launcher batteries, the Green Pine radar and the Citron Tree fire-control system. The 'Green Pine' is a semi-trailer-mounted active phased-array multi-function radar capable of search, track and guidance. ARROW-2 is the interceptor which has a two-stage, solid propellant rocket motor booster and sustainers and can manoeuvre utilising both aerodynamics and thrust vector control (by flexible nozzles). The warhead is a high-explosive focused-blast fragmentation type (thus using a proximity fuse). ARROW-2 has a maximum effective range of approximately 70 km. Minimum intercept altitude is 8 km; maximum altitude is 50 km.

FIGURE 3.27:
Super Green Pine radar and ARROW-2 missile launch [97].

ARROW-2 has been operational since the beginning of 2000 with the deployment of one ARROW Weapon System (AWS, codename Homa (Fence)) battery near Tel Aviv. A second AWS has been assembled in northern Israel. Funding for a third battery has been approved by the U.S. Congress. This battery will also be equipped with the new Super Green Pine Radar whose range is well in excess of the 480 km range of the Green Pine radar.

The AWS is a flexible system designed to keep up with the threats by adding new components to the overall system. The latest addition is the high altitude ARROW-3 component now in development with an expected Initial Operational Capability (IOC) of 2016. Its development is geared to offer several capabilities like increased detection range (for instance by using a large unmanned air vehicle, see Airborne Early Warning) and the use of additional segments of the EM spectrum (Infrared and electro optical). The installation of the ARROW-3 on-board of ships to offer Aegis-like capabilities is also considered. The new system will also have the option to divert the exo-atmospheric kill vehicle in case the target trajectory is not determined at launch and anti-satellite capability. Finally the system should also have increased performance against salvos of incoming missiles [98].

THAAD

The mission of THAAD (Terminal High Altitude Area Defence) is to provide additional coverage to protect population centres and enable a larger spread of friendly forces. THAAD is focussed on short to medium-range BMs and provides a shoot-look-shoot capability, (see introduction Section 3.5). THAAD was designed to hit Scud-like ballistic missiles, but has a limited capability against ICBMs as well.

FIGURE 3.28:
THAAD TPY-1 radar and launcher [100].

The THAAD interceptor is a single-stage solid-propellant missile with a liquid propellant kill vehicle on top. The kill vehicle has an IR seeker for a hit-to-kill capability. The interceptor has a maximum effective intercept range of approximately 200 km and maximum altitude of approximately 150 km. To date two THAAD batteries have been created, more are however to follow during the next few years. In addition a THAAD unit has been deployed to Hawaii to intercept potential launches from North Korea [99].

S-300V

The Russian S-300 family of surface-to-air missiles (SAMs) consists of two main branches; the S-300V and the S-300PMU-series. The first was specifically designed for the interception of ballistic missiles, cruise missiles and aircraft. For this purpose each battery carries two types of missiles, of which the larger Giant (NATO designation SA-12B) can intercept ballistic missiles at altitudes between 20 and 40 km. The threat is eliminated by means of proximity fusing for which a 150 kg high explosive warhead is used. The latest upgrade, the Antey-2500 is claimed to be able to intercept ballistic missiles with a range up to 2500 km (IRBMs).

FIGURE 3.29:
(Top left) Two 9A82 TELAR, (bottom left) several 9A82 TELARs and the 9S457ME command post. (Top middle) 9S19 "High Screen" acquisition radar, (top right) 9S15 "Bill Board" all-round surveillance radar and (bottom right) the 9A83 TELAR [101].

As Figure 3.29 illustrates the system is track-mounted and fully mobile decreasing the time required for relocation when compared to systems like THAAD or ARROW. The S-300V has been exported to countries in Europe, the Middle East and Asia due to its ability to provide a cost-effective anti-ballistic missile capability [83].

S-300PMU1/2

The other branch of the Russian S-300 family is the S-300PMU1/2 series, which offers some capability to defend against tactical and theatre ballistic missiles and some measure of defence against strategic ballistic missiles. Both versions consist of up to 12 launcher units made up out of a mix of 5P85SE2 self-propelled and 5P85TE2 trailer launchers. The latest variant of the two, the

S-300PMU-2 was unveiled during the MAKS air show and exhibition in 1997 and can engage targets flying at a speed up to 10,000km/h at distances up to 200km [102]. Figure 3.30 shows the various components that make up the S-300PMU-2 system.

FIGURE 3.30:
(Top left) Two 5P85 TELs and the 30N6E2 “Tomb Stone” engagement radar. (Left middle) the 64N6E2 “Big Bird” detection radar and (bottom left) the 54K6E2 command post. (Middle) A 5P85TE2 TEL launching a 48N6E2 interceptor. (Right) The 76N6 “Clam Shell” low altitude acquisition radar [19], [75].

The use of different radars by the S-300PMU system allows it to detect and engage both low (above 10m) and high flying targets (below 27km). This highly mobile system has been exported to, among others, various former USSR countries and the People’s Republic of China.

3.5.4 C-RAM

While the need for protection against Rockets, Artillery and Mortars attacks (counter-RAM or C-RAM for short) had already arisen in Israel, it was the deployment of the multinational force to Iraq and Afghanistan that sparked international interest in C-RAM systems. Due to the short flight time of these types of weapons the threat assessment and engagement procedure needs to be entirely automated. Several different types of systems were developed which are able to engage targets on short notice.

Iron Dome

The need for a C-RAM system has been felt nowhere more clearly than in Israel, which recently fielded the Iron Dome system able to engage targets launched between 5 and 70km away [103]. This all-weather system consists of several launchers spread around the protected area and a detection and tracking radar. Once an incoming threat is detected the battle management and control system computes the likely point of impact, if it falls within the protected area a launcher is tasked to fire an interceptor (which is guided in contrast to other C-RAM systems) [103]. Its use in the defence of Tel Aviv in 2012 also proved the ability to deal with volleys of incoming threats launched from various sites [13].

FIGURE 3.31:
(Left) Iron Dome launcher and (right) its truck-mounted radar [104].

Centurion

The US system (Centurion) is based on the Phalanx CIWS (Close-In Weapons System) originally developed for the US Navy for protection against anti-ship missiles. While it uses the same sensors (a Ku-band radar and Forward Looking Infrared or FLIR) the munition was changed to M246 or M940 HEIT-SD (High-Explosive Incendiary Tracer, Self-Destruct) rounds in order to reduce collateral damage [105].

FIGURE 3.32:
Centurion mounted on a trailer [106].

MANTIS

The German Army has taken delivery of the MANTIS (Modular, Automatic and Network capable Targeting and Interception System) C-RAM system whose concept is similar to the Centurion system, though in this case the sensor and shooter parts of the system have been decoupled from each other. A single MANTIS unit consists of two sensor stations and up to six highly automated Oerlikon 35 mm guns [107].

FIGURE 3.33:
MANTIS C-RAM system [108].

Directed Energy C-RAM Systems

As with boost phase intercepts the short time available for detection, analysis and intercept allows for only a small margin of error. In order to increase the time available for acquisition and analysis directed energy weapons have been considered for this task. One example of such a system was the Tactical High Energy Laser (THEL) and its mobile version (MTHEL).

FIGURE 3.34:
(Left) Artist's impression of a C-RAM concept using directed energy weapons [8]. (Top right) THEL beam director [112] and (bottom right) an impression of the mobile version of the THEL [113].

During the 2000’s the performance of these platforms against Katyusha artillery rockets, artillery shells and mortars was tested at the White Sands Missile Range in New Mexico. While it proved to be effective against these threats the program, whose original goal was the development of an operational system, was cancelled due to its prohibitive costs [109]. However, research on directed energy weapons for C-RAM still continues in the shape of several programs. One of them aimed at delivering a more cost effective solution using a mobile multi-hundred kilowatt class solid state laser is the High Energy Laser Technology Demonstrator (HEL TD) weapons system program [110]. A mobile version of this system began testing in 2012 [111].

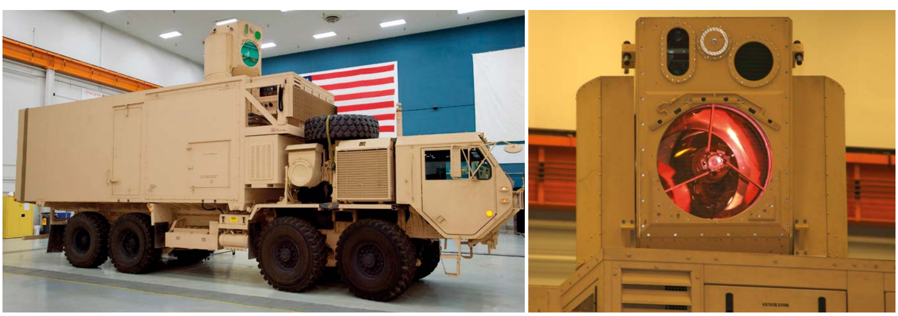


FIGURE 3.35:
(Left) The mobile version of the HEL TD [111] and (right) its laser turret [114].

3.6 Passive Defence

Passive Defence measures are actions that reduce the vulnerability of friendly assets and minimise the effects of damage to friendly assets or population caused by a missile. First, an attempt is made to prevent the enemy attacking valuable and vulnerable assets by degradation of enemy targeting. This includes methods such as deception, camouflage and concealment. Furthermore, the vulnerability of assets including the population is reduced by warning the population about possible missile impacts, CBRN protection (e.g. gas masks), hardening (e.g. sheltering), mobility and dispersal. Finally, the effects of a missile attack can be minimised by facilitating recovery and reconstitution after an attack by redundancy, repair capability and decontamination.

3.6.1 Consequence management

If a missile is intercepted, it does not necessarily imply that the threat to people on the ground has been eliminated. Important factors are among others: type of payload, altitude of intercept, atmospheric conditions, relative intercept geometry and speed between interceptor and threat.

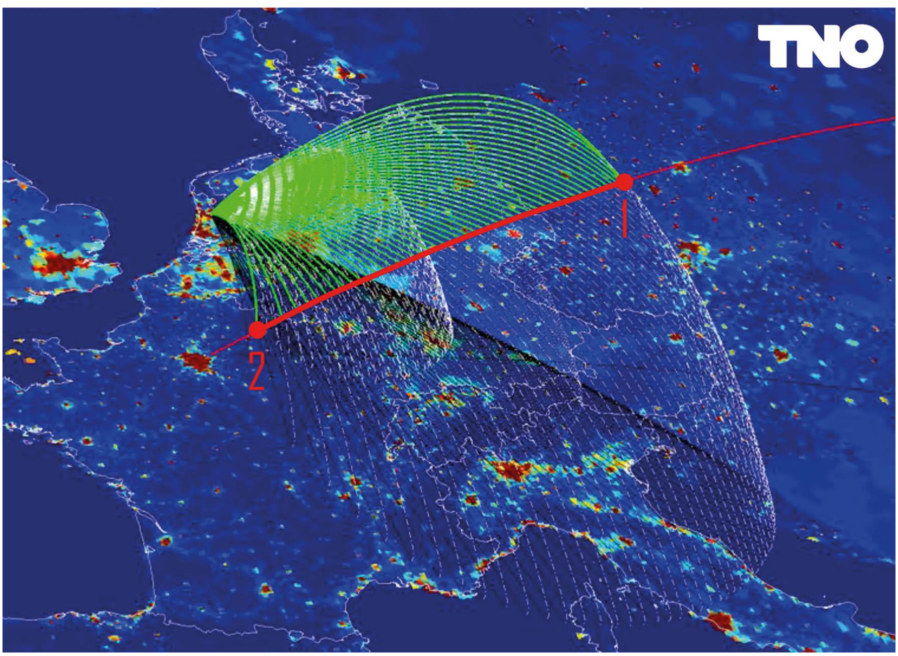


FIGURE 3.36:
Apart from the threat, interceptors themselves also cause debris that can end up in populated areas. This plot shows the flight paths of the debris from a three stage interceptor for various possible fly outs. The red zone between 1 and 2 represents the first and last intercept opportunity and is called the intercept window.

Consequences after intercept of missiles containing chemical agents
When a missile contains a chemical bulk load, the altitude and relative velocity of intercept will predominantly determine if any effects will occur on the ground. Another important factor is the way in which the released liquid drops break up. Some chemical agents can, directly after intercept and subsequent release, descend in the form of frozen drops and still contaminate the surface. Other types of chemical agents can still come down in the state of droplets, depending on the intercept altitude.

When a missile contains submunitions, conditions of intercept and altitude of intercept are relevant with respect to possible effects on the ground. Depending on the intercept conditions, the exact location where the warhead is hit determines the number of submunitions that is destroyed. A shift of only approximately 20 cm in this location can result in significantly more submunitions surviving the intercept, see Figure 3.37.

FIGURE 3.37:
Depending on the distance from the nose where the warhead is hit by the interceptor, a varying percentage of submunitions is destroyed (red colour). The surviving submunitions (green colour) can still pose a lethal threat after intercept.

Submunitions that survive intercepts can subsequently be subjected to thermal heating during the descent to Earth. The heating and possible degrading effects on the functioning of the content of the submunition are strongly dependent on the type of chemical agent, the intercept altitude and the velocity with which the submunitions are released.

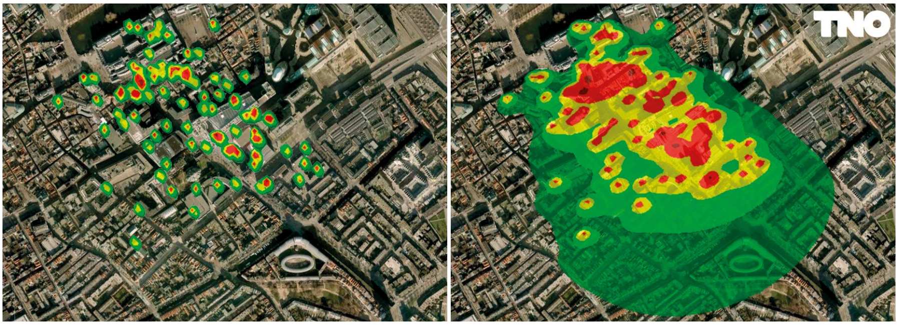


FIGURE 3.38:
(Left) Spread of chemical agent in the liquid form directly after impact.
(Right) Spread of the chemical agent in vapour form sometime after impact.

Consequences after intercept of missiles containing biological agents

The same issues exist for intercepts of warheads armed with biological submunitions. As the number of biological submunitions that are carried is usually larger than the number of chemical submunitions, and taking into account the larger area of contamination, it is even more critical that the threat is intercepted within optimal conditions, such that the maximum number of biological submunitions is eliminated.

Consequences after intercept of missiles containing nuclear loads

When a threat with a nuclear payload is intercepted, it is quite possible that detonation will still occur, certainly when the threat is equipped with the so-called salvage fusing principle (though such a system can cause adverse effects for the attacker as well). This is a mechanism that detonates the nuclear charge when the threat is hit by an interceptor, even if the main detonation mechanism is not hit. An intercept at high altitude can even lead to a continental-scale electromagnetic pulse (EMP), see also Section 2.2.5.

3.7 Battle Management, Command and Control, Communications, Computers and Intelligence (BMC4I) & International BM Programs

Besides the three building blocks CCFO, Active Defence and Passive Defence that together outline MD as shown in Figure 3.1, there is also the supporting pillar BMC4I. This pillar consists of the capabilities, processes, procedures and information for coordinating and synchronising both offensive and defensive measures, and supports Active Defence and Passive Defence as well as CCFO. The BMC4I pillar is, however, often linked to BMD programs since the command structure is an inherent part of the BMC4I setup. Thus in order to discuss BMC4I systems some attention will have to be devoted to the various missile defence programs.

BMC4I consist of three parts:
1. Battle Management, Command and Control, (BMC2);
2. Communications and Computers;
3. Intelligence;

Battle Management, Command and Control
BMC2 includes planning, directing, controlling, co-ordinating and executing operations.

Communications and Computers
Communication is the dissemination of information concerning missiles, enemy missile capabilities, infrastructure and BMC2 between BMD systems. Interconnectivity can be defined as the capability of two or more systems to manage common information to maximise the operational effectiveness of each system and the collective effectiveness of the combined force (see text box at the end of this section). Apart from communications, computers are also important for executing most of the other parts of BMC4I.

Intelligence
Intelligence is the assessment of a threat by identifying enemy capabilities, activities and intentions in order to obtain indications of the location from which missiles will be launched, towards which targets they will be launched, what kinds of warheads can be expected, etc. Intelligence Preparation of the Battle Space (IPB) builds an extensive database for each potential area in which a unit may be required to operate. The database is then analysed in detail to determine the impact of the enemy, environment, and terrain on operations. IPB is a continuing process and provides important information for all MD pillars.

BMD Programs
While many countries have national BMD programs this section will focus on international collaborations in the form of the Phased Adaptive Approach (PAA) and the NATO BMD program.

NATO BMD

In 2005 NATO decided to develop the capability to protect deployed NATO forces against short and medium-range BMs. This program is called the Active Layered Theatre Ballistic Missile Defence (ALTBMD). The components that make up the ALTBMD system consist of various low and high-altitude weapon systems, early warning sensors and radars contributed by the member nations of NATO. These systems have already been introduced in Section 3.3 and 3.5. In addition NATO provides the BMC4I component in order to integrate the various assets offered by NATO members [115].

By 2010, as the ALTBMD program was nearing operational readiness, NATO expanded its goals and created the NATO BMD program. Rather than merely providing protection for deployed forces this program aims at providing a defence against the BM threat for all NATO European populations, territories and forces (a quote from the Lisbon summit declaration stating this goal can be found in the introduction of the book). The BM4CI component developed for the coordination of the contributing assets is called the Air Command and Control System (ACCS) and will be discussed next [116]. While the NATO BMD uses assets from many NATO members key among them are those made available by the US under its own international BMD program; the Phased Adaptive Approach (PAA) which will be discussed after the ACCS system.

NATO ACCS (Air Command and Control System)

ACCS is the Air Command and Control System programme of NATO, which will replace the various existing air command and control systems in Europe from 2011 onwards. At the highest level it comprises the Combined Air Operations Centre (CAOC) from which the air battle is run. Beneath this level of command are the Air Control Centre (ACC), Recognised Air Picture (RAP) Production Centre (RPC) and Sensor Fusion Post (SFP). The programme encompasses both static and deployable elements. Under separate funding, NATO will also procure deployable sensors for the deployable ACCS component (DAC).

US PAA

In 2009 the US revised its approach to missile defence and commenced with a new BMD program. The new effort focussed on an incremental approach, where new capabilities would be added as they emerge and as the threat evolves. In addition it uses a more flexible structure that would allow for tailor made solutions for specific regions of the world.

"…the United States will pursue a Phased Adaptive Approach (PAA) within key regions that is tailored to the threats unique to that region, including the scale, scope, and pace of their development, and the capabilities available and most suited for deployment. This approach means we will phase in and implement the best available technology to meet existing and evolving threats, and adapt to situations that evolve in an unforeseen manner."

- Frank A. Rose
Deputy Assistant Secretary

The three key regions are Asia-Pacific, Middle-East and Europe. Of which the latter is of specific interest as it is strongly connected with the NATO BMD effort. Under this program the US provides early warning and intelligence using the previously mentioned EW assets (such as the DSP and SBIRS satellites) for the NATO BMD program [117]. The various assets and there relation to each another and the BMD programs can be found in Figure 3.39.

Under Phase 1 of the EPAA Aegis equipped ships began patrolling the Mediterranean sea and a TPY-2 radar had been deployed to Turkey. A key component of Phase 2 of the EPAA will be the installation of ground based SM-3 interceptors (see Aegis BMD in Section 3.5) and the construction of a ground based version of the SPY-1 radar in Romania. Phase 3 envisions a similar site in Poland. Finally Phase 4 could see the deployment of more advanced interceptors in order to protect the US from potential launches of ICBMs from the Middle East [117]. The EW information and coordination of US interceptors, ships and radars is carried out by the national BMC4I system of the US, called the C2BMC (Command and Control, Battle Management, and Communications). This system interfaces with the NATO ACCS system when used by the NATO BMD program and will be discussed next.

C2BMC

C2BMC integrates BMD information from innumerable sources and provides the combatant commanders (COCOMs) and Department of Defence leadership with an integrated picture of the BMD battle space. It provides a global warning of a potential ballistic missile launch. C2BMC also provides US strategic command (STRATCOM) and the other commands with planning and crisis-action tools to facilitate courses of action. The system became operational in 2004. Current C2BMC capabilities include global situational awareness of the BMD battle space and early warning of a ballistic missile attack on the US homeland [118].

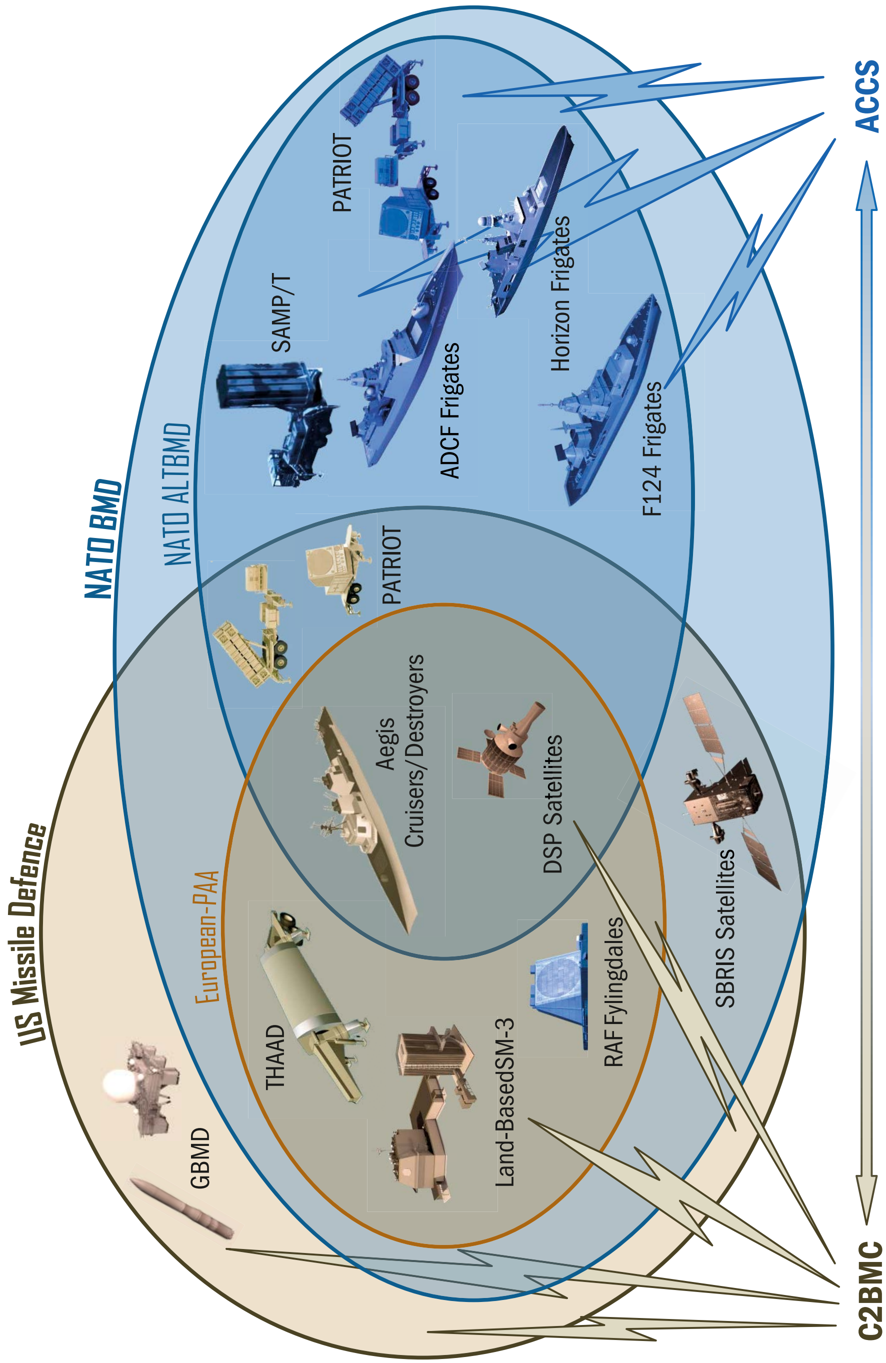


FIGURE 3.39:
NATO BMD and US PAA programs overlap.

LINK-16

Link-16 is a radio (RF) data link used to exchange (near) real-time information between tactical units and was developed to meet the information requirements of all tactical units, supporting the exchange of surveillance data, Electronic Warfare (EW) data, mission tasking, weapon assignments and control data.

Link-16 uses timeslots assigned to all units participating in the network to connect all members. Everyone knows during which timeslots they are allowed to send data in, and during which timeslots they need to listen to other participants sending data. Although Link-16 provides the means to change an active Link-16 network, it requires network designers to build a network before an operation. The Link-16 network uses UHF, limiting the range to Line Of Sight (LOS). The typical range of a Link-16 RF network from end-to-end is 555 km assuming LOS is achieved. In reality relay techniques are used to extend the range to whatever is operationally required. For example, JRE (Joint Range Extension) is used to send Link-16 data over a conventional wired network using TCP or by the use of satellite communication. When using satellite communication the latency becomes an important aspect. When an RF-network is used latency is negligible (assuming enough timeslots have been assigned to the unit wanting to send data) but when a satellite is used as a relay, latency can increase to an order of seconds.

Besides the command and engagement messages for BMD purposes Link-16 allows friendly units to exchange their position, the position and velocity of the incoming BMs and the predicted launch and impact point (with the uncertainty ellipse). The latter two can be used for CCFO and passive defence. In addition a message format exists which allows friendly units to coordinate their engagement by exchanging the engagement availability, shoot-look-shoot opportunity or expected probability of kill.

Link-16 in its current implementation is less suited for C-RAM as the update rate of 12 seconds is probably too low for that type of threat. Modifications are being investigated and tested that include providing a network designer the possibility of assigning higher update rates for certain units. Other modifications include the sending of much more data (Link-16 Enhanced Throughput or LET) and the proposals for controlling and handing-over of a weapon in flight from one participant to another.

SUMMARY

At the present day, an unparalleled number of international actors, be it national governments or non-state groups, have acquired or are seeking to acquire both weapons of mass destruction and the means to deliver them. Those means of delivery can be Ballistic Missiles that can bridge vast – even intercontinental – distances. The use of Ballistic Missiles with conventional warheads is also an evolving threat as witnessed by the Chinese anti-ship ballistic missile. The defence of land forces and vulnerable areas against short range threats such as rockets, artillery and mortars has also become an increasingly pressing issue, due to the involvement of Western forces in the operations in the Middle–East and Northern Africa. As sophisticated technologies continue to proliferate and the intentions of actors are uncertain, an increasingly complex threat environment emerges, which stresses the importance of Missile Defence.

Missile Defence aims at prevention of the launch of missiles, destruction of missiles in flight and minimisation of the damage caused by missiles after impact. Due to the increasing proliferation of missiles, their increasing ranges and the possibility that they possess a chemical, biological, radiological or nuclear warhead, Missile Defence remains a topic high on the national and international defence agendas.

This book has provided an overview of Missile Defence. It has described the missile threat in some detail, from general characteristics of Ballistic Missiles to their trajectories, warheads and countermeasures. Furthermore, the four pillars of Missile Defence have been presented:

- Conventional Counter Force Operations, with the aim of preventing the launch of missiles;
- Active Defence, with the aim of destroying the missiles in flight;
- Passive Defence, with the aim of minimising the damage of the missiles after impact;
- Battle Management, Command Control, Communication, Computers, Intelligence and Early Warning, with the aim of supporting the first three pillars.

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By means of this book TNO aims at providing an overview of the topics related to Missile Defence (MD) and the systems used for this purpose. While traditionally the scope of MD covers defence against Ballistic Missiles (BMs), short range surface to surface missiles, Cruise Missiles (CMs) and Air-to-Surface guided Missiles (ASMs), within the framework of this book the latter two are omitted in favour of protection against rockets, artillery and mortars (C-RAM). This book is valuable to people unfamiliar with Missile Defence, and those with detailed knowledge of specific areas of Missile Defence. TNO, the Netherlands Organisation for Applied Scientific Research, conducts extensive research in the field of Missile Defence, on the basis of which this book was largely written.

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