MISSILE DEFENCE: CONCEPTS AND TECHNOLOGIES

ANAND SHARMA

During the 1950s, counter-force attack was the only effective solution against ballistic missiles, i.e. by destroying them while they were still in silos or on launchers. However, efforts were progressing to develop some sort of anti-missile shield to counter the ballistic missiles that were launched. As the research and development (R&D) of anti-ballistic missile systems continued gaining effectiveness and advance capabilities, counter-measures to missile defence also matured and were outflanking the efforts. This offence–defence play-off brought ballistic missile defence into prominence in security planning. Many technologies have come to the fore to provide defence against annihilating ballistic missile attacks.

A great deal of political, technical and public debate is persistently focussed on the extreme issue of efficacy of missile defence. The answer in the extreme is 'no'; however, it is appreciated that though the phenomenal technological growth and advancement may not provide foolproof security, missile defence still has its importance in mitigating the effects of a preemptive strike and deterring the adversary from believing that a ballistic missile attack can provide him a clear military or political advantage.

* Wing Commander **Anand Sharma** is a Research Fellow at the Centre for Air Power Studies,New Delhi.

Defending against ballistic missile attacks is a challenging technical task. The defensive system needs to hit a warhead smaller than an oil drum that is travelling in space at speeds greater than 18,000 km/hr.

The scope of this paper is to study the concepts and various technologies which have evolved to provide a useful defence against ever improving, sophisticated offensive threats. The paper reviews the characteristics of the relevant technologies and outlines the key uncertainties concerning those technologies' potentials. It researches the imperatives of defences in various phases of missile flight and against numerous counter-measures.

INITIAL ENDEAVOURS

From the late 1950s till 1970, both the superpowers developed the anti-ballistic missile systems using nuclear tipped missiles as interceptors. US efforts included the Nike, Spartan, Sprint and Sentinel missiles. When using nuclear tipped interceptors, difficulties could spring up from collateral damage or blinding of the defence's own radar tracking system and communications.

The Soviet Union's missile defence programme also progressed through their ABM-1 to ABM-4 systems, namely, the Griffon Galosh, Gazelle, and Gorgon. The USSR missile defence capabilities were successful and remained operational with nuclear warheads till the late 1980s.

Given the concerns about using nuclear tipped interceptors, in the 1980s, the US Army began studies about the feasibility of hit-to-kill vehicles, where an interceptor missile would destroy an incoming ballistic missile just by colliding with it head-on. The first successful programme, which actually tested a hit-to-kill missile interceptor was the army's homing overlay experiment [1] (HOE), which used a kinetic kill vehicle (KKV)[2] on June 10, 1984, intercepting

1. A.Fenner Milton,M.Scot Davis, John Parmentola, *Making Space Defense Work: Must the Superpowers Cooperate*? (UK: Pergamon-Brassey's International Defense Publishers Inc., 1989), Ch.1, p. 8.
2. The KKV was equipped with an infrared seeker, guidance electronics and a propulsion system. Once in space, the KKV could extend a folded structure similar to an umbrella skeleton of 4 m (13 ft) diameter to enhance its effective cross-section. This device would destroy the ICBM reentry vehicle on collision.<www.nationmaster.com/encyclopedia/National-missile-defense#Homing_Overlay_Experiment>

the Minuteman RV (reentry vehicle) with a closing speed of about 6.1 km/s at an altitude of more than 160 km. The feasibility of kinetic energy intercept technology as demonstrated subsequently became the most matured basis of ground-based defence system concepts.

Ideally, it is preferable to intercept ballistic missiles as far away from their intended target and as early in their flight trajectory as possible while offering the opportunity for multiple shots.

The beginning of the second era coincided with the origins of the Strategic Defence Initiative (SDI) programme, which had, as its goal, the development of non-nuclear missile defences. Much of the technologies that Reagan proposed for the system were at the very edge of technology. They included space and ground-based lasers, rail-gun kinetic energy interceptors, space sensors, particle beam weapons, etc. The concepts of ballistic missile defence have been evolving with each of these technologies.

CONCEPTS OF BALLISTIC MISSILE DEFENCE

Defending against ballistic missile attacks is a challenging technical task. The defensive system needs to hit a warhead smaller than an oil drum that is travelling in space at speeds greater than 18,000 km/hr. Counter-measures such as decoy warheads further complicate the problem of intercepting targets. It is essential to exploit the particular vulnerabilities that a ballistic missile presents during the phases of its flight: boost phase, mid-course phase, and terminal phase. The characteristics of different phases of the ballistic missile trajectory are as shown in Table 1 below:

Table1: Phases of Ballistic Missile Trajectory

Phase	Duration	Description
Boost Phase	1-3 minutes for tactical short range missiles. 3-5 minutes for long range missiles.	Powered flight of the rocket boosters lifting the missile payload into a ballistic trajectory.

Post-Boost Phase	10s of second to 10s of minutes.	Most intercontinental ballistic missiles (ICBMs) now have a "post-boost vehicle" (PBV), an upper guided stage that ejects multiple, independently targetable reentry vehicles (MIRVs) into routes to their targets. If these RVs are to be accompanied by decoys to deceive ballistic missile defence (BMD) systems, the PBV will dispense them as well.
Mid-Course Phase	About 20 minutes (less for sea-launched ballistic missiles (SLBMs).	RVs and decoys continue along a ballistic trajectory, several hundred to 1,000 km up in space.
Reentry Phase	30-100 seconds.	RVs and decoys reenter the earth's atmosphere, decoys first slow down in upper atmosphere, then burn up because of friction with the air and RVs are protected from burning up in friction by means of an ablative coating, At a preset altitude, their nuclear warheads explode.

Ideally, it is preferable to intercept ballistic missiles as far away from their intended target and as early in their flight trajectory as possible, while offering the opportunity for multiple shots. To interdict a missile and its warhead in any phase of its flight i.e. boost, mid-course or terminal, requires an ability to detect and intercept the attack within a very few minutes or to track and destroy the attacking missiles and their warheads during their longer mid-course journey through space before their reentry into the atmosphere so that the debris will burn up on reentry. Finally, the last ditch attempt would be to destroy the attacking missiles as they reenter and pass through the atmosphere to the target in their terminal phase.

Each of these phases furnishes intercept opportunities, but also has inherent limitations that must be taken into account in the design and deployment of the missile defence architecture, as shown in Table 2.

Table 2: Implications of Intercepting Ballistic Missiles During Different Phases

Phase	Advantages	Disadvantages
Boost	Missile's thermal signature is large. Easy detection and tracking. Booster is large physical target and missile is vulnerable due to slower speed, large cross-section. Decoys are difficult to deploy. Multiple engagement opportunity.	Time available for intercept is short (about three to five minutes). Interceptor must be positioned close to country from which missile is launched. Rocket plume can obscure the missile's body Missile's acceleration complicates the tracking solution. Hitting the booster can leave a live warhead that falls short of its target.
Ascent/Early Ascent (Post-Boost)	Missile is still large and hot. Extends the time available for intercept. Missile mostly would be flying a predictable ballistic trajectory.	Warhead separation on the missile being targeted may be very rapid. Interceptor must be positioned close to country from which missile is launched. Interceptor must destroy warhead because warhead has enough speed to reach its target.
Mid-Course	Longest time is available for intercept. Missile is probably flying a predictable ballistic trajectory. Defences can be positioned in the oceans.	Missile's thermal signature is small, making it difficult to detect and track. Warhead is small physical target. Decoys can dilute defences

Terminal	Most decoys are stripped away during atmospheric reentry. Forward deployment is unnecessary.	Time available for intercept is very short. Debris from the intercept may fall on defended territory.

Layered Defence

As anti-missile capabilities emerge from R&D programmes and progress made to date in missile defence development efforts, it can be reasoned out that the best way to counter even a limited number of missiles attacks is through *defence in depth*[3]. Multiple defensive layers, with system elements working together synergistically are central to the approach.[4] Promising technologies and approaches include space-based detection sensors, ground-based and seaborne early warning and tracking sensors and also include kinetic energy (hit-to-kill) and directed-energy interception systems with various land, sea, air and space basing.

To achieve a high probability of ballistic missiles' destruction in flight, a layered defensive approach is imperative.

To achieve a high probability of ballistic missiles' destruction in flight, a layered defensive approach is imperative. Layered defences are built on the premise that although technological limitations might keep any one layer from having an adequate chance of successfully intercepting its target, multiple layers could together provide an effective defence. The layered approach provides multiple opportunities to engage the warheads from detection in the boost phase till the reentry phase, thus, reducing the burden on any single layer of defence. Further, layered defences complicate the design of the adversary's offensive systems as the offensive systems have to cater to multiple layers of defences, demanding complex counter-measures, thus, reducing the payload capacity or compromising in attributes such as range and speed.

3. Defence in depth means there will be a number of opportunities to destroy missiles as they are launched and transit through the various stages of their flight paths or trajectories.
4. Milton, et. al, n.1, Ch 2, pp 24-32.

Sensor and data processing technologies are crucial to an advanced ballistic missile defence system.

However, there are drawbacks as well to layered defences. The most obvious problem is that more layers will cost more—especially if the layers are completely independent.

Second, the degree to which the layers can combine to produce high effectiveness will depend on how independent the layers are. To take an extreme example, if all the layers depend on the same sensor system and that sensor system fails, all the layers will fail. The layers must be able to take advantage of the other layers without being overly dependent on them.

Third, the robustness of the system against the loss (or severe degradation) of one layer will depend on how much capacity is built into the system to compensate for that loss. For example, if boost and post-boost defences permit twice the expected number of objects to reach mid-course, and if that in turn substantially degrades the mid-course defence's ability to sort objects, the mid-course may let through not only the additional RVs but also many of the ones it would otherwise have intercepted.[5]

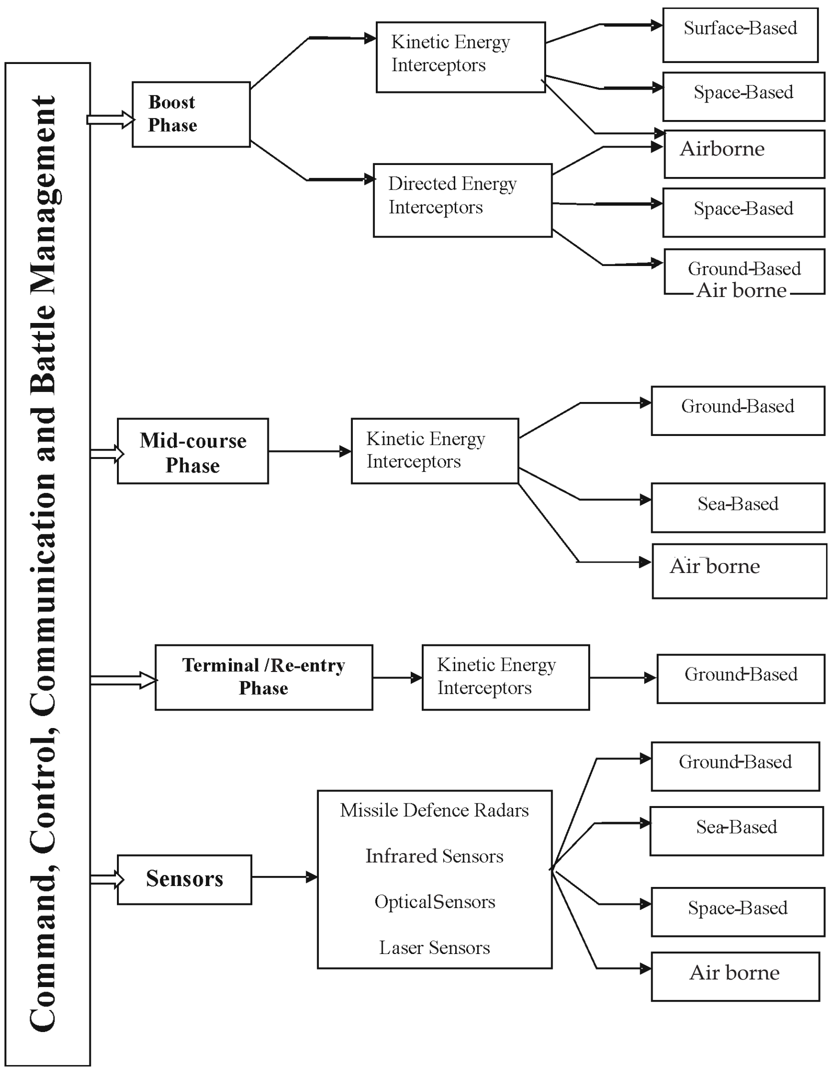
There is a wide variety of technologies which could, in principle be integrated to form a comprehensive ballistic missile defence (BMD) system. Each technology, however, is limited by physical laws. These limitations complicate, but do not eliminate, the possibility of a working system based on that technology. For example, the limitation on the distance travelled in the time available, due to finite velocities (kinetic energy weapons); inability of the energy-delivery device to penetrate the atmosphere effectively (particle beams, X-rays, possibly kinetic energy); the curvature of the earth (pop-up systems). The relevant criteria used to determine the usefulness of the different technologies mostly concern their ability to neutralise targets in a shortest possible time (seconds, at the most).

Sensor and data processing technologies are crucial to an advanced ballistic missile defence system. The chain of operations which each layer must perform as individual tasks are *surveillance* and *acquisition, discrimination*

5. Richard L.Garwin, "Enforcing BMD Against a Determined Adversary?" in Bhupendra Jasani, ed., *Space Weapons and International Security* (SIPRI, Oxford University Press , 1987), pp.73-74.

of actual missiles and warheads from decoys and other debris, *pointing* and *tracking* with precision as required by the weapon designated to destroy that target, *target destruction* and *kill assessment*. In addition, if it can be determined why a targeted warhead was not destroyed (for example, incorrect pointing), the analysis can be used for a subsequent attack.

Fig. 1 Layered Integrated Ballistic Missile Defence Architecture



Kinetic Energy Interception

As early as 1962, the concept of ballistic missile intercept through interceptor rockets was developed which would catch up the attacking missiles and get close enough to kill them by exploding nuclear warheads. By the mid-1980s, small, light, accurate guidance systems made it possible to do away with warheads altogether[6], and to create actual collisions between interceptor rockets and missiles.

Kinetic weapons for targeting objects in space flight i.e. anti-satellite or anti-ballistic missiles, need to attain a high velocity so that they can destroy their target with their released kinetic energy alone.[7] The force of the impact destroys the attacking missile or warhead, renders it inoperable, or diverts it from its intended target without the potential collateral effects of nuclear warhead explosions inherent in earlier BMD systems. Absence of a warhead saves weight and there is no detonation which is required to be precisely timed. This method, however, requires direct contact with the target, which requires a more accurate trajectory because a near-miss has the same effect as a large miss. This places greater demand on the homing guidance system, the amount of fuel required for homing and the required peak acceleration to transfer maximum kinetic energy at the point of impact.

Kinetic weapons for targeting objects in space flight i.e. anti-satellite or anti-ballistic missiles, need to attain a high velocity so that they can destroy their target.

The 'eyes' of a kill vehicle typically include seekers (basically, one or more sensors) that 'acquire' the target and help guide the interceptor to the final impact point. Initially, the KKV must home in on the rocket plume, and then switch to home in on the missile body near the impact point. Seekers may be active or passive. There are passive seekers for a broad portion of the

6. Eric Croddy, James J. Wirtz, *Weapons of Mass Destruction: An Encyclopedia of Worldwide Policy, Technology, and History* (Oxford, UK: ABC-CLIO, 2005), p. 216.
7. Compare the energy of TNT, 4.6 MJ/kg, to the energy of a kinetic kill vehicle with a closing speed of 10 km/s, which is 50 MJ/kg and, hence, explosives are not necessary. i.e. it has about 12 times the energy of a high explosive such as TNT. Anything that gets in the way of the attacking missile—even a plain rock—is likely to destroy it.

Designers could compensate for a system that took longer to commit by producing faster interceptors, or they could make up for slower interceptors by speeding up a system's commit time.

electromagnetic spectrum, including short, medium, and long-wave infrared as well as ultraviolet and visible wavelengths. Active seekers may include conventional radar or laser imagers or rangers.

Exo-atmospheric and endo-atmospheric kill vehicles design and requirements are quite different because the aerodynamic drag and lift forces on an endo-atmospheric kill vehicle will substantially affect its performance. An endo-atmospheric kill vehicle requires a shroud to reduce the aerodynamic drag and a window to protect the infrared sensors from overheating. However, endo-atmospheric kill vehicles have an advantage that they can manoeuvre with aerodynamic lift forces, thus, requiring less fuel for divert manoeuvre.

Boost Phase Interception

The missile boosters are accelerating targets. The time available for intercept, coupled with the distance that an interceptor must travel to reach its target, which results from the geography of a particular scenario, determines the response time and interceptor speed needed for a boost phase interceptor.

A boost phase interceptor engagement can be conceptually divided into two stages. The first is the commit stage, which lasts from when the threat missile is launched until the interceptor is fired. During the commit stage, the system must detect its target, track it, and decide to commit an interceptor to an engagement. The second stage is the fly out stage, which lasts from when the interceptor is launched until it reaches and destroys its target.

Designers could compensate for a system that took longer to commit by producing faster interceptors, or they could make up for slower interceptors by speeding up a system's commit time. Alternatively, the total time available for an intercept might be extended by incorporating the capability to hit a missile in its early-ascent phase.

During the boost phase, however, a ballistic missile's signature comprises both the missile body itself and the large rocket plume. At high altitudes, the plume 'blooms' around the missile—in effect, creating a smokescreen of hot exhaust gas that, depending on the kill vehicle's angle of approach, can obscure the body of the rocket. A kill vehicle must be able to detect and hit the missile within the plume. Light detection and ranging (LIDAR) systems that use a laser to penetrate the plume and locate the missile body have been developed for that application. However, a LIDAR system's potential to improve the probability of hitting the target must be weighed against its disadvantages, which include increased complexity, weight, and costs relative to other alternatives.

Ballistic missiles can manoeuvre during their boost phase, thus, introducing errors in the predicted intercept point.

More importantly, ballistic missiles can manoeuvre during their boost phase, thus, introducing errors in the predicted intercept point. The divert and altitude control system (DACS) is the propulsion package that not only gives the kill vehicle, manoeuvring capability for the intercept but also keeps it balanced and pointing in the right direction.

The characteristics of ballistic missiles against which the defences have to be developed influence the performance of the defensive systems. For example, the type of booster used in an intercontinental ballistic missile (ICBM) is particularly important to designers of boost-phase intercept systems. Solid-fuel ICBMs usually have shorter boost phases than liquid-fuel ICBMs. Thus, a boost phase interception (BPI) system designed to counter solid-fuel ICBMs will need higher performance because its interceptors will have a short time window for intercept. The effectiveness of interceptor rockets would require that interceptors be based in near vicinity of the possible boost-phase flight paths of attacking missiles. In general, because less time is available to reach the target, more BPI sites are needed so that interceptors can have a shorter fly out distance. The size and location of potential threat countries play a role in determining the effectiveness of a BPI system by determining the distance that an interceptor must fly to reach its target.

Similarly, because of the short engagement time, engagement should include two interceptor shots (salvo) to increase the probability of a successful intercept. Some surface-based boost phase interceptors could be based at sea on the navy's surface combat ships, thus, extending the reach of interceptors in the boost phase.

It is widely believed that the best basing mode available is a submarine as it offers a lot of flexibility. It enables positioning of the interceptor missile closer to the enemy's launch site, thus, offering a huge advantage in the boost phase intercept. With submarine basing, one has the advantage of ambiguous presence because the enemy is always uncertain about their location.

The performance of space-based interceptors is less sensitive to geographic factors; however, geography is an important factor in determining the number of space-based interceptors needed in the defensive system. Orbital dynamics requires that the higher the latitude of the country to be covered, the more the interceptors that must be deployed. Space basing provides an advantage of access to any point on earth, including the interiors of very large countries that could never be reached with a surface-based interceptor launched from an adjacent country.

The space-based kinetic energy experiment (KEE) has its origins in the Brilliant Pebbles of the Reagan era. While geostationary orbit is an attractive location for continuous observation and defence, it is too far away from earth (about 35,000 km) to be useful for any practical weapon system. Thus, a space-based system would be a constellation of interceptor satellites located in low-earth orbit at an altitude of about 250 to 300 km. A kill vehicle near the missile launch site would then use its onboard propulsion and sensors to accelerate out of its orbit and home in on the target missile. Satellites in inclined low-earth orbits are not fixed over one spot and instead follow a sinusoidal ground track as they move over the earth. Thus, providing full coverage of a specific threat country requires a constellation of space-based interceptors (SBIs) with their orbits positioned such that at least one SBI is capable of reaching the threat at any given time. At lower orbits, however, satellites would have shorter life spans because of atmospheric drag. The number of space-based interceptors needed to cover a threat country depends on the performance of the system (which determines the coverage area, or footprint, of each satellite) and the latitude of the country. Further, the shorter burn time of solid-fuel ICBMs results in a smaller effective footprint for each space-based interceptor which means that the size of the constellation must increase.

The orbit of these space-based interceptors would be at low altitude and predictable, leaving them vulnerable to attack by inexpensive, short-range missiles.

A 2003 American Physical Society study showed that many hundreds or thousands of space-based interceptors would be required to provide limited global coverage against ballistic missiles and given the technology expected for the next decade, each SBI would weigh a ton or more. As a result, deploying such a system would be hugely expensive.[8]

On the negative side, the orbit of these space-based interceptors would be at low altitude and predictable, leaving them vulnerable to attack by inexpensive, short-range missiles. By eliminating only those few relevant interceptors, an attacker could create a hole in the defence. The defence could also be defeated by simultaneously launching multiple missiles from one location, overwhelming the system. In short, a defence based on deploying hundreds or thousands of space-based interceptors, at enormous cost, could be defeated by a handful of enemy missiles.

Mid-Course Interception

The mid-course phase provides a longer time-frame for interception of the missile or its payload. For an ICBM, this phase may account for as much as 80 percent of the missile's total flight time. Therefore, the mid-course phase allows the longest window of opportunity to intercept an incoming missile. Conversely, a longer intercept window also provides an opportunity to the

8. "The Missile Defence Space Test Bed"<www.ucsusa.org/global_security/space_weapons/space-test-bed.html>

A sea-based system might be more expensive to procure than an equivalent ground-based system.

attacker to deploy counter-measures against the defensive system.

The principal disadvantage of interception during the mid-course phase is that the RVs and decoys would have already been dispensed, increasing by a factor of up to 10 the real number of targets. Approximately, 10 to 100 mid-course decoys can be deployed at the expense of one RV. These decoys travel alongside the RVs and pose an enormous challenge of discrimination of decoys from RVs. Very good decoys travelling on the right trajectory with the right shape, radar signatures and thermal properties take up more space and consume valuable time in discriminating the decoys and also make the other task of battle management (surveillance, tracking and kill assessment) perplexing.

Countries capable of fielding an ICBM would be capable of developing counter-measures and these counter-measures would have a significant impact on the effectiveness of ground-based mid-course defence (GMD). Rather than focussing on making decoys resemble a warhead, they configured the warhead to make it look like a decoy, which would be a simpler prospect. Also, the warhead can be covered in a liquid nitrogen-cooled metal shroud, which will make it more difficult for the interceptor kill vehicle to detect in time to manoeuvre into its path.

A multiple kill vehicle (MKV) [9] launched from interceptor missiles will counter complex ballistic missile threats during their mid-course phase. MKV payloads do not require the BMD system to pinpoint a single lethal object within a threat cluster. Instead of pairing one kill vehicle with one interceptor missile, the MKV payload allows a single interceptor missile to deliver several kill vehicles that can attack multiple threat objects within the threat cluster. This arrangement of MKV dramatically increases the probability of destroying the lethal object within a threat cluster.[10]

9. Missile Defence Agency Factsheet <www.mda.mil/mda.info@mda.mil>
10. "Multiple Kill Vehicle" < www.mda.mil >

Sea-based mid-course interceptor platforms will be intrinsically mobile and highly dispersed, and would offer the opportunity to engage the threat early in its trajectory, possibly as early as in its ascent phase of mid-course cruise, thereby, reducing the susceptibility to counter-measures. Sea-based systems also can be operated in forward (i.e. overseas) locations in international waters, without the need for negotiating basing access and without restrictions from foreign governments on how they might be used.

At reentry, the defence can discriminate the warhead unambiguously and launch interceptors with greater confidence.

Conversely, a sea-based system might be more expensive to procure than an equivalent ground-based system due to the potential need to engineer the sea-based system or fit it into a limited space aboard a ship. Also a sea-based BMD system operating in a forward location might be more vulnerable to enemy attack than a ground-based system, particularly a ground-based system sited in a rear location. Defending a sea-based system against a potential attack would increase the cost of defence by means of additional ships.

An integrated (combined land and sea) architecture could provide more operational flexibility and robustness than architecture that relies solely on sea-based interceptors or on a single land-based interceptor site. This would provide an additional defence layer that can engage the threat ahead of the land-based interceptors, and, thus, provide a multi-tiered defence architecture that has the potential for more robust and more confident protection.

Terminal Phase Interception

The terminal phase provides missile defence systems with a last shot opportunity. During this phase, the warhead, along with decoys or chaff, reenters the atmosphere at an altitude of about 100 km, creating a bright infrared signature. Atmospheric drag then produces dramatically differing behaviour for lighter as compared to heavy objects. Decoys decelerate significantly and burn up, but the warhead does neither. Thus, at reentry, the defence can discriminate the warhead unambiguously and launch interceptors with greater confidence. The terminal phase has many advantages compared to other phases such as the reaction time provided by the early warning is long. Second, both sensors and interceptors can be based within a geographic area, thus, reducing the cost. Third, ranges are short, thus, small, high frequency, hardened or mobile radars can be used for tracking instead of larger radars which are expensive and vulnerable. Finally, the penetration aid problem (counter-measures) is manageable.[11]

However, terminal defence presents severe challenges resulting from the very high speed of the offensive warhead and the very short time in which terminal defence operates. The terminal phase is the last one or two minutes of a ballistic missile's flight. Several counter-measures are available to combat a terminal-phase defence:

- **Speed**: Early reentry vehicle designs used blunt shapes which caused them to decelerate significantly during reentry. Modern reentry vehicles are cone shaped to minimise aerodynamic drag, providing high-speed re-entry. It carries the collateral benefit of reducing the duration of exposure to terminal missile defences.
- **Trajectory and Manoeuvres**: A ballistic missile can follow a lofted trajectory or a depressed trajectory. A lofted trajectory gives less time for engagement, thus, complicating the terminal phase defence. Further, it is possible to design a reentry vehicle that will perform simple but unpredictable and intense manoeuvres upon reentry. This can be done by using a slightly bent nose, a small fin at the rear, or an internal weight that is moved laterally during reentry. In the 1970s, the US developed a manoeuvring reentry vehicle, the Mark 500, for the Trident 1 submarine-launched ballistic missiles (SLBM). Its tests were successful and included 200G manoeuvres that would severely challenge any defence. Manoeuvring reentry vehicles of this type sacrifices some accuracy and payload; however, these are not significant.
- **Ladder Down**: A nuclear warhead exploding in the upper atmosphere would create a cloud of ionised gas that would be opaque to a radar for

11. Milton, et al., n.1, Ch.2, p. 43.

several minutes. One tactic available to the offence would be to use such a precursor explosion to mask a following reentry vehicle. The reentry vehicle would become visible after passing through the cloud, but the time remaining for the defence would be significantly reduced.

DIRECTED ENERGY WEAPONs (DEWs)

The advanced technology has raised the possibility of countering an ICBM attack through the directed-energy weapons, which possess profound lethality and unmatchable key features. Their ability to fire shots at or near the speed of light (186,000 miles a second), which would seem like relatively freezing even high-speed targets in their motion; their ability to engage multiple targets very rapidly; and their very long range (thousands of kilometres in space) are the key features. There are three principal forms of directed-energy weapons: the particle-beam weapons, high power microwave (HPM) weapons and the high-energy laser.

The advanced technology has raised the possibility of countering an ICBM attack through the directed-energy weapons.

By virtue of their cost and unique capability, development of DEWs may provide truly transformational war-fighting capabilities, which may signal a revolution in military hardware; perhaps more so than the ballistic missiles. Some unique characteristics which mark them as potentially revolutionary are:

- First, the speciating facets are speed and distance. There is a clear advantage to propagating lethal energy over militarily significant distances within a blink of an eye. That means many of the problems associated with aiming and firing existing weapons are effectively eliminated, because virtually no time elapses between firing a directed-energy weapon and its impact on the target.
- Second, the cost of discharging such weapons is typically a small fraction of what it costs to fire a missile, because the method of destruction is pure energy. Although directed-energy devices may require a major investment

in weapons technology development and support infrastructure, the price of intercepting a missile or aircraft may be only one or two percent of what conventional munitions would cost. A DEW provides an efficient alternative wherein it costs only a few thousand dollars per shot to achieve equivalent or superior probability of kill. For comparison, procurement costs of the join direct attack munition (JDAM) are US $ 21,000 (tail kit only); for the joint stand-off weapon (JSOW) $ 660,000; for the joint air-to-surface stand-off missile (JASSM) $ 300,000; and for the advanced medium range air-to-air missile (AMRAAM) $ 386,000. Even the basic Maverick can cost $ 152,000. By contrast, the fuel required per shot of the large laser in the airborne laser (ABL), costs approximately $ 10,000. For a 100 kilowatt (KW) solid state laser, the cost of the fuel required to generate electricity for each shot is less than a dollar.[12]

- Third, directed-energy weapons provide war-fighters with surgically precise and discriminate firepower. While indiscriminate damage is certainly within their capability, it is possible to employ directed-energy weapons in ways that generate no collateral damage at all. A related feature of DEW technology is the ability to customise the weapon by adjusting the amount of energy incident upon targets. This allows for a wide range of results: lethal or non-lethal, destructive or disruptive.
- Fourth, directed-energy devices potentially enable war-fighters to rapidly engage many different targets, because of their instantaneous effects and the relative ease of reaiming them.
- Energy beams are essentially immune to gravity which also frees them from the kinematics and aerodynamic constraints that limit more traditional weapons. Hence, the complex calculations required to determine ballistic trajectories and other flight characteristics of conventional munitions are irrelevant to directed-energy devices
- Finally, another feature contributing to their multi-target capability is the

12. Richard J. Dunn, " Operational Implications of Laser Weapons", (Analysis Centre Papers, Northrop Grumman, September, 2005), <http://www.analysiscenter.northropgrumman.com/files/Operational_Implications_of_Laser_Weapons.pdf>

> compactness and low cost of the fuel that drives them. Directed-energy weapons could be based on a variety of platforms, and they come in a wide range of power levels.

While DEWs are technologically revolutionary, their associated requirements will have to develop in a similar fashion. Such weapons also have unique disabilities. The lethal power of their beams may quickly degrade on interaction with the surrounding medium, such as when a laser beam passes through water vapour or dust. In the absence of reflectors, they are strictly line-of-sight weapons. But their weaknesses, like their strengths, contribute that directed-energy weapons are fundamentally different from past technologies of war, and are potentially transformational.

Particle beam weapons work by accelerating a stream of atoms or sub-atomic particles near to the velocity of light and projecting them in a beam. Particle beam weapons can be divided into neutral particle beam weapons and charged particle beam weapons. Both electrons and protons can be used to form this beam, and would be the choice for a weapon to be used within the atmosphere. Hydrogen atoms are the preferred choice for an extra-atmospheric weapon—they have a neutral charge, and, thus, the beam wouldn't be deflected by the earth's magnetic field, or scattered by the mutual repulsion of similar charged particles.

Particle beam weapons increase the kinetic energy of a large number of individual atomic or sub-atomic particles which are propagated at essentially the speed of light and then direct them collectively against a target. Every particle in the beam that strikes the target will transfer a fraction of its kinetic energy to the target material. If enough particles hit the target in a short time, the deposited energy would be sufficient to burn a hole in the skin of the device, detonate the chemical explosives, disrupt the electronics inside or result in damage from the swift temperature increase and possibly an explosion; for example, the effects of a lightning bolt—which is essentially a charged particle beam—and this gives an idea of how destructive such a weapon could be.

However, particle beam weapons are yet to be practical because of the

Since its invention in the early 1960s, the laser has proved to be an extremely useful device not only for the scientific and commercial communities, but also for the military.

huge power requirement i.e. of millions or even billions of watts, in a very short time as a powerful burst, necessary to create destructive pulses.[13] The technology to create such a power source already exists; the problem is in making it small and light enough to be portable. Since the beam is strongly affected by passage through the atmosphere and also due to the earth's magnetic field, precision is questionable in practicality.

High-power microwave (HPM) weapons are also known as radio frequency weapons and ultra-wideband weapons. HPM weapons have been in development in the United States, Russia, and China for decades. An HPM device employs electromagnetic radiation as its weapon effect. Not as powerful as nuclear electromagnetic pulse (EMP) weapons, HPM weapons create a narrower level of microwave electromagnetic radiation as the atmosphere is generally transparent to these frequencies. As a rough point of comparison, HPM systems produce 100-1,000 times the output power of modern electronic warfare (EW) systems[14]. For example, a high-power microwave device can be aimed at an aircraft, immediately upsetting its onboard electronics and sending it into a fatal dive without firing a projectile or even leaving evidence of its use. Such a weapon was successfully field tested by the US in April 2001, and reported to have been deployed during Operation Iraqi Freedom.[15]

The laser is perhaps the most important optical invention in the last several decades. Since its invention in the early 1960s, the laser has proved to be an extremely useful device not only for the scientific and commercial

13. "Neutral Particle Beam" <http://www.fas.org/spp/starwars/program/npb.htm>
14. "Space Operations: Through The Looking Glass," A Research Paper presented to "Air Force 2025 "<http://csat.au.af.mil/2025/volume3/vol3ch14.pdf>
15. Stuart Millar, article published in the *Guardian* on March 19, 2003 < www.guardian.co.uk/profile/stuartmillar>

communities, but also for the military.[16] At first, it was considered to be "a solution without a problem," and today, the laser is at the heart of an extensive array of military applications: range finders, satellite communications systems, remote sensing, target designation, and laser radar-based navigational aids.

The employment of laser-guided munitions in Operation Desert Storm brought new meaning to the idea of "precision engagement," and represents just one example of how the laser has shifted to become "a solution." In fact, numerous countries are now developing their own laser technologies for weapons applications. Since the early 1990s, lasers have demonstrated the capability to produce sufficient energy to merit serious consideration, even by the most ardent sceptics, as potential weapons against the ballistic missile threat. There are four fundamental approaches to high—and medium—power laser energy: chemical lasers, solid-state lasers, fibre lasers, and free electron lasers.[17]

In the case of lasers, intense beams of monochromatic light can be precisely aimed across hundreds or thousands of kilometres to disable a

16. Lasers are extremely flexible weapons, producing effects that cover the full "spectrum of force." At low power, laser beams can be used as battlefield illumination devices, to designate targets from space, blind sensors in the laser's optical band, ignite exposed flammable objects, raise the temperature in localised regions, perform as an emergency high-bandwidth laser communication system, and serve as a laser probe for active remote-sensing systems. At slightly higher powers, the enhanced heating produced by the laser can be used to upset sensitive electronics (temporarily or permanently), damage sensor and antenna arrays, ignite some containerised flammable and explosive materials, and sever exposed power and communications lines. The full power beam can melt or vaporise virtually any target, given enough exposure time. With precise targeting information (accuracy of inches), a full-power beam can successfully attack ground or airborne targets by melting or cracking cockpit canopies, burning through control cables, exploding fuel tanks, melting or burning sensor assemblies and antenna arrays, exploding or melting munitions pods, destroying ground communications and power grids, and melting or burning a large variety of strategic targets (e.g., dams, industrial and defence facilities, and munitions factories)—all in a fraction of a second. <http://csat.au.af.mil/2025/volume3/vol3ch14.pdf>

17. Chemical lasers can achieve continuous wave output with power reaching multi-megawatt levels. Examples of chemical lasers include the chemical oxygen iodine laser (COIL), the hydrogen fluoride (HF) laser, and the deuterium fluoride (DF) laser. Diode-pumped solid-state (DPSS) lasers operate by pumping a solid grain medium (for example, a ruby or a neodymium-doped YAG crystal) with a laser diode. Combining the outputs of many fibre lasers (100 to 10,000) is a possible way to achieve a highly efficient HEL. Free-electron lasers (FELs) use a relativistic electron beam (e-beam) as the lasing medium. Generating the e-beam energy requires the creation of an e-beam (typically in a vacuum) and an e-beam accelerator. This accelerated e-beam is then injected into a periodic, transverse magnetic field (undulator). By synchronising the e-beam/electromagnetic field wavelengths, an amplified electromagnetic output wave is created.

Multi-megawatt class lasers (much larger than any system under development today) would be required to defeat the faster and much harder targets.

wide range of targets, from missiles to satellites to aircraft to ground vehicles and even people. They can also be reflected off mirrors in space to hit targets not visible from their source while retaining much of their initial fluence. These special features make it possible to focus the laser energy with mirrors into narrow beams characterised by small divergence angles. Thus, a laser with 1 micrometre (=1 micron) wavelength projected with a 1 metre mirror could have at best a 1.2 micro radian divergence angle, making a spot 1.2 metres wide at a range of 1,000 km. A 10 metre mirror with a hydrogen fluoride (HF) laser beam would yield a 0.32 micro radian divergence angle and create a laser spot 1.3 metres in diameter at a range of 4,000 metres. The distribution of 20 megwatts (MW) over the laser spot would create an energy flux of 1.5 kilowatts per square centimetre (KW/cm^2). The laser spot would need to dwell on the target for 6.6 seconds to create the nominal lethal energy of 10 kilojoules per square centimetre (kJ/cm^2). At a range of 2,000 metres, the destruction of the booster would require 1.7 seconds of illumination. This perfect performance is called the diffraction limit[18].

Laser light can damage boosters in two distinct ways. With moderate intensities and relatively long dwell times, the laser simply burns through the missile skin and is called thermal kill. The second mechanism requires very high intensities but only one short pulse, the high intensity causes an explosion on and near the missile skin, and the shock from the explosion injures the booster. This mechanism, called impulse kill, is more complex than thermal kill.[19]

DEW systems can be land-based, sea-based, or space-based. Since lasers can theoretically defeat artillery and missile attacks, any group fielding an effective laser system will gain decisive advantages in ground, air and

18. Matthew Mowthorpe, "The Revolution in Military Affairs and Directed Energy Weapons," *Air & Space Power Chronicles*, March 8,2002 < www.iwar.org.uk>

19. Stephen D. Rockwood, "Technical Issues for Strategic Defence Research," in Jasani, ed., n.5, pp.63-65.

space combat. Under radar control, lasers have shot artillery shells in flight, including mortar rounds. [20]

Ground-Based Directed Energy Weapon

Ground-based lasers are well suited to terminal point defence of critical targets. These lasers can fire tens of shots against offensive missiles very quickly, making them difficult to overwhelm. The chemicals consumed per shot cost much less than the millions of dollars for defensive missiles. Thus, even taking into account the initial cost of the laser weapons, laser-based BMD may prove to be a highly effective and more affordable means of adding an additional layer of defence against theatre ballistic missile (TBM) attack.

They can complement missile defence against longer range missiles. Megawatt-class chemical lasers could defeat a TMB. Multi-megawatt class lasers (much larger than any system under development today) would be required to defeat the faster and much harder targets. In both cases, the effectiveness of a laser defence would depend on developing systems concepts that overcome the potential effects of clouds, fog or dust storms. For example, aircraft basing would allow the laser weapon to operate above these weather effects.

The ground-based laser architecture may consist of multiple ground stations with high-energy lasers placed in different regions of the country. Lasers are not all-weather systems. Clouds absorb and scatter laser light, removing power from the beam and distorting the beam's 'footprint'. Thus, the ground-based lasers systems must be located in regions that have good weather all year round.

Each of the ground systems would include a high-energy laser, beam director, adaptive optics[21], acquisition and tracking systems, and related

20. India Daily, "The Race for Developing Deadly Solid-State Laser Weapons that can Change the Future battlefield," March 10, 2005, < http://www.indiadaily.com/editorial>

21. Adaptive optics techniques such as the Guide Star System have been developed to correct atmospheric distortions to low-power laser beams projected from earth to space and back again. Adaptive optics systems developed to date depend primarily on deformable mirrors—mirrors with small actuators that change the mirror's shape to pre-compensate the beam and correct anticipated or pre-measured distortions. Further advances will be required in this technology, both in terms of bandwidth and number/size of actuators, to make this technology work for weapons class lasers. < "Space Operations: Through The Looking Glass",http://csat.au.af.mil/2025/volume3/vol3ch14.pdf>

support systems. The laser beam is transmitted through the atmosphere to a constellation of mirrors in space. Changes in the altitude of the space mirrors will affect the diameter required for the beam director's primary mirror, relay mirrors, and mission mirrors, and as well as the number of space mirrors. A total of four relay mirrors in geosynchronous orbit would provide the necessary worldwide coverage. One of these mirrors would be positioned as close as possible to the zenith of the ground lasers to minimise atmospheric effects.[22]

Space-Based Directed Energy Weapon

For the boost phase intercept, the Strategic Defence Initiative Organisation (SDIO) proposed several hundred satellites armed with powerful (>100MW) lasers. Microwave and particle beams were also considered but lasers remain the more developed technology. Space-based lasers (SBLs) can be located on satellites placed in low-earth orbit. The satellite needs to be at an altitude sufficient to enable it to intercept the farthest boosting missile it can see.[23]

In the late 1990s, SBL planning was based on a 20-satellite constellation, operating at a 40° inclination, intended to provide the optimum tactical missile defence (TMD) threat negation capability. At this degree of deployment, kill times per missile will range from 1 to 10 seconds, depending on the range from the missile. Retargeting times are calculated at as low as 0.5 seconds for new targets requiring small angle changes. It was estimated that a constellation consisting of only 12 satellites can negate 94 percent of all missile threats in most theatre threat scenarios. Thus, a system consisting of 20 satellites is expected to provide nearly full threat negation.[24]

22. Lt Col William H. Possel, USAF, "Lasers and Missile Defence: New Concepts for Space-based and Ground-based Laser Weapons," *Occasional Paper,* No. 5 Centre for Strategy and Technology Air War College, July 1998.< http://www.fas.org/spp/starwars/program/docs/occppr05.htm>

23. Matthew Mowthorpe, "The Revolution in Military Affairs and Directed Energy Weapons," *Air & Space Power Chronicles*, March 8,2002 < www.iwar.org.uk>

24. "Space-Based Laser" [SBL] < http://www.globalsecurity.org/space/systems/sbl.htm>

AIR-BASED MISSILE DEFENCE

Ballistic missile defence components can also be mounted in or on aircraft. Sensors can be interconnected into the missile defence network and aircraft can carry the means of intercepting ballistic missiles, particularly early in their flight, while their rockets are still burning. The means of intercept can employ either directed energy (lasers) or kinetic energy.

The airborne laser (ABL) is the avant-garde of a revolution. While the phrase "revolution in military affairs" is overused, the emergence of systems utilising directed energy for tangible war-fighting applications is worth noting. Efforts during the 1970s provided that it was possible for an airborne laser to intercept aerial targets and confirmed that lasers had weapon potential. Iraq's use of the Scud missile as a terror weapon during the Gulf War exposed a potential mission. This led the United States Air Force (USAF) to propose an ABL weapon system that would be capable of locating, tracking, and destroying such missiles in their boost phase. A 747 aircraft, an advanced detection and tracking system, adaptive optics, and a revolutionary high-energy laser, are all being integrated into a single weapon system for the first time.

The ABL is among the first generation of deployable directed energy weapons with potential to present the US not only a new capability to destroy ballistic missiles, but, more importantly, a foundation of an entirely new defence architecture. The ABL is also being evaluated for its suitability to perform other adjunct missions. These include cruise missile defence (CMD), intelligence, surveillance and reconnaissance (ISR) and protection of high value airborne assets (PHVAA).

Under cloud-free line-of-sight conditions the ABL's infrared surveillance system can detect both aircraft and TBM, and acceleration and altitude will permit discrimination among target types. However, identifying them as positive hostile targets will require off-board confirmation such as airborne warning and control system (AWACS) warning. The ABL can destroy aircraft before they penetrate close enough to fire their air-to-air missiles. Cruise missiles, though similar to aircraft, are more difficult targets, particularly those flying low-level profiles. Detecting and identifying cruise missiles as hostile will be the ABL's most challenging target and probably require off-board help. Flying low to avoid the ABL's high energy laser (HEL) will shorten the ABL's effective range. Obviously, this capability has gaps that can only be filled by the traditional weapon, the fighter, and its long-range eyes, the AWACS.

BALLISTIC MISSILE DEFENCE SENSORS (BMDS)

BMD sensors detect, identify, track and assess the missile launch and generate accurate targeting coordinates and stimulate a target shootdown. New and innovative approaches to these requirements are being developed which include not only detecting and tracking of targets but also discriminating targets from decoys and debris.

For a layered BMDS, multiple sensors, with the different characteristics, are essential. This would provide information using network-centric ability by gathering data from various land-based, airborne, sea-based and space-based sensors. Multiple sensors will not only provide redundancy but also utilise important characteristics of various sensor systems like radar, infrared sensors, optical sensors or laser detection sensors. For example, the boost phase detection is ideal for an infrared seeker whereas during the mid-course phase, RVs emit little energy and detection would be difficult by infrared sensor but would be a better target for a radar sensor system.

The resolution and accuracy of the sensor system are also worked out as per the weapon system being used for interception. For a DEW system, the resolution required is of a few centimetres so as to keep the laser focussed on one spot. The KEI system would require less accurate information from a remote sensor because a homing sensor onboard an interceptor would give the fine resolution needed in the last few seconds to approach and collide with the target.

For a layered BMDS, multiple sensors, with the different characteristics are essential.

Resolution improves with reduction in distance to the target. Therefore, a sensor satellite placed in geostationary orbit at 36,000 km surveys the entire earth but the resolution will not be of practical value. Even a constellation of satellites at altitudes around of 4,000 km would not be adequate for DEWs. Further, the vibration and jitters would preclude the transmission of target position to the weapon platform with 10 cm accuracy. Therefore, each DEW would need its own sensor to provide final pointing accuracy.

Kill assessment is an important factor for sensors. Missed targets have to be retargeted and disabled targets should be ignored.

Kill assessment is an important factor for sensors. Missed targets have to be retargeted and disabled targets should be ignored. Though KEI weapons' kill assessment is mostly simple and straightforward, in the case of partial damage of a booster, leaving the missile intact, it will be a precarious situation as the kill assessment would be affirmative.

In the case of DEW, assessment of damage of the target is a difficult process. A laser or a neutral particle beam might burn through the critical component without detectable damage and divert the missile from its intended course.

For surface-based radars, BMDS relies on fixed and transportable radar. These radars include X-band radars in the form of the sea-based X-band (SBX) radar. An X-band (wavelength 2.5-4 cm; frequency 8-12 GHz) radar can search, detect, and track missiles, and distinguish between warheads and counter-measures. The SBX radar is built upon a movable sea platform that will improve the ability to acquire, track, and discriminate counter-measures during the mid-course phase of flight. The ground-based mid-course defence system also includes the upgraded early warning radar (UEWR) and the L-Band (Cobra Dane) radar. These radars provide long-range missile surveillance, acquisition and tracking, and object classifications, as well as update information for the BMDS exo-atmospheric kill vehicles.

Space sensors fulfill five functions in supporting the BMDS. First, 'situational awareness;' second, sensors send a wake-up call—'the early warning'; third, 'sensor-to-sensor cueing,' which allows a sensor with a threat missile in track to pass pertinent information on that missile to another sensor; the fourth and fifth functions are 'launch' and 'engage'. Sensor accuracy, timing, information latency, coverage, and availability are all system attributes that determine if a possible sensor system is capable of supporting these five functions. For example, highly accurate information that is too late or timely information that is inaccurate can negatively affect the execution of the BMDS mission. This balancing act between accuracy and timeliness is one of the major design traits that dominates the sensor capability analysis. The space sensor assets that can most readily be incorporated into BMDS are overhead non-imaging infrared assets. Future systems with advanced radar technologies to improve system robustness, reduce cost, and enhance radar performance parameters for all-weather missile tracking are under development.

The enemy can try to degrade the BMDS performance in several ways. Reduction of observables of RV i.e. stealth, by the shape of the RVs such that it gives minimum radar signatures, using either super lofted or super depressed trajectories so as to avoid the search volume, etc. However, such tactics are relatively easily countered by expanding the sensor search volume. Infrared sensors can be degraded either by reducing the signal originating from the target (cooling the target) or by increasing the competing signal coming from the background.[25]

COMMAND, CONTROL, BATTLE MANAGEMENT AND COMMUNICATIONS (C2BMC)

The C2BMC programme is a key enabler for implementation of the missile defence system in all three phases of flight. Responding to ballistic missile threats presents an unprecedented challenge of speed, precision, and coordination among numerous weapon systems, sensors, and war-fighters. Decision cycles are reduced to minutes, and, in some cases, seconds, during which air, ground, sea, and space sensor-interceptor-communications elements must be orchestrated into engagement scenarios that seamlessly detect, track, target, and engage incoming missiles. Unlike the other elements, this is not primarily a hardware issue, but rather a software development challenge. The C2BMC element is the critical tool that links the various individual sensor-interceptor-communications elements into one coordinated system utilising

25. Stephen Weiner, "System and Technology," in Ashton B. Carter, David N. Schwartz, ed., *Ballistic Missile Defense* (Washington, DC: 1984), Ch.3. pp.49-59.

the best offensive/defensive attributes of each element, ensuring the highest BMDS capability for protection against all types of ballistic missile threats in any phase of flight. C2BMC can be thought of as 'middleware' linking decision-makers, weapons, and sensors together in a networked environment.

C2BMC is an evolutionary concept that integrates modelling and simulation, deliberate planning and analysis algorithms together in a time constrained manner to 'propose' solutions and engagement sequences to the decision-makers. It is a method of data processing and comprehensive algorithms that describes, organises and provides prioritisation to a multitude of variables—most of which change rapidly in an operational situation.

C2BMC ***Functional Attributes***

C2BMC must be able to see, understand, analyse and prioritise the threats and it must do so in compressed timelines commensurate with the nature of the threat. Once C2BMC validates the threat, it begins to formulate the BMDS response.C2BMC has the following functions:[26]

- Planning capability to optimally locate sensors and weapon systems to counter identified threats.
- Situational awareness of the evolving battle and status of defensive assets at all leadership levels. Situation awareness tools and intelligence updates will provide indications and warning to allow decision-makers to move the BMDS to higher states of alert when necessary.
- Networking and integration of sensors, weapon systems, and war-fighters.
- Provision of automated, real-time, multi-source information to project a single, near real-time command and control (C2) picture to allow commanders to quickly assess missile threats and execute coordinated, immediate responses.
- Missile detection and battle management to optimally pair sensors and shooters for effective and efficient BMDS asset utilisation and engagement of multiple threats for the highest probability of kill.

26. <http://www.lockheedmartin.com/products/c2bmc/index.html>

One of the problems is that there are numerous ways that offence can attack, thus, making it impossible to achieve the desired confidence in the defensive system.

- Efficiently manage and distribute essential data in support of advanced strategic planning and supporting military echelons 24x7. Additionally, C2BMC must perform the above activities for each threat and continuously iterate them when new information is received and assessments made

Peace-time activities include the day-to-day operations of the system, including planning updates, training, maintenance, asset management, logistics and data base updates, including intelligence. These updates, to the greatest extent possible, should be automated.

Engagement control (EC) incorporates the traditional capabilities of command, control and battle management, and recognises the evolutionary and transformational capabilities that are different from traditional C2BM but are required for successful C2BMC. Engagement control will use and support two distinct C2 paradigms: traditional C2 requiring approval before continuance, and management by exception (MBE). Traditional C2 is the accepted human-in-control paradigm where the human makes the key decisions regarding execution plans, weapons engagements and re-tasking. MBE, on the other hand, represents the C2BMC computers, prosecuting the engagement by proposing and executing all necessary products and decisions automatically. In MBE, the human operator will review the proposed plans and engagement sequences and has to manually stop the C2BMC process to make changes.

Additionally, the C2BMC capability must have the adaptability to take inputs from the combat commander regarding changes to defended assets and changes to priorities, and automatically cascade these changes through the situational awareness and planning tools.

The communications capability required for C2BMC must necessarily be robust, interoperable, collaborative, and provide connectivity to the entire community of interest. It will be net-centric and allow for common access to

BMDS data sets and databases. It will provide connectivity across operational echelons and geographic locations. C2BMC communications are a foundational element and key enabler for all the other C2BMC key capabilities.

The attributes of an effective communication system would include:

- Adequate band width and range.
- Reliability.
- Tolerance of component damage.
- Security from interception or take-over.
- Tolerance of nuclear effects.
- Jamming or spoof resistance.

OPERATIONAL IMPERATIVES

With the ever progressing technologies, many innovative systems and approaches to missile defence will evolve. So is the case with the offensive missile technologies which are improving consistently in range, accuracy and lethality. This offence-defence challenge is the key factor to analyse the requirement of a comprehensive missile defence system. For a country to appropriate a missile defence system, the decision has to rest on serious assessment in terms of its effectiveness against offensive missiles capabilities and counter-measures, its survivability, its affordability not only for acquisition but also for operation as well as maintenance and also its completeness to provide a comprehensive defence with known and trusted limitations.

Testing of missile defence systems is especially difficult. The basic reliability of individual components can be ascertained but for the system as a whole, is a challenging task. One of the problems is that there are numerous ways that offence can attack, thus, making it impossible to achieve the desired confidence in the defensive system. Simulation may provide a near realistic picture but estimation of leakage is the challenge. Similarly, simulation of counter-measures may not be realistic and, thus, correct assessment of defensive effectiveness may

Preemptive attack against the components of the defence is most likely and one of the most deadly counter-offensive actions.

A well integrated, layered, defensive system using different technologies and basing methods depending on geography, threat perception, envisaged capability and cost analysis is the only answer.

not be valid in the actual scenario.

The survivability of a defensive system can be challenged through many means. For example, the defensive system can fall apart if its sensors have been nullified or destroyed. Preemptive attack against the components of the defence is most likely and one of the most deadly counter-offensive actions. Blinding the satellite sensors can be achieved with a laser based on a high altitude aircraft. The simplest form of counter-defence attack can come from an anti-satellite (ASAT) interceptor launched from the ground. Measures like hardening, manoeuvrability, self-defence and redundancy could be used to protect the defensive system against ASAT systems.

Completeness of a missile defence system can be said to be achieved if it can address the vulnerability to attacks not only from ballistic missiles but also from other weapons such as cruise missiles, bombers or unmanned aerial vehicles (UAVs). For this, BMD must also support the conventional air defences while integrating each other's assets.

Notwithstanding the limitations and vulnerabilities, ballistic missile defence, even with imperfect defence, can drastically alter the calculus of military planning of the adversary by introducing an extra element of uncertainty and raising the cost of destroying important military targets. A partial defence may also be able to reduce casualties, particularly in the event of limited attacks. Thus, even partially effective defence would strengthen deterrence by reducing the confidence of the adversary that the attacks would not achieve their objectives.

SUMMARY

As discussed in the preceding paragraphs, missile defence is a 'system-of-systems' comprising various technologies and concepts. The distributed nature of the system-of-systems described above can be its greatest strength or its greatest weakness. The system-of-systems must be designed carefully to minimise or eliminate all critical nodes. Critical nodes that cannot be eliminated must be protected by deception, added defences (hardening, placement within a secure environment), or redundancy.

Such capability acquisition by a country must be based on various important attributes such as timeliness, responsiveness, precision, survivability, reliability, selective lethality and cost. Various methods of basing of weapon systems, i.e. ground-based, sea-based or space-based systems, all have their inherent unique advantages and limitations. (For example, space strike weapons are currently not possible without reliable and affordable access to space.)

As we carefully study the characteristics and capabilities of various candidate weapon systems, it becomes evident that there is no 'super weapon system' that can provide complete defence. A well integrated, layered, defensive system using different technologies and basing methods depending on geography, threat perception, envisaged capability and cost analysis is the only answer.

The overall architecture should have the desired flexibility and adaptability of integrating future advance technologies, [for example, airborne weapon system, transatmospheric reusable aerial vehicle (TAV), etc.], new offence tactics and new offensive weapon counter-capabilities.