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A2/AD and the missile threat

— systems, countermeasures and models

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Summary

In this report we discuss the (relatively) novel military term A2/AD, which is an acronym for Anti-Access/Area Denial. We cover both general aspects related to how the term should be understood, Russian A2/AD capabilities in terms of long range precision missiles, and measures for defending against such capabilities.

A2/AD can be understood both as a capability and as a strategy, ranging in both cases from a weaker (AD) to a more encompassing (A2) version. An AD strategy is a strategy of denial, utilizing attrition and suppression in order to end the war by showing the enemy that the cost of winning is too great. On the other hand, an A2 strategy aims at maintaining complete control over an area, by denying all access to the enemy.

A2/AD capabilities may be used to suppress or deny enemy access within these strategies. Clearly, almost any offensive or defensive capability can thus be referred to as an A2/AD capability. However, the introduction of the term A2/AD is strongly connected with certain novel technologies, particularly long range precision missiles (LPVs), and in the remainder of the report we focus on these.

Russia has a plethora of different long range missile systems of various ages, some of which are of the modern high precision type. Particularly famous are the Iskander-M short range ballistic missile, the Kalibr land attack and anti-ship cruise missiles, and the S-400 air defence system. Other new developments are the Bastion-P coastal defence system, the Kinzhal air launched ballistic missile, the Kh-101 air launched cruise missile and the 9M729 land based cruise missile, which allegedly caused the dissolution of the INF treaty. These must be considered in combination with a considerable amount of shorter range rocket artilleries, a large number of older cruise missiles with ranges measured in thousands of km, and several older air defence systems. All in all this adds up to a considerable long range fire power, which may be utilized if Russia were to establish an A2/AD zone.

There are multiple measures for defending against long range precision missiles. In addition to more offensive measures, attacking launch platforms, C3 networks or sensors, we describe in this report several defensive measures. These consist of physical protection, air defences, concealment, deceptive measures, manoeuvring, dispersal and damage mitigation. We discuss these in the context of defending airborne, naval and land based units as well as stationary infrastructure.

In the final section of the report we develop a simple quantitative model for evaluating defensive measures. The model is not primarily intended as a predictive model, but as an illustration of the individual and cumulative effects of different defensive measures. We make an assessment of our model in four example cases: defence of radar stations, patrol aircraft, manoeuvring army units and operational headquarters. Among these the model is best suited for the first case, where it may even be of some use for prioritizing between different measures.

Sammendrag

I denne rapporten diskuteres det relativt nye forsvarsbegrepet A2/AD, som er en forkortelse for Anti-Access/Area Denial. Rapporten dekker både generelle aspekter knyttet til hvordan begrepet bør forstås, russiske A2/AD-kapabiliteter i form av langtrekkende presisjonsvåpen, og tiltak for forsvar mot slike våpen.

A2/AD kan forstås både som en kapabilitet og som en strategi, og strekker seg i begge tilfeller fra en svakere (AD) til en sterkere variant (A2). En AD-strategi bør forstås som en nektelsesstrategi, der gradvis nedbrytning og undertrykkelse benyttes for å vise fienden at kostnaden ved seier er for stor. En A2-strategi tar på den andre siden sikte på å skaffe total kontroll over et område ved å nekte fienden all adgang.

A2/AD-kapabiliteter er de kapabilitetene som benyttes innenfor disse strategiene, henholdsvis til undertrykkelse og nektelse. Dette innebærer naturlig nok at nesten enhver offensiv eller defensiv militær kapabilitet kan dekkes av begrepet A2/AD. Likevel er innføringen av begrepet sterkt knyttet til visse moderne teknologier, og særlig til såkalte langtrekkende presisjonsvåpen (LPV-er). Hoveddelen av rapporten fokuserer derfor på disse.

Russland har svært mange langdistansemissilsystemer med ulik alder, hvorav mange er av den moderne høypresisjonstypen. Særlig omtalte er det ballistiske missilet Iskander-M, krysser-missilene i Kalibr-familien og luftvernsystemet S-400. Blant slike moderne systemer hører også kystvernsystemet Bastion-P, de luftbårne missilene Kh-101 og Kinzhal, og det landbaserte kryssermissilet 9M729, som visstnok var utløsende årsak til oppløsningen av INF-avtalen. Disse må vurderes sammen med et stort antall rakettartillerier, eldre kryssermissiler med rekkevidder målt i tusener av km, og en hel del eldre luftvernsystemer. Alt i alt utgjør dette en betraktelig ildkraft av langdistansevåpen som vil kunne utnyttes av Russland til å sette opp en A2/AD-sone.

Det finnes mange tiltak som kan benyttes for å forsvare seg mot langdistansevåpen. I tillegg til offensive fremgangsmåter som angrep mot utskytningsplattformer, C3-nettverk eller sensorer, beskriver denne rapporten en rekke mer defensive tiltak. Blant disse er fysisk beskyttelse, luft-vern, skjuletiltak, narretiltak, manøvrering, spredning og skadebegrensning. Disse tiltakene diskuteres i kontekstene forsvar av fly, skip, landenheter og stasjonær infrastruktur.

I siste del av rapporten utvikles en enkel kvantitativ modell for evaluering av forsvarstiltak. Den er ikke primært ment som en prediktiv modell, men som en illustrasjon av de individuelle og kumulative effektene av forskjellige forsvarstiltak. Vi vurderer modellens egnethet i fire eksempeltilfeller: forsvar av radarstasjoner, patruljefly, manøvrerende hærenheter og et operasjonelt hovedkvarter. Modellen er best tilpasset det første tilfellet, hvor den til og med kan ha en viss nytte for prioritering av ulike tiltak.

Contents

1 Introduction

This report is funded by FFI-project 1552 Operational analysis support. Its topic is Anti-Access/Area Denial (A2/AD), which is a much used term in recent defence analysis literature. While a more thorough description is provided later in the report, briefly stated A2/AD has to do with efforts to deny deployment and suppress operations of opposing forces within a region. Originating among researchers studying Chinese military developments, the term is now increasingly also being applied to Russia.

For Norway, there are three issues related to A2/AD which should be of particular interest. The first is that Norway may itself use A2/AD as a defence strategy. The second is that Norway may be involved in offensive operations against nations employing A2/AD, as part of alliance obligations. The third possibility is that some neighbouring states may create an A2/AD zone covering parts of Norwegian territory, thereby infringing upon Norway's operational freedom and national sovereignty. Some parts of this report may be of use also to discussions of the two first issues, but the third is its main topic.

The purpose of this report is threefold. First we wish to give the reader an understanding of what A2/AD is, and how the term should be understood. This is covered in Section 2. The second purpose is to provide an overview of Russian A2/AD capabilities. This is because, in the current geopolitical situation, Russia is the one of Norway's neighbours which is most likely to assert an A2/AD zone extending into Norwegian territory. Such Russian capabilities are covered in Section 3. As explained in Section 2, there are multiple capabilities and systems which may contribute to A2/AD, but our overview in Section 3 is limited to that of long range precision missiles.

The third purpose of the report is to discuss options for countermeasures against A2/AD capabilities. An overview of such measures is given in Section 4. In Section 5 we introduce models that are useful for understanding and thinking about these measures. We introduce both a qualitative model and a simple quantitative model. The quantitative model estimates the additional cost that countermeasures impose upon an attacker. It is still primarily intended as an illustrative model, but may give useful order of magnitude estimates, and thus also help operational and long term planners to systematically consider options within their scope.

Finally, a summary of our most important conclusions related to these three purposes, can be found in Section 6.

2 Definitions and general considerations

2.1 What is A2/AD?

Over the last decade, the term A2/AD has been frequently employed in the defence analysis literature, first in relation to developments in the Chinese military [1] [2], and more recently also to Russia [3] [4] [5]. Nevertheless, getting a clear understanding of what the term actually means is not all that easy. Some analysts employ it as though it refers to a particular strategy or an operational concept [6] [7]. Others use it as though it refers to military capabilities, or to systems delivering such capabilities [3]. Others again seem to use the term interchangeably in both fashions without ever making a clear distinction [2], and finally some seem to use it mainly as a buzzword without any particular meaning at all.

Although it has been suggested that any attempt to define the A2/AD term more concretely could end up being counterproductive [8], it is our view that analysis is best done with as clear and concise understanding of the involved concepts as possible. In particular, the lack of clarity in distinguishing between A2/AD as a strategy and A2/AD as a capability seems to create unproductive discussions. Indeed, attempts at examining the A2/AD capabilities of Russia are sometimes met by critique claiming that Russia does not actually have an A2/AD strategy [6]. This may or may not be true, depending on what precisely is meant by such as strategy, but it is in any case not all that relevant to an analysis of capabilities.

In view of this, our approach here will be to explicitly make this distinction, and to attempt to give both applications a concrete and precise definition. Some attempts at making this distinction more clear have already been made in the literature [9].

2.2 Definition of A2/AD as a capability

The most clear cut definition of A2/AD as a capability seems to be provided in FOI's work Bursting the Bubble [3], and accordingly we will follow their line in defining the involved terms. Below, the term "region" may refer to a geographic region spanning the physical domains, or to a virtual region in a virtual domain. Further, whatever the type of region, it is assumed to be of strategic consequence. In the case of geographic regions, this usually means it must be of a certain size, typically what is referred to as a "theatre".

2.2.1 Definition of Anti-Access (A2)

Anti-Access (A2) capabilities refers to a military capability to deny opponents access to a particular region [3]. The denial of access may be limited to a subset of the opponents' systems.

2.2.2 Definition of Area Denial (AD)

Area Denial (AD) capabilities refers to a military capability to suppress or endanger the presence and operations of opponents within a particular region [3]. The suppression/ endangerment may be limited to a subset of the opponents' systems.

2.2.3 Definition of A2/AD

A2/AD is a collective term for A2 and AD, and as such A2/AD capabilities refers to a military capability to either deny opponents access to a region, *or* suppress or endanger their presence and operations within the same region [3]. An A2/AD capability may be limited to a subset of the opponents' systems.

2.2.4 A2 vs AD

Clearly, there will often be a fluid line between A2 and AD. Exceptions to this occur when defences are only in effect near the border of the specified region, so that they become ineffective once the opponents break through to the interior. These systems would then only provide A2, not AD. But when defence systems are instead effective throughout the specified region, the distinction between A2 and AD depends on the effectiveness of the system [3]. In order to provide Anti Access, a defence system must be so effective that it guarantees complete incapacitation of opposing forces once they move into the region, or at least makes incapacitation so likely that the risk associated with moving into the region becomes unacceptable. If the system is less effective, there may still be considerable risk or inconvenience associated with operating in the region, and in that case the defence system provides Area Denial.

2.2.5 Other definitions

In view of the above definitions, we can define A2 and AD systems respectively as systems delivering A2 and AD capabilities, and A2/AD systems as a collective term for these. Similarly, we define A2 and AD zones respectively as regions wherein A2 and AD capabilities are applied, and an A2/AD zone (or A2/AD bubble) as a collective term for A2 and AD zones.

2.3 Definition of A2/AD as a strategy

A very reasonable interpretation of A2/AD as a strategy is suggested by Sam Tangredi, who claims A2/AD is just a new term for what used to be called a strategy of denial, or deterrence by denial [7] [10]. Such a strategy is employed by a weaker part against a stronger, but distant, opponent, and has been applied in numerous conflicts throughout history, ranging from the Persian invasion of ancient Greece to the American invasion of the Japanese empire in WW2. According to Tangredi, the distinguishing feature of such strategies is the utilization of a geographical advantage to complicate both the employment and the sustainment of enemy forces in a region. The goal of such a strategy is to drag the conflict out, deny the opponent any opportunity at a decisive engagement, and to cause him so much attrition and expenditure that he eventually judges the inevitable victory to just not be worth the effort.

An advantage of this understanding of A2/AD is that it is considerably more general, and thus more applicable than the perhaps implicit alternative understanding where an A2/AD strategy is intimately connected with the application of specific modern technologies (parodied by the term "angry red circles on a map" [6]). However, in order to maintain a certain symmetry with the above definitions of A2/AD as capabilities, it is perhaps natural here also to distinguish between A2 and AD. In that case, it seems that Tangredi's conception should be denoted as an AD strategy, since it is intimately connected with AD-capabilities, without really requiring the stronger A2-capabilities. Thus, with some risk of introducing a third pope, we propose the following definitions:

2.3.1 Definition of Area Denial (AD) strategies

An Area Denial (AD) strategy is a strategy of war where the employment, sustainment and operations of opposing forces within the region of conflict are continuously being challenged and endangered. The ultimate goal of the strategy is to cause so much attrition and expenditure that the opponent can no longer justify the war effort. As such it is also a goal to stretch the conflict out in time, and accordingly to avoid decisive engagements.

2.3.2 Definition of Anti-Access (A2) strategies

An Anti-Access strategy is a strategy where the aim is to deny the opponent all opportunities to employ forces in, or attack the region of conflict, for the entire duration of war. Thus, successful application of an A2 strategy requires sustainable A2 capabilities across all domains and against all enemy systems able to enter the region. In order for this effort to be sustainable, the defenders systems must be kept safe within the A2 zone.

2.3.3 Definition of A2/AD strategies

An A2/AD strategy is a flexible strategy of war where the choice between A2 and AD is modified according to what currently seems possible. Thus, a defender may pursue an A2 strategy against a weak attacker, but turn this into an AD strategy when facing a stronger opponent. Further, if initial attempts at A2 seem to be failing, ambitions can be lowered to an AD strategy, and vice versa, if AD capabilities turn out more effective than expected, ambitions can be raised to the pursuit of A2.

2.3.4 Are A2-strategies possible?

While Tangredi gives several historical examples of the application of what we above have defined as AD strategies [7], the reader might legitimately wonder whether there are any real examples of the application of an A2 strategy. Clearly, the success of such a strategy requires a very strong advantage of defensive relative to offensive measures. While there has generally throughout history been some advantage to the defender, this has usually not been large enough for a pure A2 strategy of the type described above to be realistic. One exception to this might be the period just preceding and including WW1, where the technological balance was leaning particularly heavily in favour of defence. If that particular state of affairs had remained, it might have been possible for highly self-sufficient nations to rely on A2 strategies for their defence. Today, the general opinion seems to be that the technological balance has shifted to the opposite side, and now strongly favours the attacker. This would mean A2 strategies can only be successfully applied by defenders having a decisive technological advantage over their opponents. Thus, Israel's defence against missile attacks could be seen as a modern example of an A2 strategy, admittedly with some strain of the definition.

Also, a particularly strong geographic advantage could potentially have enough impact to change this balance. For instance, in a conflict between the US and China the defender would have a huge advantage in that the attacker must transport his forces across the enormous distances of the pacific. Potentially, this could be enough to compensate for the current technological advantages of offensive operations, and allow an A2 strategy to be successful even against a peer opponent.

2.3.5 Comparison to denial and control

The older terms of Control and Denial [11] are related to A2 and AD as defined above, but are not in perfect correspondence with these. In particular, we have already mentioned that AD strategies are also referred to as strategies of Denial. Denial can however also be applied on a smaller scale as an operational concept, in much the same way. Control, on the other hand, is a condition wherein the defender is able to operate freely within an area. While one way of achieving Control is to pursue an A2 strategy, there are also other ways of assuring such freedom. I.e. it is sufficient to keep track of invading systems and take necessary countermeasures whenever operations are actually required.

2.4 Classification of A2/AD systems

In general, there are two ways of suppressing enemy operations within an area. Either the enemy's movement can be inhibited using physical obstacles, or one can take measures to incapacitate opponents entering the region. Such measures of incapacitation can be further divided into those that are delivered at a distance, and those that only pose local threats, for instance mines. Finally, it makes sense to divide distance-delivered systems into two groups according to their range, since systems with longer range will be easier to utilize as an A2/AD capability. Nevertheless, precisely where the line should be drawn between systems of short and long range obviously becomes somewhat arbitrary. Below we draw this line at 100 km. The reason for this is threefold. First, it is a nice round number, second, 100 km is about the maximum range of high end rocket artillery, and finally, ranges measured in hundreds of km is typically where individual platforms start having strategic consequences.

It is also useful to classify A2/AD systems according to the type of enemy forces against which they defend. Thus, in addition to the classification described above, we distinguish between

A2/AD systems intended for defence against land, naval and air units. The following table shows some examples of A2/AD systems classified according to these schemes:

Table 2.1 Examples of A2/AD systems.

	Against land units/infrastructure	**Against naval units**	**Against air units**
Physical obstacles	Walls, ditches, barbwire, caltrops		
Local means of incapacitation	Land mines, melee combatants, sabotage	Sea mines, sabotage	Sabotage
Short range distance-delivered means of incapacitation	Artillery, direct fire-combatants, tactical missiles, most electromagnetic defences	Torpedoes, short range coastal defence systems, most electromagnetic defences	Short range air defence systems, short range air to air missiles, air to air gun fire, most electromagnetic defences
Long range distance-delivered means of incapacitation	Long range cruise missiles, ballistic missiles, cyber-attacks, some electromagnetic defences, influence campaigns	Long range cruise missiles with terminal guidance, ballistic missiles with self-homing RVs, cyber-attacks, some electromagnetic defences	Long range air defence systems, long range air to air missiles, cyber-attacks, some electromagnetic defences

2.5 Impact of modern technology

The first three rows in Table 2.1 denote methods of accomplishing A2/AD that date quite far back, as they have been employed for periods ranging from thousands of years to about a hundred in the case of the two first rows, and on the order of a hundred years in the case of the third row. The fourth row of the table however, describes a newer development, depending heavily on modern technology. While the ability to fire missiles over such long distances goes back to the beginning of the previous century, the ability to hit specific localized targets at such distances require high-tech capabilities that have become available only more recently. Also, what has been dubbed 'information warfare' is obviously also heavily dependent on modern information technology.

The introduction of these systems represents a serious change in A2/AD capabilities, and is the underlying technological reason behind the recent focus on A2/AD, and for the introduction of this new term for such ancient concepts. In previous eras, when A2/AD systems were limited to those described by the first three rows of Table 2.1, the ability to impose A2/AD over large geographic regions was very limited. This can be understood from the simple fact the density of deployed platforms in an effective A2/AD system is inversely proportional to the range of the systems. Thus, when employing short range systems, A2/AD capabilities will be limited to weak AD unless enormous expenses are committed to support a huge number of platforms. Examples of such extremely resource demanding A2/AD systems would be the frontline defences of WW1 and the 'Atlantic wall' of WW2.

With the arrival of long-range systems like those described in the fourth row of Table 2.1, this picture has changed. Potentially, the long range missiles described there can incapacitate opponents within ranges measured in thousands of km. This makes it possible to set up enormous A2/AD zones without the equally enormous costs that would previously have been associated with this decision. Also, while their impact is still very uncertain, information warfare campaigns are completely unaffected by distance, as long as some channel of communication is maintained.

Thus, it seems that while modern long-range systems are definitely expensive, the total cost of an A2/AD zone is no longer proportional to the size of the zone, only to the size of the threat that must be handled. In addition, such modern systems make it possible for nations to project A2/AD zones far outside of their own borders, and even into the territory of other nations. Thus, classical A2/AD studies express a concern over China's ability to project an A2/AD zone over the South China Sea, and over Russia's ability to project such a zone over the Baltic or over the airspace of northern Scandinavia [1] [2] [3] [4] [5].

However, it is important to keep in mind that A2/AD systems based on long range missiles require not only the ability to fire such missiles over long distances, but also the ability to make sure the missiles hit what they are actually intended to hit. If there is not a direct line of sight from firing platform to target, information about the targets location must be gathered by an elevated or forward placed sensor, and then communicated to the firing platform. The speed requirements of this communication depends on the mobility of the target, as does the navigational requirements of the missile. For fixed targets or land-based units that are currently stationary, the firing platform requires only a single report of the targets location, and the missile requires only the ability to navigate to a specified coordinate. For units moving at moderate speeds, such as a typical naval unit, it is likely that the target will change location during the flight of the missile, and so at minimum the missile needs the ability to relocate and home in on its target during in the terminal phase.

Finally, for aerial threats like airplanes or enemy missiles, the target may be moving at speeds comparable to that of the missile itself, and may move considerable distances during the missile's flight. Thus, for particularly large ranges the missile may require the ability to make course corrections before it itself has a direct line of sight to the target. This requires the establishment of a direct or indirect electromagnetic datalink between the missile and remote sensors, and frequent and accurate location updates via this link. The ability of different vehicles to share sensor data in this way is referred to by the US Navy as Cooperative Engagement Capability (CEC). It is considered an advanced high-tech capability, and experts estimate that Russia is at least a decade away from developing CEC [3]. However, some disagreement has been expressed concerning this [12], and it should be mentioned that the American definition of CEC is considerably more encompassing than that of a single data link between a missile and a forward placed sensor [13]. It should also be mentioned that there is considerable scepticism as to whether even the US military is able to maintain CEC in the chaos of real battle [14].

2.6 Restriction of scope

As indicated by Table 2.1 and the discussion above, there is an almost unlimited amount of different systems, weapons and capabilities that could potentially be branded as A2/AD. Recently, there has also been a renewed interest in the role that the systems of the first three rows of Table 2.1 might play in an A2/AD strategy or capability. Thus, recent literature has discussed the role of conventional shorter range land forces and traditional air-to-air power [6] [15] [16], as well as influence campaigns, sabotage and other forms of hybrid warfare [17].

Clearly, when conducting offensive operations against an opponent employing an A2/AD defence strategy, short range systems and approaches cannot be ignored in the account of total A2/AD capabilities. However, for small and somewhat peripheral nations like Norway, the main concern is not so much the problems created by A2/AD capabilities for offensive operations, but rather that we might suddenly find parts of our own territory included in an A2/AD zone, set up as a defensive measure by one of our neighbours. For this problem, the capabilities described in the fourth row of Table 2.1 is really the main concern. The threat described there can be divided into three components: The long range missile threat, information warfare, and long rage electromagnetic defences.

Of these, information warfare is again divided into two components: the information-technical component, referring to cyber-attacks, and the information-psychological component, referring to influence campaigns [17]. It is incredibly difficult to assess the effect such information warfare would have in a modern war between technologically advanced opponents. In a sense this is the great unknown of modern warfare, comparable in many respects to the unknowns created by new technologies at the beginning of the previous century, which made particularly the First World War such a surprise to everyone. While an effort to understand this topic better is thus of utmost importance, this is a too comprehensive and demanding task to handle in a short report of the type presented here. Initial analysis is found in some of our previous reports [18] [19].

When it comes to long range electromagnetic defences, due to the inverse square law describing electromagnetic radiation, such long range effects are realistically speaking limited to the jamming of quite weak signals, like those received by GPS devices. Thus, the threats of such systems, and possible counter measures, are best dealt with in specialized literature dealing with robust communication and navigation. The scope of this report has accordingly been restricted to the long range missile threat. Readers interested in other components of A2/AD, such as shorter range systems, long range jamming, and information/hybrid warfare, are encouraged to check out the references included in this section, many of which are gathered in the recent anthology by FOI [20]. It should also be mentioned that while some long range missiles may carry nuclear weapons, we make no attempt at discussing nuclear warfare in particular.

3 Russian long range missile systems and their projection in Northern Europe

As mentioned above, the major A2/AD related concern for a small state like Norway is that one of its neighbouring states might create an A2/AD zone covering parts of its territory. In the case of Norway in particular, while still unlikely, the *most* likely neighbour to perform such an action is definitely Russia. Thus, this section contains an overview of Russian long range missile capabilities, with illustrations of the regions that could potentially be covered by these in Norway's surroundings. Note that all of the presented information is based on open sources, which it must be in order for the report to remain unclassified. Naturally, this means that the accuracy of the information is quite limited, and should largely be regarded as order of magnitude estimates.

3.1 A brief explanation of missile related terms

This section introduces and explains some terms related to missiles and missile technology, and is intended for readers not familiar with this terminology. The remainder of this chapter will make extensive use of these terms.

3.1.1 Cruise missiles

A cruise missile is basically an unmanned aerial vehicle on a suicide mission. It is an unmanned flying vehicle, usually similar to a small airplane, and equipped with an autopilot, a navigation system, and sometimes a terminal seeker. It carries an explosive device which detonates when the missile reaches its target. The propulsion of the missile can be provided by any type of engine employed by other flying vehicles. Shorter range cruise missiles often make use of solid fuel rocket engines, but in order to achieve really long ranges, an air breathing engine is required. This will typically be a jet engine.

3.1.2 Ballistic missiles

Technically, the meaning of the term ballistic missile is any type of missile which follows a ballistic trajectory, i.e. any missile which is neither self-propelled nor generates lift. Thus, this technical meaning applies also to artillery shells, short range rockets, and even arrows fired from a bow. However, in practice the term ballistic missile is reserved for rockets of a certain range. Note that the rocket engine is only used to get the missile up to speed. After this the missile follows the same path it would have followed if it was fired from a canon, i.e. a ballistic trajectory.

The warhead of the missile is sometimes released before the missile renters the atmosphere, and enters on its own in manner similar to a bomb released from extreme altitudes. Such warheads are referred to as re-entry vehicles (RVs). A missile can also contain more than one RV, and modern RVs often have a guidance and navigation system similar to that of guided bombs.

Ballistic missiles are classified according to their range:

- *Short range ballistic missiles (SRBMs)* have a range of 500 km or below. Sometimes one distinguishes between short range and tactical ballistic missiles, where tactical missiles have a range of 300 km or shorter. Rockets with ranges shorter than 100 km are usually not referred to as ballistic missiles, but as artillery rockets or just rockets.

- *Iintermediate range ballistic missiles (IRBMs)* are, following the INF-treaty, those missiles that have a range between 500 and 5500 km. Sometimes one distinguishes between intermediate and theatre range missiles, where theatre range ballistic missiles (TRBMs) have ranges below 3500 km.

- *Intercontinental ballistic missiles (ICBMs)* are ballistic missiles with ranges above 5500 km.

3.1.3 Navigation systems

- Inertial navigation systems (INS). An inertial navigation system keeps track of a vehicle's position by adding together changes calculated from its speed and orientation. The speed and orientation is also kept track of by adding together changes, and these are obtained by measuring the vehicles acceleration. The advantages of INS systems are that there are almost no limitations to their use, since they are not dependent on external communication or measurements. A major disadvantage however, is that the system quickly loses accuracy due to the accumulation of errors when adding together many small changes. Typically, the more modern electronics employed by the system, the longer it can maintain its accuracy.

- ***Satellite navigation (Satnav)***. A satellite navigation system keeps track of position by triangulation relative to a selection of satellites. Each satellite sends a signal containing information about its current position as well as the time the signal was sent. Receiving this information from four different satellites is enough for the system to estimate its current position. The most well-known Satnav system is the Global Positioning system (GPS), which is operated by the US. However, several countries are working on their own Satnav constellations, for instance the Russian GLONASS. Presently, all countries are free to use the GPS system, so these alternatives are mainly backups in case the US system becomes unavailable. Satnav is a very reliable form of navigation, but is highly vulnerable to jamming of the communication channel used by the satellites.

- ***Terrain comparison (TERCOM)***. A TERCOM system uses a radar altimeter to measure changes in the height of underlying terrain as the missile is flying over it. The measurements of the altimeter are then compared with a map containing the height profile of the relevant area, and a search is made to find the path which best fits the measured profile. The current position of the missile is estimated as the end point of this path.

- ***Optical terrain comparison***. An optical TERCOM system uses exactly the same approach as the above radar TERCOM, except that an optical camera is used rather than an altimeter. Pictures of the underlying terrain is compared with a map, and the position which results in the best fit between the two is used as an estimate of the current position.

- ***Stellar navigation***. A stellar, or astro-navigation system, uses an approach similar to optical terrain comparison, except that the position is estimated by taking a picture of the sky rather than the underlying terrain, after which the observed position of stars is compared to a list of stellar coordinates. An advantage of this method relative to optical scene matching is that one does not need an accurate map of the terrain over which the missile is flying, and that it can also be used when flying over the sea. Disadvantages are however that stars must be visible in the sky, which means that the system can only be used at night time or at extreme altitudes. In addition, the system must carry an accurate clock, in order to correct for how the position of stars vary with the time of day.

3.1.4 Terminal seekers

- Active radar homing (ARH)**.** A radar homing seeker uses a radar signal to locate its target. That the radar seeker is active means that it also contains a radar source, which is used to illuminate the target. Radiation is thus emitted from the seeker itself, reflected off the target, and then reabsorbed by the seeker.

- ***Semi-active radar homing (SARH).*** In a semi-active radar seeker, the illumination of the target does not originate from the seeker or missile itself, but from some external radiation source, referred to as an illumination radar. SARH is most commonly employed by air defence systems, in which case the illumination radar is usually located on the ground, near the launcher.

- ***Passive radar homing.*** When passive radar homing is used, the target is not illuminated by any external radiation source. Thus, passive radar homing can only be employed against targets that are themselves emitting electromagnetic radiation. These can be enemy radars, communication equipment, or electronic warfare devices.

- ***Infrared homing (IRH).*** An infrared seeker works in a similar manner to a passive radar seeker, except that it looks for infrared radiation rather than more low frequent forms of electromagnetic radiation. Thus, this seeker is most useful when used against a source of heat, such as the jet stream of an aircraft.

- ***Optical target recognition.*** Optical target recognition works by using an optical camera to take pictures of the area near the target. This is then compared with a stored image of the target, and if a match is found in the observed picture, then this is used to identify the target and estimate its position. Note that the requirements of an optical target recognition system is exactly the same as those of an optical TERCOM system. Thus, as long as the camera is suitably positioned, an optical TERCOM system can also be used for optical target recognition.

- ***Imaging infrared (IIR).*** Imaging infrared seekers combine the technologies of infrared homing and optical target recognition. Rather than an optical camera, it uses an infrared camera, which again makes it particularly useful against heat sources. Apart from this the mechanism of location is identical to that of optical target recognition. The advantage of using IIR rather than just IR homing is that IIR seekers are more difficult to fool, and are able to locate their targets more precisely.

- ***TV-guidance.*** In a TV-guidance system, continuous video from an optical camera is transmitted back to a human operator, typically located at the launch platform. The operator has control over the missile via remote control, and uses the video feed to home in on the target.

3.2 Summary of Russian long range missile systems

Over the years Russia and its precedent USSR have developed a plethora of missiles of various types, many of which are either still in operation or in storage. This section is only a brief summary of these capabilities. A more thorough overview is provided in Appendix A.

3.2.1 Ballistic missiles

In addition to various ICBMs, Russia seems to currently have three operational ballistic missile systems with shorter ranges. These are the Tochka-B, the Iskander and the Kinzhal. The Kh-15 and the Scud missiles are thought not to be in operation, but are probably still in storage. In addition, the Smerch rocket artillery has sufficient range to fall within what we above classified as long range capabilities. These missiles are summarized in table 3.1 below, together with their launch platforms and estimated ranges.

Most of these missiles use INS for navigation, but some of the more modern use Satnav, either in the form of GPS or GLONASS, and some older ICBMs also use stellar navigation. Some missiles are also thought to have a terminal homing capability, making use of active and passive radar, as well as optical target recognition. While the older missiles have accuracies measured in hundreds or even thousands of meters, more modern ones such as the Iskander reportedly has an accuracy off about 5 m. A more detailed description of individual missiles can be found in appendix A.1.

Table 3.1 Current Russian ballistic missiles.

Missile/system	Platform	Range estimate (km)
Smerch (Tornado-S)	TEL[1]	120
Tochka-B	TEL	120
Kh-15?	Air launched	140–300
Scud-A	TEL	180
Scud-B	TEL	300
Iskander	TEL	500
Kinzhal	Air launched	1500–2000
ICBMs	TEL, Silo, Submarine	5000–16000

3.2.2 Land attack cruise missiles

Notable missiles among Russias cruise missiles intended for land attack, are the Kalibr 3M14, the 9M729 which reportedly was the triggering cause for the dissolution of the INF-treaty, and the Kh-55 family, which includes the Kh-101/102. Land attack cruise missiles thought to be in operation or in storage are summarized in table 3.2 below, together with their launch platforms and estimated ranges.

Table 3.2 Current Russian land-attack cruise missiles.

Range estimate (km)	Air launched	Submarine	Surface ship	TEL
115	Kh-59M			
450–550 (1000?)	Kh-59MK2			9M728 S-35?
2000–2500		3M14K S-10	3M14T	9M729
3000–3500	Kh-55SM Kh-555			
2500–4500	Kh-101 Kh-102			

[1] Transporter-Erector-Launcher

Most of these missiles use INS and TERCOM for navigation, in combination with Satnav in the more modern cases. Some of the shorter ranged missiles instead use INS in combination with TV-guidance. Some missiles also seem to have a terminal homing capability, making use of ARH or IRH. Range estimates vary from 25-150 m in the older cases, to 3-5 m in the case of the most modern missiles. All of the missiles are thought to be subsonic. A more detailed description of individual missiles can be found in appendix A.2.

3.2.3 Anti-ship cruise missiles

Russia has a considerable amount of different anti-ship cruise missiles, launched from the sea, from the air and from coastal defences. The ones that are most likely to be in current operation or storage are summarized in table 3.3, together with their launch platform, range estimate and velocity class. All of these missiles use ARH for terminal phase homing, but some use passive radar or IRH in addition. Most of them use INS for navigation, combined with Satnav in the more modern cases. A more detailed description of individual missiles can be found in appendix A.3.

Table 3.3 Current Russian anti-ship missiles.

Velocity class	Range estimate (km)	Air launched	Submarine	Surface ship	Shore based
Subsonic	70–130	Kh-35	P-120	Uran P-120	Bal
Subsonic	285–300	Kh-59MK Kh-35M		Uran (M)	Bal (M)
Mach 2-3	110–250	Kh-31			
Mach 2-3	250–300 (600?)	Kh-61? Kh-41?	P-800 Oniks P-270?	P-800 Oniks P-270?	Bastion-P
Mach 2-3	550–660		P-500 Bazalt P-700 Granit 3M54K	P-500 Bazalt P-700 Granit 3M54T	
Mach 2-3	700-1000		P-1000 Vulcan	P-1000 Vulcan	
Mach 3-5	200-600	Kh-22			
Mach 3-5	800-1000	Kh-32			

3.2.4 Air defences

3.2.4.1 Land based and naval air defence

A quite detailed unclassified discussion of Russian land based air defence is provided in a previous FFI report [21]. The details of this section, which is intended only as a brief summary, is taken from that report except where otherwise marked. Another useful summary is given in one of the chapters of FOI’s new anthology [12].

Russia's land based air defences may be categorized into classes of short, medium and long range. The medium range systems consists mainly of the Buk family, while the short range systems are made up by the Tor, Tunguska and Pantsir families, as well as various man portable weapons. Short and medium range systems typically have a range of no more than a few tens of kilometres, and will accordingly not be covered here. The long range systems that are currently in use are all members of the S-300 family. This family has three branches, corresponding to systems used by the army, navy and air force. The S-300V branch is used by the army. It consists of the **S-300V**, the **S-300VM** and the newest **S-300VMD**, of which little is presently known. These systems are carried by tracked vehicles and intended to be highly mobile in comparison to other long range systems. The main launcher vehicles carry their own engagement radars, and are known as TELARs.

The S-300P branch is used by the air force. It consists of the **S-300PT**, **S-300PS**, **S-300PM**, **S-300PM2**, and finally the newest operational model, known as the **S-400**. In addition there are development projects working on even newer upgrades: the S-500 and possibly the S-1000. The systems of the S-300P branch are heavier and less mobile than those of the S-300V family, and are carried by wheeled vehicles. The launcher vehicles are normal TELs, and the engagement radar is carried by a separate vehicle.

Finally, the S-300F family is used by the navy. It consists of the **Fort** and **Fort-M** systems, which are essentially ship mounted versions of the S-300P family. Fort has been mounted on Kara, Slava and Kirov class ships, while the Fort-M seems as of yet only to have been mounted on a single ship, the Pyotr Velikiy, which is of the Kirov class.

Missiles employed by the S-300 family are summarized in the table below, together with their launch platforms and various specifications. While many of these missiles are intended for use against airplanes and helicopters, those with highest specifications are intended for use against ballistic missiles. More details can be found in previous report [21].

Table 3.4 Current Russian surface to air missiles in the S-300 family.

Missile	Range (km)	Top speed	Max altitude (km)	Seeker	Launch platform/ system
9M82	100	Mach 6	30	SARH	S-300V/ VM/VMD
9M83	75	Mach 4	25	SARH	S-300V/ VM/VMD
48N6	150	Mach 6	27	SARH	S-300PM/M2 S-400
48N6M	200	Mach 6	27	SARH	S-300PM/M2 S-400 Fort/Fort-M
48N6M2	250	Mach 6	27	SARH	S-300PM/M2 S-400
9M96	60	Mach 3	30	SARH	S-400
9M96M	120	Mach 3	30	ARH	S-400
40N6	400	?	?	ARH	S-400/500?

In addition to the actual missiles, the radars employed by these systems are of huge importance to their effective ranges in practice. There are two factors which limits the range of a radar system. The first is the signal strength that the radar can pick up. The signal returned from a radar target falls off with the fourth power of distance [22], so accordingly the maximum sensor range can be determined as

$$d = \sqrt[4]{s\sigma},$$

Where s is the sensitivity of the radar system, and σ is the radar cross section (RCS) of the target. The RCS depends also on the frequency employed by the radar. Stealth targets, which are designed to have low RCS at high frequencies, will usually have a considerably higher cross section in lower frequency bands. [23]

The second factor limiting the range of radars is the curvature of earth, since targets at sufficiently low altitude and sufficient distance will be hidden below the horizon. At moderate altitudes the closest distance at which an object is able to hide behind the horizon can be determined as [3]

$$d = F\left(\sqrt{h_1} + \sqrt{h_2}\right),$$

where h_l and h_2 are respectively the radar and target altitudes above sea level, and F is a factor depending both on the radius of earth and on the degree to which atmospheric conditions are refracting the radar radiation downwards [24]. Often one uses a value of $F=4.1\ km/m^{1/2}$ [3]. However, the degree of refraction and thereby the value of F, will also depend on the frequency of the radiation, with lower frequencies resulting in higher values of F and thus a more distant radar horizon [24]. In addition, low frequency radiation can be reflected of the ionosphere, which further extends the radar range [25].

Accordingly, there are multiple advantages in using low frequency radiation, in that it both increases the RCS and pushes back the horizon. However, the long wavelengths associated with low frequencies reduce the angular resolution of the detector, which make these frequencies less useful for targeting [23]. Engagement radars therefore usually employ higher frequency bands, while some surveillance radars make use of low frequencies.

3.2.4.2 Air to air missiles

Air to air missiles (AAMs) is also an important component of Russia's air defence. In addition to several short range missiles used for close range combat, it also has a selection of air to air missiles with sufficient range to be considered part of its long range A2/AD capability. These include the R-40, with a range of 80 km and a top speed of Mach 2.5 [26], the R-33 with a range of up to 300 km and a top speed of Mach 6 [27], the R-27 with a range of up to 170 km and a top speed of Mach 4.5 [28], the R-77 with a range of up to 190 km and a top speed of Mach 5 [29] and the newest R-37 with a range of 150–400 km and a top speed of Mach 5. Development of the R-37 was finished in 2019, but it has not yet been observed in operation [30]. Another missile which is currently in development is the Novator KS-172, which will have a range of 200–400 km and a top speed of Mach 3.3 [31].

3.2.5 Future developments

Much of Russia's current R&D efforts related to ballistic missiles are concerned with the development of new ICBMs. Amongst these is the development of the new missile RS-28 Sarmat, which will have a range between 10 000 and 18 000 km, make use of the GLONASS system for navigation, and is scheduled for replacing all of Russia's heavy land-based ICBMs [32] [33] [34]. Russia is also working on a new re-entry vehicle, the Avangard, which will be a hypersonic glide vehicle [35] [36] [37]. This means that it skims along the upper edge of the atmosphere for a while after re-entering, which extends its range significantly and may create problems for current missile defence designs [38].

Russia is also running several development projects related to the development of new cruise missiles. Among the more conventional developments are the Kalibr-M, which is supposedly an improved version of the Kalibr/Biruyuza missiles [39] [40]. Slightly more ambitious projects include the 3M22 Zircon coastal defence system [41] [42], and the Brahmos-II which is developed in cooperation with India [43] [44]. Both of these are supposed to be hypersonic cruise missiles making use of scramjet technology to reach a top speed near Mach 8. Reportedly, the Zircon was recently tested in operational configuration [41] [42]. Another ambitious project is the 9M730 Burevestnik. Similar to the Kh-101 but reportedly somewhat larger, the Burevestnik is supposed to make use of some form of nuclear propulsion to achieve a virtually unlimited range and flight time [45] [37].

3.3 Projection of Russian missile threats in Northern Europe

This section includes a selection of maps illustrating the range of various Russian missile systems, and their projection in Northern Europe. The maps of figures 3.1–3.6 illustrate systems intended for land attack. Figures 3.1 and 3.2 show the range of such systems, excluding ICBMs. The next four figures shows an estimate of the maximal warning time one could hope to make use of if a land attack missile was launched. This is calculated as the missiles flight time from the launch site to its target location. The boost phase of ballistic missiles is not included in the calculation. Again ICBMs are excluded in all figures except 3.6. Figure 3.3 excludes also the air launched Kinzhal missile. Naval launch platforms are placed at arbitrary locations, while airborne platforms are (quite unrealistically) assumed to release their payload near their base.

Figures 3.7 and 3.8 shows anti-ship missiles. Figure 3.7 is intended to show the coverage of various missile types, while Figure 3.8 shows an estimate of the maximum potential warning time, which is again based on the missiles' flight time.

Finally, Figures 3.9 and 3.10 illustrate the Russian air defence system. Figure 3.9 shows the ranges of the various surface to air missiles (SAMs) discussed above, while Figure 3.10 illustrates the radar coverage and its dependence on target altitude and RCS. The illustrated sensitivity to RCS is the estimated sensitivity of the 92N6 Grave Stone, which is commonly employed as engagement radar by the S-400. For the dependency on altitude, it is assumed that the radar itself is located 50 m above sea level. The legends of the figure show the conditions that must be met in order for a target to be visible in the entire region within that colour. This means in particular that targets failing to meet one of the conditions, will not be visible outside of that particular region.

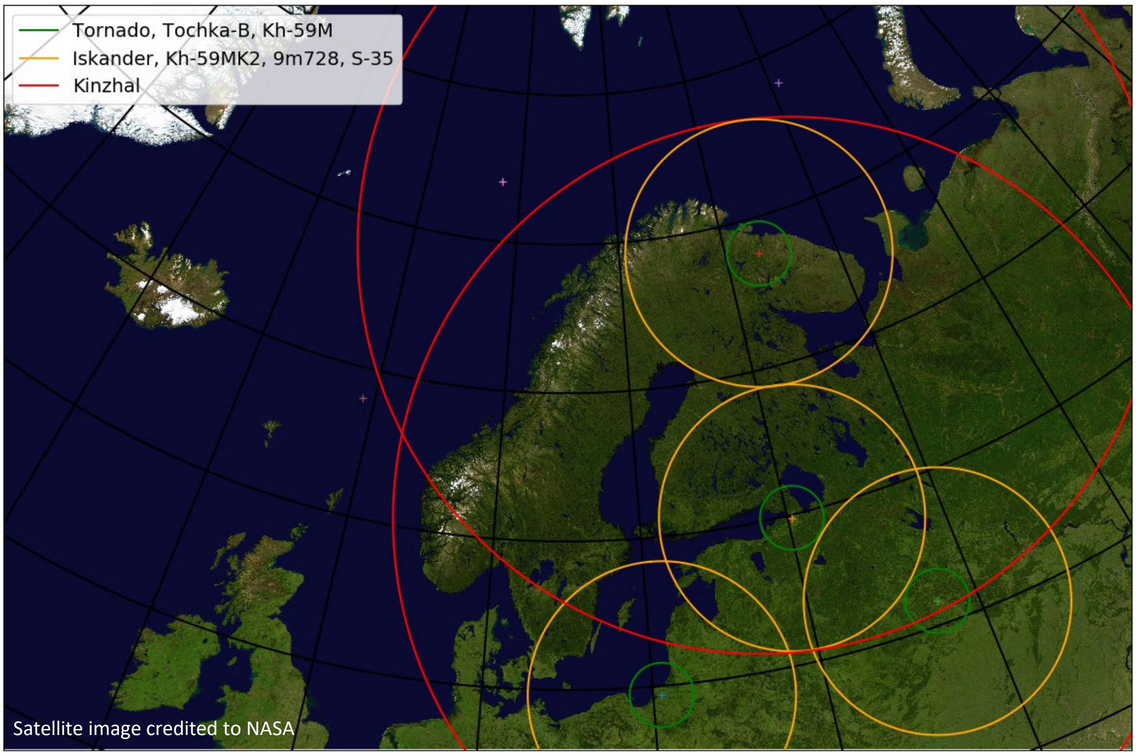

Figure 3.1 Shorter range land attack missiles.

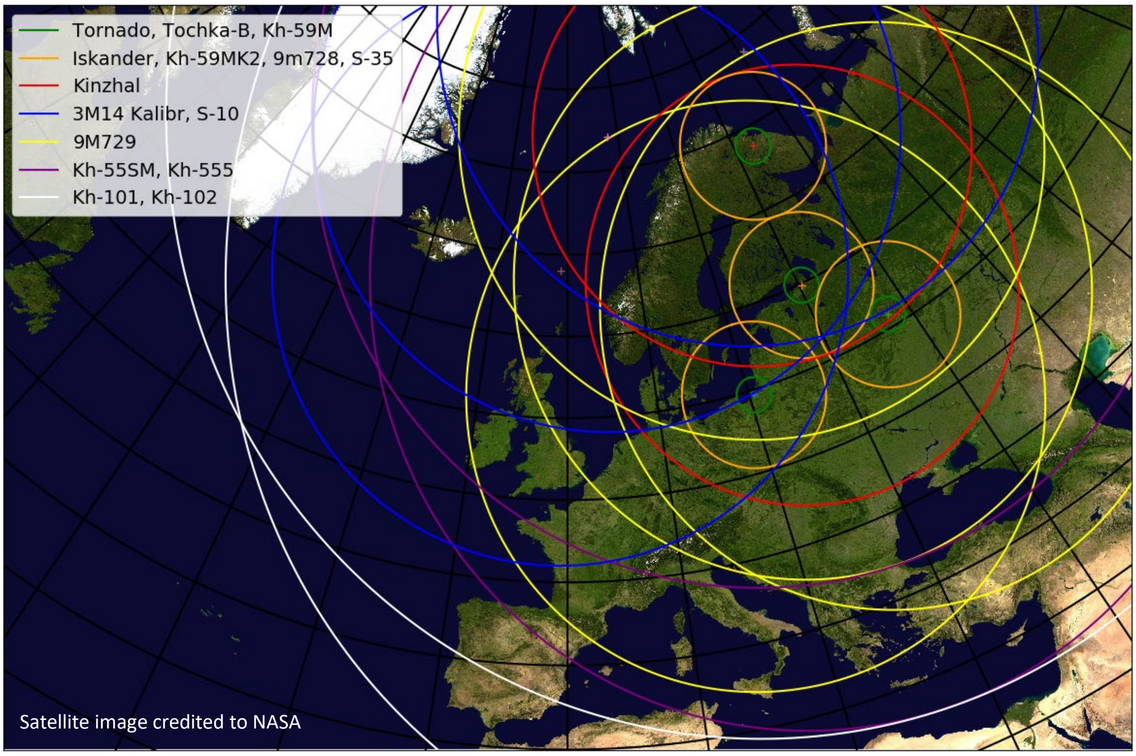

Figure 3.2 All land attack missiles, excluding ICBMs.

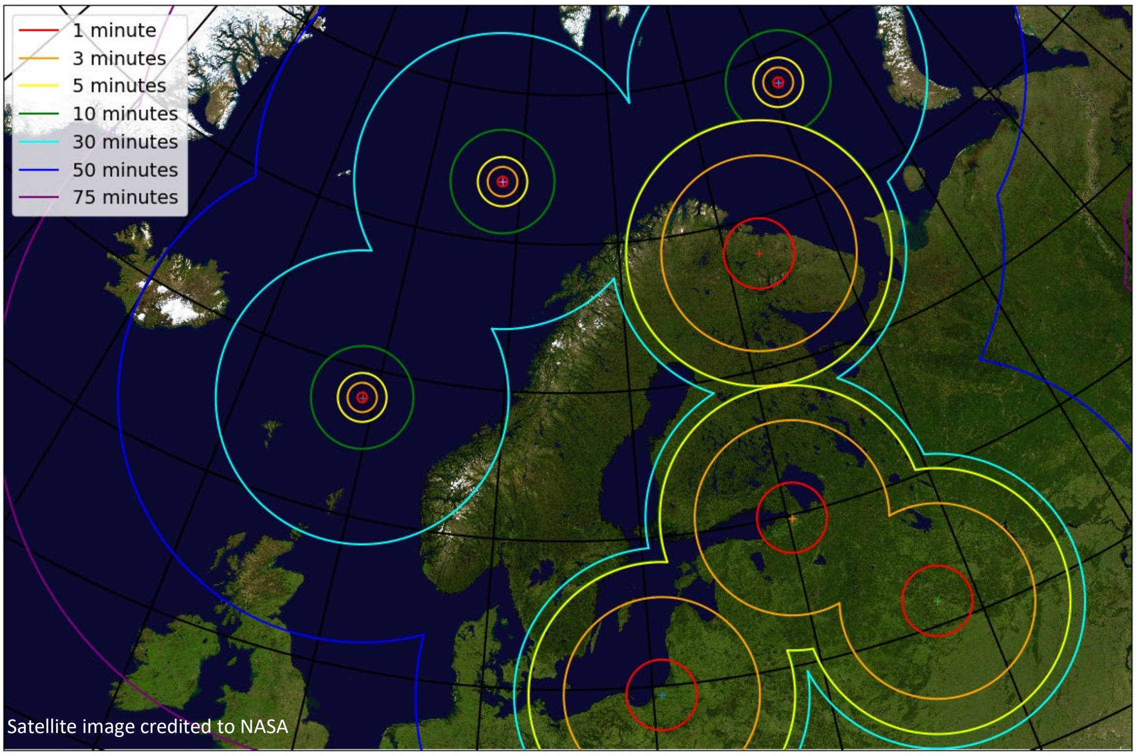

Figure 3.3 Estimated maximal possible warning time, Kinzhal and ICBMs excluded.

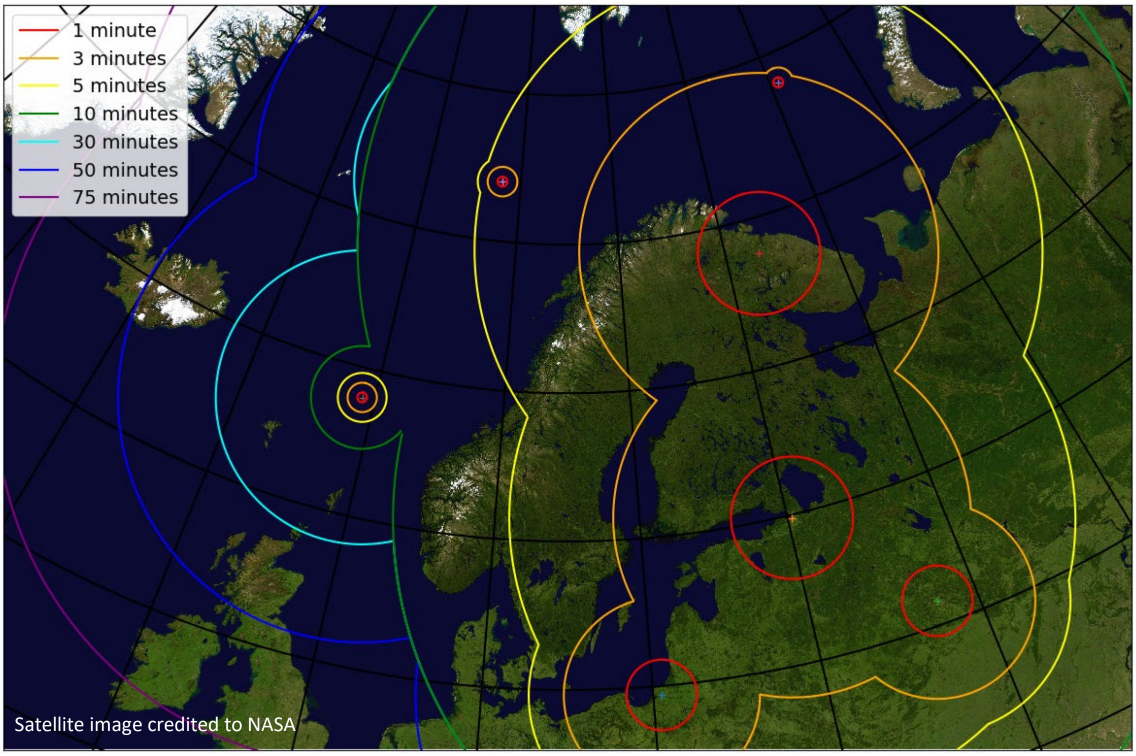

Figure 3.4 Estimated maximal possible warning time, Kinzhal included and ICBMs excluded.

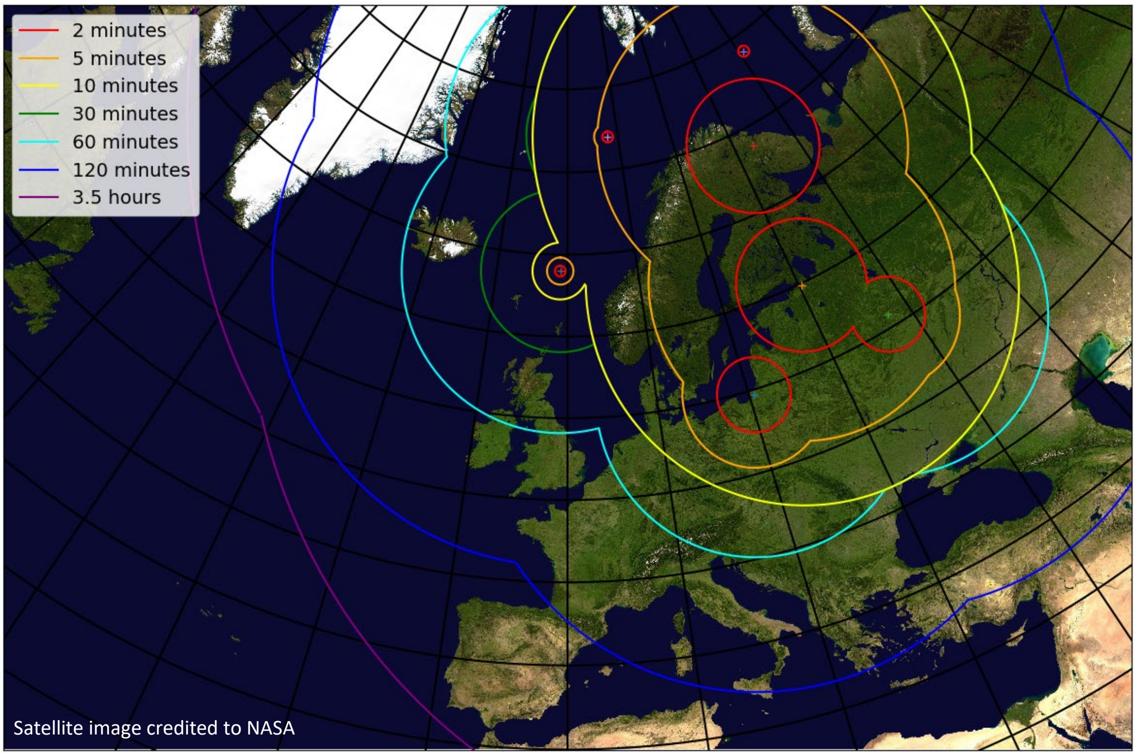

Figure 3.5 Estimated maximal possible warning time, Kinzhal included and ICBMs excluded.

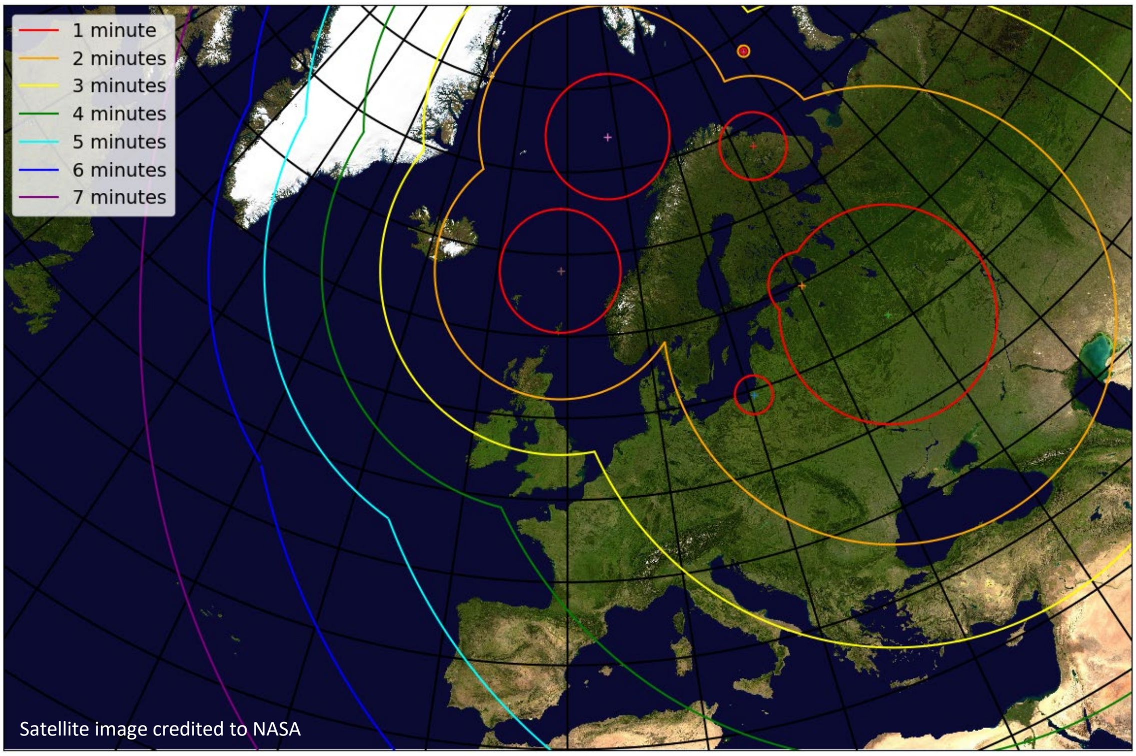

Figure 3.6 Estimated maximal possible warning time, Kinzhal and ICBMs included.

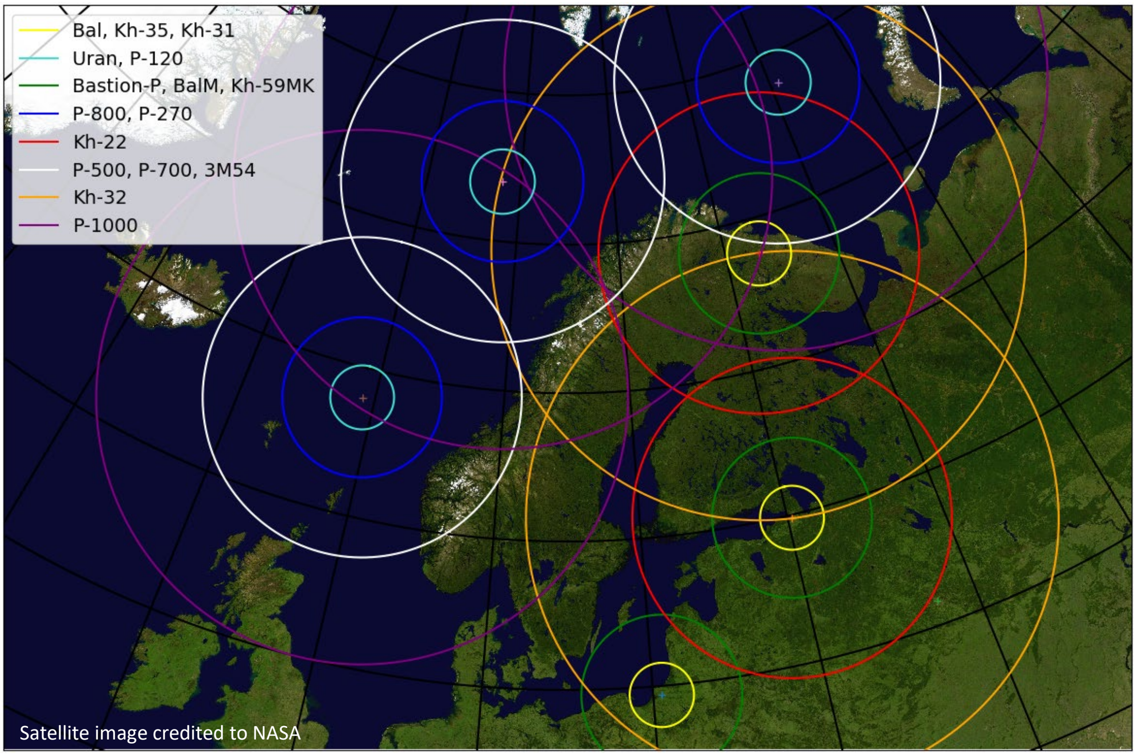

Figure 3.7 Anti-ship missiles.

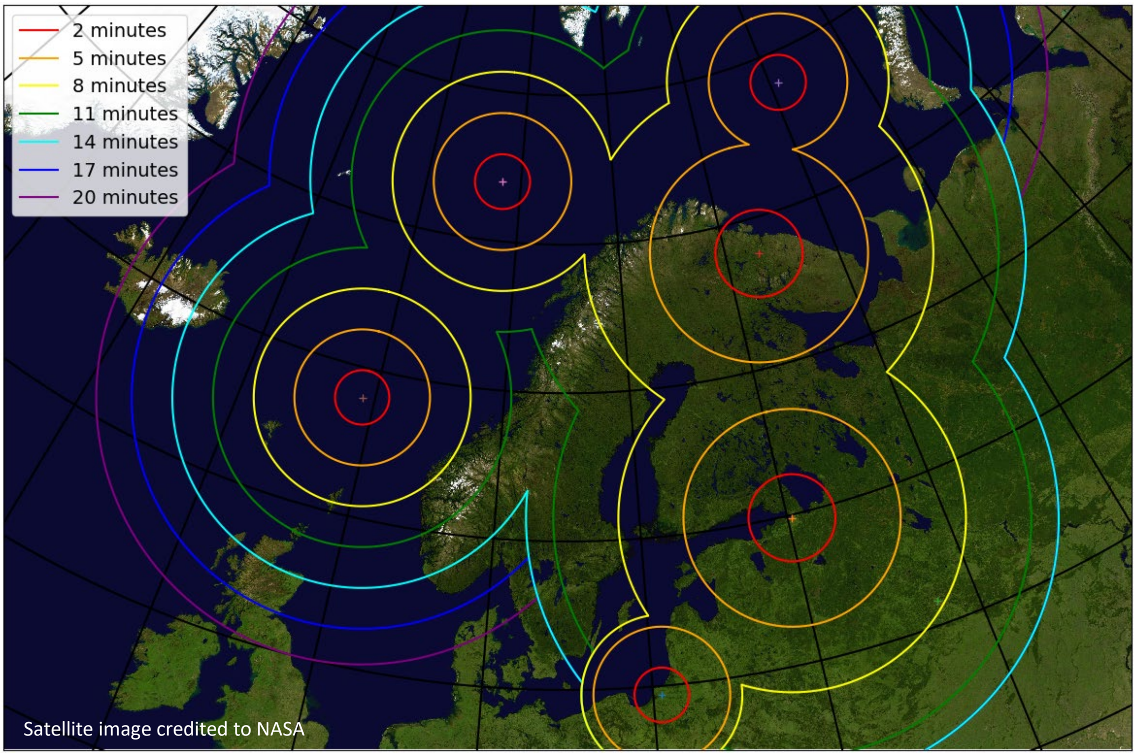

Figure 3.8 Estimated maximal possible warning time, anti-ship missiles.

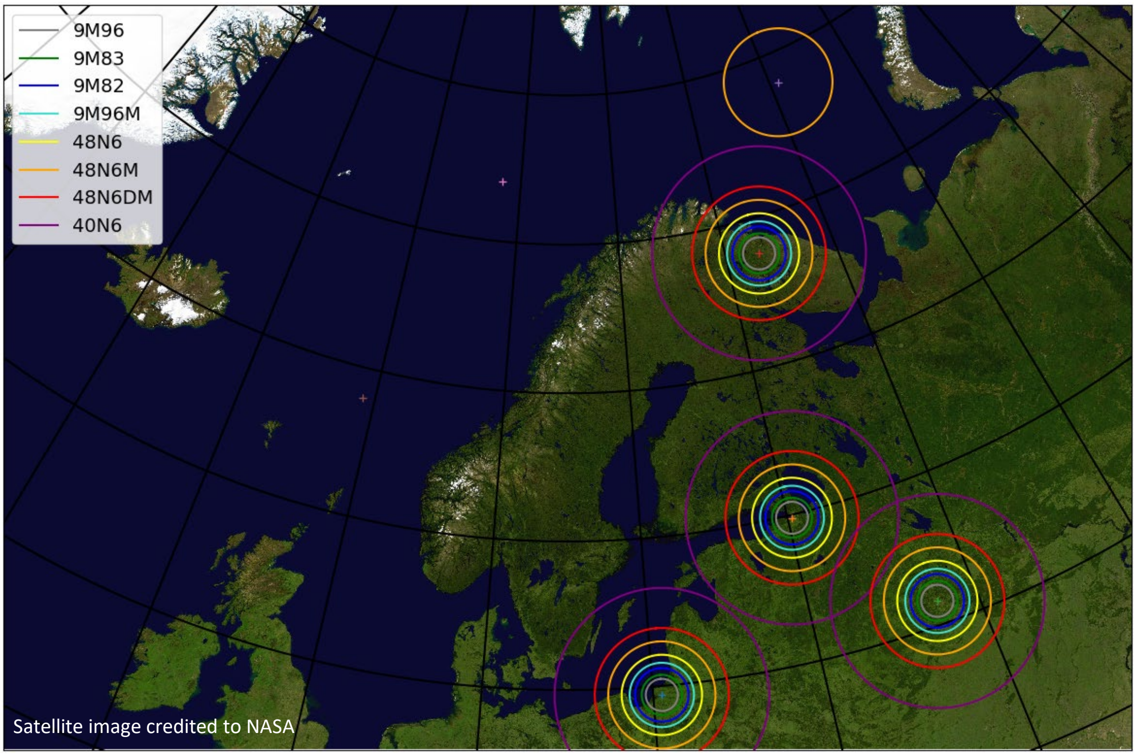

Figure 3.9 Selection of SAMs from the S-300 family.

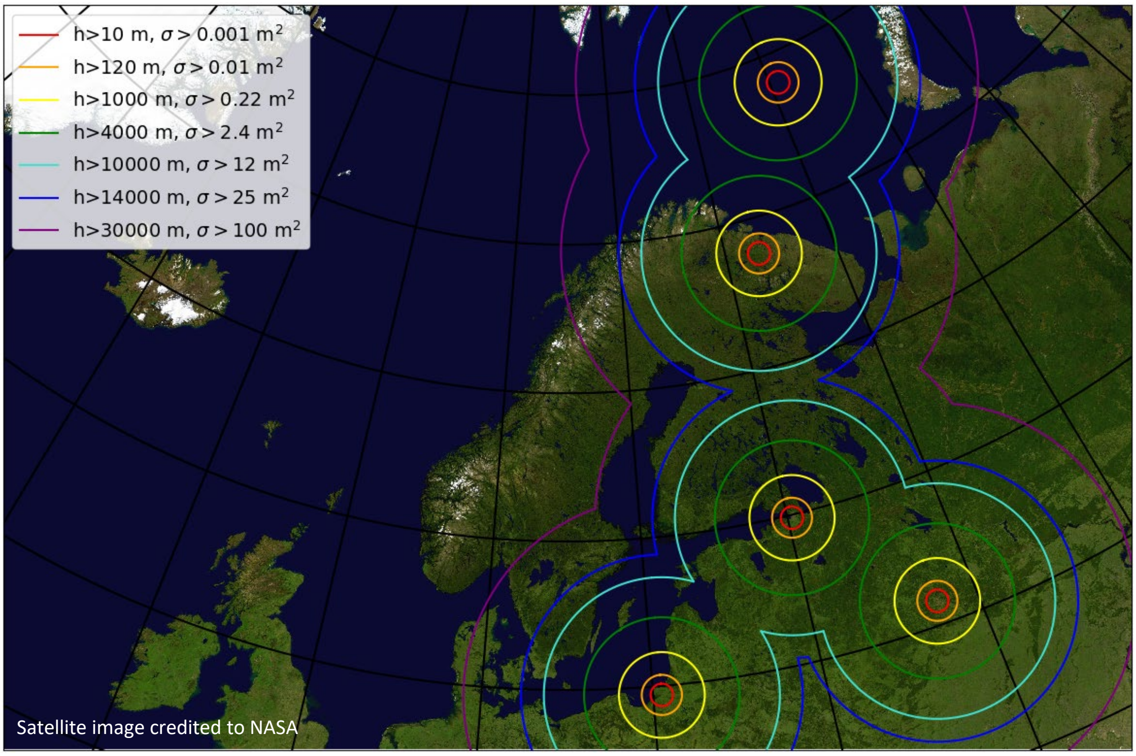

Figure 3.10 S-400 Radar coverage, dependence on target altitude h and RCS σ.

4 Measures for countering A2/AD threats

4.1 General model

In general, one can imagine two approaches to countering an A2/AD threat. Either, the threat itself can be eliminated, or one can take measures to defend against it. In order to eliminate the threat, one is required to attack at least some component of the A2/AD defence system. This component can be the missile, the firing platform itself, a component of the communication and control (CC) system, or the sensors of the system. Since at least those systems considered here are very long range systems, the firing platform as well as the CC system can be expected to be located well within the enemy's territory, which complicates attacks on these. The sensors on the other hand, is the component of the system which is required to have a direct line of sight to the target, and as such these are often the most vulnerable part. A potential problem with attacking sensors however, is that the system can contain several of these, with considerable redundancy between them. Thus, even after incapacitating all sensors that are known, one can usually not know with certainty that the system is in fact rendered ineffective.

The second way of countering distance delivered A2/AD systems, is to defend against the incoming attacks. This can be done in multiple ways. One way is to use direct protection, which can consist of physical barriers, or an air defence system with the ability to shoot down incoming missiles. A second way of defending against an A2/AD system is to attempt to deceive the sensors of the system, for instance by utilizing camouflage and decoys. One can also suppress the system's ability to target movable units by manoeuvring these regularly. This will completely incapacitate any system whose response time is longer than the time between relocations, and whose missiles are unable to receive mid-flight location updates. Manoeuvring can also significantly impede systems even when this is not the case, since its sensors must constantly relocate the manoeuvring target. Another tactic commonly applied by units with the ability to manoeuvre, is to increase the cost of an attack by spreading out potential targets over a large area, so that a large number of missiles must be expended in order to take down all of them.

Finally, attacks can be deterred by reducing their perceived benefit as seen by the enemy. If the long-time effect of an attack is perceived to be small, the likelihood increases that the enemy will not consider it worth the cost. This can be achieved by maintaining redundancy between different platforms, so that taking down a single target will not significantly reduce total capabilities. Another method will be to maintain a rapid repair and replacement capability, so that the effects of an attack will in any case not last long.

A visual overview of different measures for countering long range A2/AD systems is presented in the below table. Following this, the defensive measures are described in more detail, while discussions of offensive measure are left for other studies.

Table 4.1 Measures for countering A2/AD threats.

Offensive measures	Attack firing Platforms		
	Attack command and control systems		
	Attack sensors		
Defensive measures	Direct protection	Physical barriers	Armour
			Terrain
			Fortification/hardening
		Air defence	Short range point defence
			Long range area defence
	Deceptive measures	Hiding	Camouflage
			Terrain
			Stealth technology
		Deception	Decoys
			Electronic warfare
	Manoeuvring and Dispersal	Manoeuvring	Manoeuvring regularly
			Manoeuvring on warning
			Staying out of range
		Dispersal	Dispersing targets
			Dispersing capabilities
	Damage mitigation	Rapid repair	
		Rapid replacement	

4.2 Countering threats against naval units and sea traffic

4.2.1 Direct protective measures

The armour of heavy naval units may be considered a physical barrier. Other than this, there are few physical barriers available at sea, except possibly in the form of terrain in coastal areas. Many naval units also carry air defence, both in the form of long, medium and short range SAMs and short range gun defence.

Civilian sea traffic and military transport ships carry few defences of their own, but may be escorted and protected by combat ships carrying both air defence and anti-submarine warfare (ASW) systems.

4.2.2 Deceptive measures

Military ships are often painted in naval camouflage colours, which does make them slightly harder to identify using optical means. Reduction of noise reduces chances of detection by acoustic sensors, and like aircraft ships can also be shaped so as to reduce their radar cross section (at least in high frequency bands). Both optical, radar and sonic sensors can also be confused by the use of physical decoys, which may consist of equipment placed out by the ship itself, or of additional inexpensive unmanned and automated craft.

Decoys that generate electromagnetic signals can be considered a form of electronic warfare (EW). Other forms of protection by electronic warfare can be the jamming of incoming missiles, or of nearby ISR[2] platforms. Such jamming can be used to confuse radar sensors, or to disturb data links and satellite navigation. More advanced EW platforms also allows for the creation of virtual decoys.

4.2.3 Manoeuvring and dispersal

When operating at sea, dispersal and manoeuvring will be the default state of seaborne units. As long as they are not at port, naval ships will typically be on the move. Indeed, this is why a distinction is made between land attack and anti-ship missiles. Long range anti-ship missiles must be designed for attacks where considerable movement of the target between launch and contact is the norm. Thus, they typically have a higher speed and shorter range than their land attack counterparts, and more often than these have some form of terminal homing capability. The situation faced by attacking platforms and missiles can be made even more complicated by periodically altering course and speed settings.

Operating naval units will usually also be spread out to some extent, simply to avoid crashing into each other. This default dispersal is probably sufficient to make sure a conventionally armed missile will only incapacitate a single unit, but may not be sufficient for nuclear attacks.

[2] Intelligence, surveillance and reconnaissance.

When ships are docked at port, these advantages go away. They are then stationary targets, and in addition neighbouring ships may be docked quite close together. The situation can be mitigated to some extent by having as few ships as possible docked simultaneously at the same port, and by making sure valuable units spend as little time as possible in port. In addition, when in port the use of physical barriers is more of an option.

4.2.4 Damage mitigation and rapid repair

Damage suffered by ships at sea can be mitigated to some extent by having an on-board repair capability, which can be essential also in peace time. As long as the damage is somewhat modest, such repair capabilities could even save a ship from sinking.

4.3 Countering threats against air traffic and airborne units

4.3.1 Direct protective measures

In the air, there are even fewer physical barriers available than at sea, and the use of armour is less of an option, since weight is a considerable issue for airborne units. Some armour can be used to protect the most crucial sections of the plane from low energy impacts. Many airborne units also carry AAMs and guns for protection against airborne threats. Potentially these could also be used to shoot down incoming air defence missiles or long range AAMs.

Physical barriers, hardening and air defence can also be used at air bases to protect units while they are on the ground.

4.3.2 Deceptive measures

The release of various decoys is a common technique employed by warplanes to defend against incoming missiles. These decoys may be simple pieces of material designed to fool radar sensors, or they may be flares intended to fool IR sensors. Long range sensors and ISR platforms can also be fooled by UAVs with a radar signature similar to that of warplanes.

The use of stealth technology to make aircraft less visible to radar is nothing new, and in particular the fifth generation of fighter planes are characterized by their stealth properties. Other measures that can be used to reduce visibility include measures to reduce engine noise, reduction of light emission at night, and altitude adjustments to keep the plane above cloud cover, or below cover from the terrain or horizon. Camouflage may also have some effect against certain types of sky, and while the plane is on the ground.

Electronic warfare capabilities can be employed by airplanes in much the same way as discussed for ships above, by using emitting decoys, jamming missiles and ISR platforms, and by generating virtual decoys. Typically, dedicated aircraft are employed for this role.

4.3.3 Manoeuvring and dispersal

Manoeuvring and dispersing is the default state for airborne units to an even larger extent than for those at sea. Indeed, fixed wing aircraft must keep moving simply in order to not fall down. The large speeds involved also means a considerable distance is normally kept between each aircraft, to reduce the chance of collisions. The high speeds and manoeuvrability of aircraft also means long range SAMs and AAMs must have even more advanced capabilities for navigation and homing than those of anti-ship missiles.

Similar to the case with ships, these advantages are to a large extent lost while the airplanes are on the ground. The increased vulnerability can be mitigated by dispersing these over multiple bases, by keeping some distance between planes at the same base, and by using various means to protect the base itself. This is discussed more in the section on protecting stationary infrastructure.

4.3.4 Damage mitigation and rapid repair

Doing serious repair work while in the air is not an option. However, organizing repair work on the ground in such a way as to minimize down time can mitigate the effects of some cases of damage.

4.4 Countering threats against mobile land units

4.4.1 Direct protective measures

Land based units have the opportunity of utilizing terrain for protection, for instance by taking cover behind mountains or other land features. These features can also be modified, for instance by digging ditches in which to take cover. Many land units are also armoured, and manoeuvring army units will often include mobile short and long range air defence platforms.

4.4.2 Deceptive measures

In addition to opportunities for cover, terrain also provides ample opportunities for hiding or masking land units behind various features. This, together with camouflage, make up the most important deceptive measure undertaken by land units. The use of decoys in the form of cheap structures designed to look like valuable army gear is also common. Stealth technology and electronic warfare is also an option. Even in cases where the missile does not make use of radar homing, EW can have a debilitating effect on the navigation system of an incoming missile, by denying it use of satellite navigation and forcing it to make use of less accurate INS. In addition, EW can be used against ISR platforms, particularly to inhibit their communication with the C2 network.

4.4.3 Manoeuvring and dispersal

Unlike the case with air and naval units, manoeuvring is not necessarily the default state for land units in the field. However, it is still common to undergo movement at regular intervals. If these intervals are sufficiently short, regular manoeuvres can create severe difficulties for land attack cruise missiles, many of which move at subsonic speeds and are set to navigate to fixed coordinates that cannot be changed after launch. However, as seen from the map in Figure 2 above, this would require relocations at least every hour, which must be expected to be at least occasionally unpractical. But even considerably less frequent relocations can create difficulties in targeting units, since after every movement, time and effort must be spent by ISR platforms to relocate and identify the unit and determine its new position. It is also worth noting that the probability of successfully evading incoming missiles by manoeuvring would be significantly increased if early warning of the missiles could be provided, for instance by a surveillance radar system. Such early warning would also increase the probability that the missile could be shot down by a long range air defence platform.

The benefits of manoeuvring are thus particularly large against slow moving cruise missiles, but somewhat smaller against ballistic missiles. While the benefits of complicating ISR would still be present, it is unlikely that a land unit would be able to evade an incoming high precision ballistic missile by manoeuvring. The flight time of a short range ballistic missile is only a few minutes, and over such short time scales a land unit is unlikely to be able to move out of the missiles terminal homing area. Effective use of deceptive measures, or luck in the form of cloud cover might improve upon this situation. In addition, ballistic missiles have due to their expense conventionally been employed mostly against stationary targets.

The dispersal of units is also something that must be done more deliberately in the case of land units. While the conditions of movement enforces at least some distance between naval and air platforms, no such conditions offer themselves to slow moving units on land. In addition, terrain features might make it more tempting to keep units close together, and war fighting against other land forces might cause them to keep close in order to increase own fire power. Thus, deliberate decisions are required to maintain adequate distance between units, with the goal of making sure each missile meeting its target destroys only that one target.

4.4.4 Damage mitigation and rapid repair

Clearly, the ability to rapidly repair or replace damaged equipment, and to replace wounded personnel as quickly as possible, can have important mitigating effects on units that have suffered moderate damage from missile fire.

4.5 Countering threats against stationary infrastructure

4.5.1 Direct protective measures

Hardening and utilization of terrain for cover are both commonly applied for protection of stationary infrastructure. Particularly valuable assets can even be placed underground, or on the inside of mountains. Various air defence platforms may also be used for protection, and these platforms have less requirements for mobility than those protecting manoeuvrable units. While particularly valuable military installations are often protected by short range point defences, most civilian infrastructure will require protection from long range area defences. These area defences may consist of long range SAM systems, possibly with some contribution from intercepting fighter planes.

4.5.2 Deceptive measures

Efforts are often made to keep the location of important infrastructure secret. This can be done by using terrain features or camouflage to hide it, by hiding it underground, or by masking it as less important infrastructure, often of the same type as those in its surroundings. Use of decoy infrastructure is also possible. This can be done by constructing physical decoys, designed to resemble particular types of infrastructure, or it can be done virtually by spreading confusion about the true location of secret installations. It is however important to note that the use of deceptive means is at a disadvantage in their application to stationary targets, relative to those that are movable. This is because the time scales enemy sensors and ISR networks have available to discover such targets is so much longer. Potentially, these networks can grind away at available data and potential sources for years in advance of an actual attack, which makes it much more difficult to keep the locations secret.

4.5.3 Manoeuvring and dispersal

By definition stationary targets lack the ability to manoeuvre, which is why these are the most vulnerable elements in the face of an enemy missile attack. However, while the infrastructure itself cannot be moved, as long as sufficient warning time is available, steps can be taken to remove personnel as well as particularly valuable equipment and supplies from the location. This can greatly reduce the harm caused by such attacks. If early warning is unlikely, attacks can be complicated by constantly shifting personnel and movable equipment between different compatible locations. For instance one can regularly move aircraft between available airbases and ships between ports. As a related point, one can also make sure such equipment is spread out between multiple available locations. The stationary infrastructure itself should also be spread out, in the sense that crucial infrastructure elements should not be built close together when this is not necessary. In addition, one should avoid situations where a single piece of infrastructure is the only one that can provide some crucial capability.

4.5.4 Damage mitigation and rapid repair

Effect of missile hits can to a large extent be mitigated by making sure that damaged infrastructure can be rapidly repaired, and that damaged equipment and lost supplies can be quickly replaced. Efforts in this direction will be made easier if the most valuable and difficult to replace equipment can be moved upon warning, in the manner discussed above

5 Models

5.1 Qualitative model

The main categories of defensive measures discussed above make their impact on different stages of a missile attack. These stages are illustrated in Figure 5.1, together with the defensive means that can be used to inhibit them.

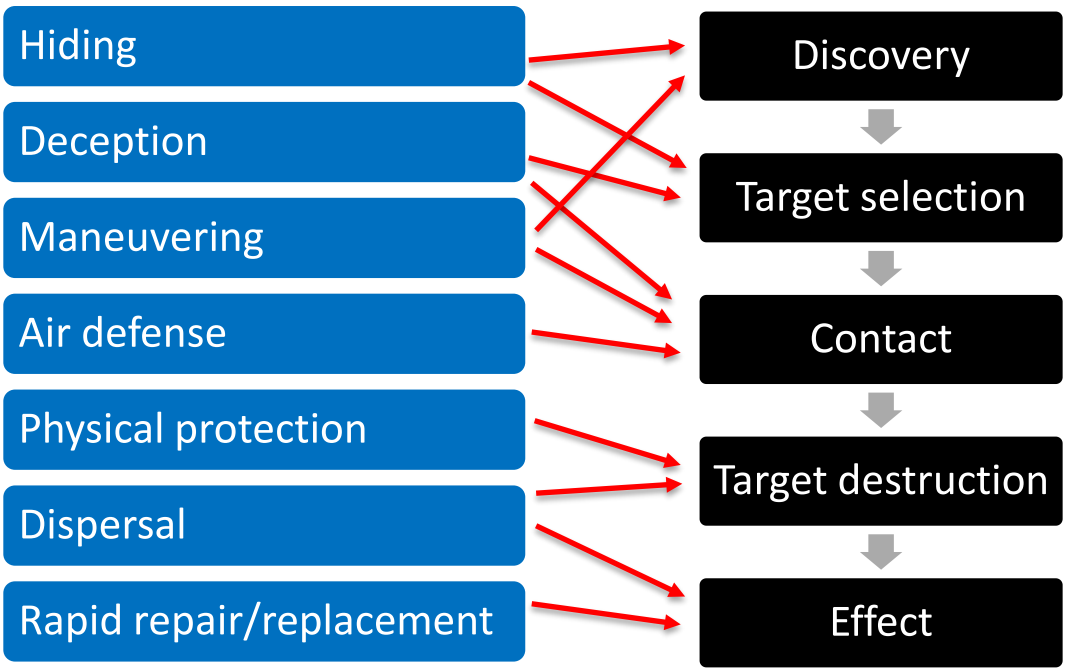

Figure 5.1 Model of the effect of defensive measures. Red arrows denote inhibition.

As can be seen from the figure, the model assumes five stages, or objectives that must be achieved for an attack to be considered successful. First, a set of relevant potential targets must be discovered. Then, actual targets must be selected among the set of potential targets. Then, the missiles must make their way successfully from the firing platform to the targets. Then some subset of the targets must be destroyed, and finally this destruction is intended to have some effect.

The defensive measures work by inhibiting one or more of these stages. Hiding clearly is intended to inhibit the discovery stage, but also works together with deception to complicate the target selection stage. Together these measures create confusion about which targets are real, and may force the attacker to include a much greater selection of locations in his attack, in order to be sure to achieve his objective.

Manoeuvring can, as discussed above, potentially have an effect both on the discovery phase and on the contact phase. If the missiles are not too fast, manoeuvring units can with some luck, or with early warning, evade incoming missiles. In addition, manoeuvring complicates the job of the opponent's ISR network, as this may have to reacquire targets after every relocation. The contact stage can also be inhibited by deceptive means, since these may confuse incoming missiles about the true location of their intended targets. Finally, another way of stopping missiles from successfully making contact with their targets, is to shoot them down with air defences.

If the missiles do successfully reach their target, the destruction of the target can be inhibited by physical protection measures. If the target is a unit with multiple subcomponents, spreading these components over a large area can also make sure most of the unit is not destroyed. Such dispersal can also be considered a way of limiting the effect of the attack, by minimizing the capability lost with each successfully destroyed target. The same effect is gained by dispersing capability over multiple units or infrastructure elements. Finally, the effect of the attack is also limited by an ability to rapidly recover lost capability, by repair or replacement.

5.2 Simple quantitative model

5.2.1 What quantity should be modelled?

Defensive measures such as those described above can have at least two different levels of aspiration. They can either aspire to make it completely impossible for the attacker to achieve his objective, or they can aspire to increase the associated cost of achieving this objective. High costs reduces the probability that the aggressor will be willing to attempt an attack in the first place. Further, if the attack is made, high costs will have strategic consequences, since the attacker must consume resources which could otherwise be spent on other objectives. Thus, sufficiently high costs may push an attack outside of the realm of rational options.

A model of defensive measures should ideally have something to say about both of these effects, i.e. to what degree it is at all possible for an attacker to achieve his objective, and in the event that it is possible, what expenses are required to achieve it. Often, conclusions about the former subject will follow as a consequence of the second, since what stops the attacker from achieving his objective is often the availability of resources. Thus, the cost of an attack seems like a reasonable choice of quantity to model.

In fact, in terms of this cost one can write down concrete mathematical expressions for what is required for successful defence, although these are obviously still difficult to apply in practice. In particular, in order to make an attack completely impossible, one requires

$$C(A) > R \quad \forall A \in S_A,$$

where A denotes an action that the aggressor may take, $C(A)$ is the cost associated with this action, R is the total amount of resources he has available, and S_A is the selection of actions A that the defender wants to stop, i.e. the selection of "attacks".

The conditions of success for the lower ambition of merely deterring attacks, can on the other hand be formulated as

$$C(A) > V(A) \quad \forall A \in S_A,$$

where $V(A)$ quantifies the "value" the aggressor expects to gain by taking action A. Note that increased costs can be imposed also by reducing $V(A)$. That is, if for some particular action $V(A)$ is reduced so much that the above condition is satisfied, then the attacker may be forced to instead consider actions that are more expensive. This applies in particular to those defensive measures which we in the above discussion have categorized as "effect mitigation".

Accordingly, we construct in the following a simple model of the cost of an attack. In order to limit the complexity of the model, we evaluate this cost simply as the number of missiles that must be expended by the attacker. We then assess the model by judging its suitability in a few example cases.

5.2.2 Construction of the model

We begin by assessing how many targets the attacker must destroy. In general we expect that the effect the attacker wishes to achieve, is to reduce the capability of the defender by some amount over some time period. In order to achieve the desired reduction in capability, the amount of units/platforms/infrastructure delivering this capability must be reduced to some level L. Assume that there are N of these elements in the first place, and that R elements can be repaired or replaced so quickly that the down time does not contribute towards the attacker's goals. Then in order to achieve the desired effect, he must incapacitate N – L + R elements.

Next, we must figure out how many targets the attacker must engage in order to achieve this amount of incapacitation. First, assume that each element has a probability P_E of successfully evading an incoming attack. Thus, if the attacker engages Y elements, only $(1-P_E)Y$ of these engagements will be successful. So in order for the objective to be achieved, at least

$$N_R = \frac{N - L + R}{1 - P_E}$$

real elements must be engaged. In addition to this, some selection of the targets perceived by the enemy may be decoys. Assume that there are a total of D decoys, and that each decoy has a probability P_F of successfully fooling the attacker into thinking it is a real target. Assume also that each real target has a probability P_H of successfully hiding. Then on average the attacker will perceive that there are $(1-P_H)$ N + P_F D targets, of which only $(1-P_H)$ N will be real. Accordingly, the probability that a perceived target is in fact a real target is

$$P_R = \frac{(1-P_H)N}{(1-P_H)\mathrm{N} + P_F D}.$$

Thus, in order for a sufficient amount of real targets to be engaged, the amount of perceived targets that must be engaged is

$$\frac{N_R}{P_R} = \left(1 + \frac{P_F}{1-P_H}\frac{D}{N}\right)\frac{N-L+R}{1-P_E}.$$

Finally, if the targeted elements are not sufficiently dispersed, each successful engagement may actually destroy or incapacitate multiple elements. So assume that on average each successful engagement destroys x of these elements. Then the total amount of engagements required is reduced by a factor of x, and accordingly the total number of locations that needs to be attacked is

$$N_L = \frac{1}{x}\left(1 + \frac{P_F}{1-P_H}\frac{D}{N}\right)\frac{N-L+R}{1-P_E}.$$

In order for this to even be possible, N_L must be smaller than or equal to the number of targets perceived. I.e. we must have $N_L \leq (1-P_H)$ N + P_F D. This inequality can be solved to find the relation

$$N - L + R \leq x(1-P_E)(1-P_H)N,$$

which simply states that the number of elements that must be destroyed cannot exceed the amount that can be destroyed, when hiding, evasion and dispersal is taken into account.

Finally, we must assess how many missiles the attacker must expend per engaged location. First, we assume that in order for a target to be destroyed, it must be hit by H missiles, or more precisely that H missiles must hit sufficiently close. We also assume that a selection of missiles approaching a location will be engaged by A air defence missiles, each of which has a probability P_k of taking down one of the incoming missiles. Then on average P_k A missiles will be shot down, so in order to destroy the target H + P_k A missiles must be launched at it. Accordingly, the total number of missiles the attacker must expend is

$$M = \frac{1}{x}\frac{1}{1-P_E}\left(1 + \frac{P_F}{1-P_H}\frac{D}{N}\right)(H + P_k A)(N - L + R).$$

5.2.3 Discussion

Clearly the above model is lacking in many ways. Some of the specific points that should be addressed when considering generalizations are:

- *The evaluation of cost in terms of expended missiles*. To obtain a more useful estimate of cost, missiles should be weighted either by monetary value or some other measure of cost which depends on the type of missile. In addition, there may be other costs not necessarily related directly to the expenditure of missiles. If multiple missile types are considered, clearly one must also take into account that other model parameters may depend on the missile type.

- *The formulation of the attacker's goal.* It may not be justified to assume that the attacker's goal is to reduce a particular set of elements to a level L for some time period. First of all, it may not be a goal of the attacker to reduce capabilities at all. Instead, his goal may be simply to use the attack as a scare or diversion tactic. Secondly, the maximum value *L* over some time period *t* is a very coarse measure of lost capabilities, and a more fine grained description might instead express this effect in terms of the integral of capabilities over the period. In that case one should also employ a more detailed description of recovery capabilities.

- *The description of the attackers target selection.* In general the situation faced by the attacker will be more complicated than one where each real target is either successfully hidden or visible, and each decoy is either successfully perceived as real, or known to be a decoy. Instead the attacker will be faced by a selection of varying signals and intelligence, and for each of these must judge the probability that it originates in a real target, as well as what level of probability justifies an attack.

- *The description of target destruction.* In general there will be some variation in how accurately a missile hits its target, causing variation in how much and if the target is damaged. In addition there is some chance that the missile could be a dud. However, both of these aspects can be accounted for by increasing the parameter H.

- *The effect of dispersal.* The model assumes that each engaged location on average causes x elements to be destroyed, independently of the distribution of perceived targets. But in reality, if two engaged locations are close together, the missiles kill zones may overlap, which would reduce the value of x. Thus, if there are clusters of perceived targets, the model overestimates the number of elements that can be destroyed.

- *The description of air defence.* In order to make accurate predictions, the model of air defence engagement would need more details, and could end up becoming quite complicated. In general the number A of air defence missiles launched may depend on the number and type of incoming missiles. As formulated here, the value of P_k will also depend on the number B of air defence missiles assigned to each individual missile, since only one of these will actually take down the missile. Further, B may also depend on the number and type of incoming missiles. In fact, it is reasonable to expect the defender to select A and B so as to maximize the chances of surviving multiple attacks. Finally, a generalization of the model may be needed to account for long range area defence, which may cover multiple locations.

- *The use of averages.* The model is obtained by making rough estimates in terms of a sequence of averages. In order to precisely calculate the required expenditure of missiles, these should instead be expressed as integrals over multivariate probability distributions. The replacement of such expressions with a product of averages is a crude approximation, and can have a quite large impact on the result. As an example, the model above assumes that if every location is engaged with $H + P_k A$ missiles, $P_k A$ of these will be shot down, and the required number of H missiles will hit each target. But in reality $P_k A$ is the average number of missiles shot down, which means that in half the cases more missiles are shot down, and in half the cases fewer missiles are shot down. Thus, if $H + P_k A$ missiles are fired at each location, only half of the engaged targets will actually be destroyed.

Even with all these simplifications and limitations, the model may have some use in its ability to produce rough quantitative estimates of the cost imposed on an attacker. In any case it is useful for illustrative purposes. As a first illustrative application, the model shows the cumulative effect and cooperative amplification of defence efforts, which is illustrated by the expression of the expenditure M as a product of five factors. Assume for instance that each of these factors are increased by one quarter. Then the expenditure M for the attacker increases by a factor of $1.25 \times 1.25 \times 1.25 \times 1.25 \times 1.25 \approx 3$, whereas if the effects were instead combined linearly, the result would have been just 2.5. Thus, due to this nonlinearity the effectiveness of each new defensive measure increases with the amount of measures already in place.

The model also illustrates well the effect of different defensive measures, as shown in table 5.1 below, which shows how the model parameters are affected by different defensive measures.

Table 5.1 Effect of defensive measures on model parameters.

Defensive measure	**Increases**	**Decreases**
Physical barriers	H	
Air defence	A, P_k	
Hiding	P_H	
Deception	D, P_F	
Manoeuvring	P_E, P_H	
Dispersing targets		x
Dispersing capabilities	N	L
Rapid repair and replacement	R	

5.2.4 Examples

In this section we consider some examples of systems threatened by A2/AD capabilities, and try to apply the above model. The numbers introduced for this purpose are arbitrary illustrative values.

5.2.4.1 Radar stations

As a first example, we can consider radar stations. Let's say there are five radar stations in total, and that four are required to cover the entire air space. Then it is reasonable to assume the enemy will want to reduce the number to three. Thus, N=5 and L=3. Further, if radar coverage is reduced even for a day, this will probably be enough for the enemy to take some advantage of the situation. Thus, we might expect the goal of the attacker to be that this reduction should last for at least a day, and since a day is probably not enough to rebuild a radar, we have R=0.

Since radars are stationary we have P_E=0, and since it is fairly pointless to build radar stations right next to each other, we can also assume x=1. Finally, we can expect it to be difficult to keep radar stations hidden, both because they are stationary and because the enemy will be able to pinpoint their location whenever they are operational. However, it could be that some radars are kept intentionally in-operational, and these will then have some chance of being undiscovered. Accordingly, we set P_H=0.05. This gives us enough information to assess whether a useful attack is possible. We have

$$N - L + R = 2 \leq 4.75 = 1 \cdot 1 \cdot 0.95 \cdot 5 = x(1 - P_E)(1 - P_H)N,$$

which means the attack is in fact possible.

In addition to the real radar stations, there might be some decoy stations. Some of these might just be passive infrastructure designed to look like a radar, while others might also emit electromagnetic signals intended to resemble radar emissions. Only the second type has any real chance of taking attention away from the true operational radars, while the first type serves only to create confusion about the whereabouts of the inoperational backup stations. In addition to this, the decoy stations are of course also stationary, which means the attacker has the advantage of time when gathering information. Thus, the decoy stations probably don't have a very great chance of fooling the attacker, and we set P_F=0.25. We will assume that there are five decoy stations, thus setting D=5.

Finally, we must assess how many missiles must be fired at each station. It is reasonable to assume that a single hit will be enough to take down the station, so H=1. Further, we might also expect the stations to be protected by air defence. We will assume that up to ten air defence missiles can be fired at an incoming barrage, at that each of these has a 60 % chance of hitting something. Thus A=10 and P_k=0.6. This gives us enough information to evaluate the number of missiles the attacker must expend. We get

$$M = 1 \cdot \frac{1}{1-0} \cdot \left(1 + \frac{0.25}{0.95} \cdot \frac{5}{5}\right)(1 + 0.6 \cdot 10)(5 - 3 + 0) = 1.26 \cdot 7 \cdot 2 = 17.6.$$

Thus, the attacker must evaluate whether an expenditure of about 20 missiles is worth the advantage he would gain by reducing radar coverage for however long it takes to rebuild a radar.

All in all, the model seems to be reasonably well suited to the situation described here. Accordingly, we can try to use it to evaluate some options for improving the defence. Since an easily identifiable cause of vulnerability is the lack of manoeuvrability, let us first consider the effect of making the radars manoeuvrable. This will mean P_E is no longer 0, and will also increase P_H. However, none of these are likely to be very large, so let us set both to 0.1. Then we still have

$$N - L + R = 2 \leq 4.05 = 1 \cdot 0.9 \cdot 0.9 \cdot 5 = x(1 - P_E)(1 - P_H)N,$$

So the attack is still possible. However, the missile expenditure is now

$$M = 1 \cdot \frac{1}{0.9} \cdot \left(1 + \frac{0.25}{0.9} \cdot \frac{5}{5}\right)(1 + 0.6 \cdot 10)(5 - 3 + 0) = 1.1 \cdot 1.28 \cdot 7 \cdot 2 = 19.7.$$

Thus, we get a marginal increase in the cost of an attack. Next, we may consider doubling the number of decoys. We then find a new value of M as

$$M = \left(1 + \frac{0.25}{0.95} \cdot \frac{10}{5}\right)(1 + 0.6 \cdot 10)(5 - 3 + 0) = 1.55 \cdot 7 \cdot 2 = 21.7.$$

A few additional options for improving the defence are considered in the table below.

Table 5.2 Defensive improvements, Radar stations.

Measure	**Assumed effect**	**Estimated expenditure M**
None		17.6
1. Making radar stations manoeuvrable	Increases P_H to 0.1, Increases P_E to 0.1	19.7
2. Doubling number of decoys	Increases D to 10	21.7
3. Improving quality of decoys	Increases P_F to 0.35	19.2
4. Doubling air defence size	Increases A to 20	32.8
5. Hardening radars	Increases H to 2	20.2
6. One additional radar station	Increases N to 6	26.5
All of the above	All of the above	83

These results are also illustrated graphically in figure 5.2 below. The included improvements are those marked by 1-6 in the above table, and they are enumerated in the same order as they are listed in the table. The results of individual improvements are shown as coloured columns. The figure also shows the result of pairing improvements, and these are shown as horizontal bars. The solid bars show the actual results estimated by the model, while the dashed bars show simple linear combinations of the individual improvements. The colours of the bars show which improvements are combined: A particular bar shows the result of combining the two improvements corresponding to the column right below the bar, and the one in the same colour.

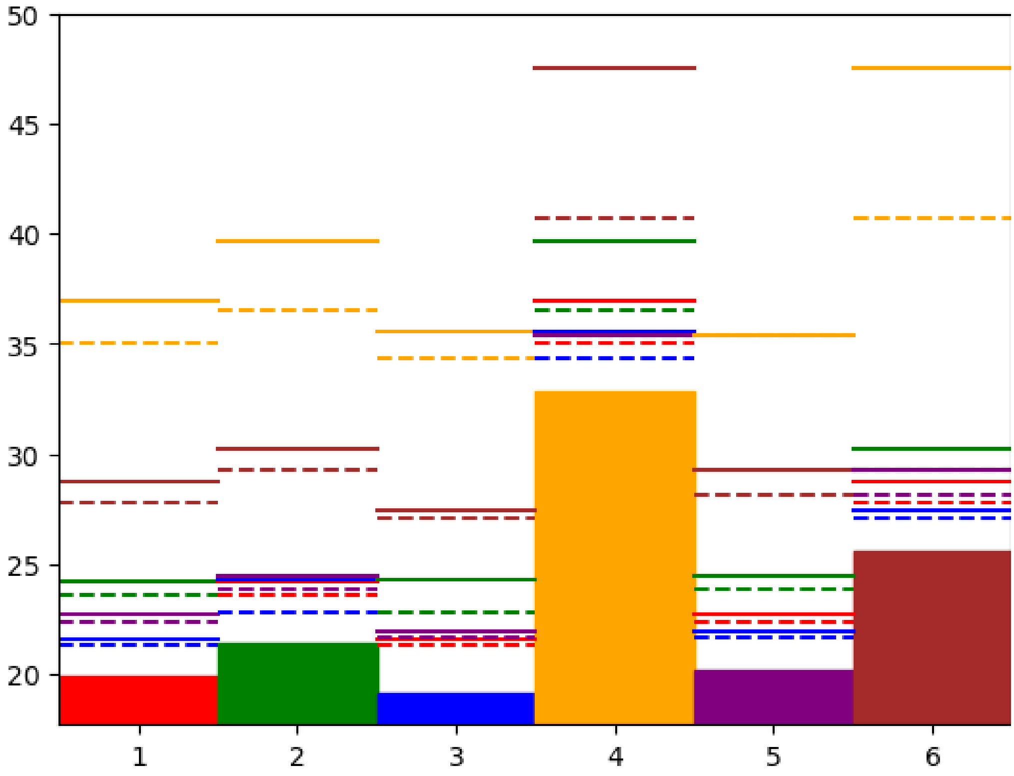

Figure 5.2 Defensive improvements, Radar stations.

The comparison of individual improvements in this figure is not all that valuable, since we have not made any attempts at comparing the costs related to these improvements. What is more interesting is the fact that the effect of the combined measures is in all cases larger than the result of the simple linear combination. This is of course in accordance with the discussion above.

To investigate more closely the effect of combining multiple measures, we include also the Figures 5.3 and 5.4. Figure 5.3 plots the total effect against the number of measures included. Again, this is not very informative, due to the large variation in effect between individual improvements. Thus, in Figure 5.4 we instead plot the same total effect against the linear combination of individual effects, i.e. the estimate showed as dashed bars in Figure 5. The result of this linear combination model is also included as a dotted line. The distinction between the two models is quite clear. In particular, the full model estimates the combination of all six measures to result in an expected expenditure of 83 missiles, whereas the simple linear combination estimated an expenditure of just about 50 missiles. This illustrates the quite significant cumulative effect of defensive measures.

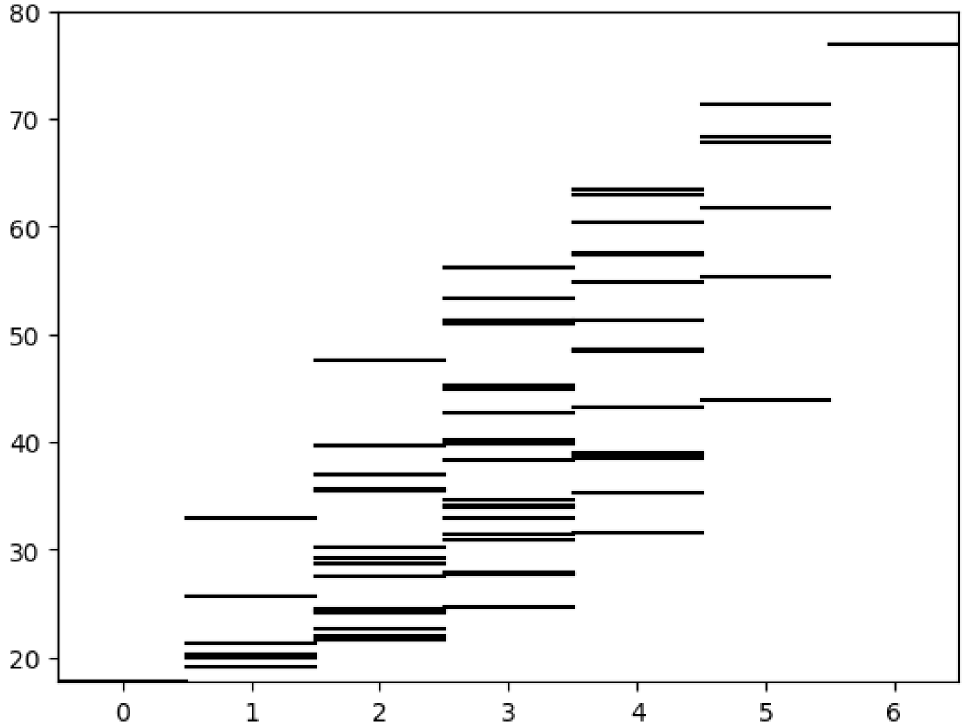

Figure 5.3 Effect vs number of combined measures.

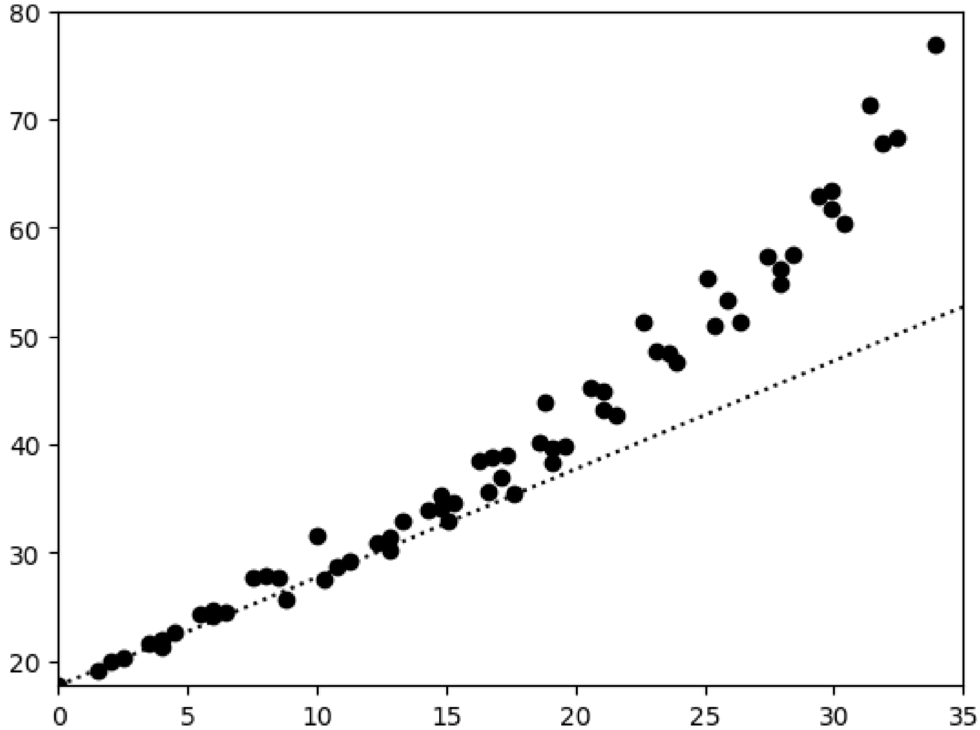

Figure 5.4 Effect vs linear combination.

5.2.4.2 Maritime patrol aircraft

As our next example, we consider maritime patrol aircraft. Again, we assume that there are five of these in total, and that four operational planes are required to provide continuous coverage. Further, we can expect the replacement of a lost plane to take some time. Thus, as in the last example we have N=5, L=3 and R=0. The planes are also non-stealthy and slow, so we assume $P_E=P_H=0$. Finally, as discussed previously, a lack of dispersal is usually not a problem in the air, so x=1. Thus, we have

$$N - L + R = 2 \leq 5 = 1 \cdot 1 \cdot 1 \cdot 5 = x(1 - P_E)(1 - P_H)N,$$

which according to the model introduced above, means it is possible for the attacker to achieve his goal. In any case, this part of the model is probably not very useful in this case, since it assumes the attacker will want to attack all units simultaneously. When attacking airplanes on patrol, this is not a realistic assumption.

We will assume that each patrol aircraft has a selection of ten decoys, being either chaffs or flares, which it can release if engaged by air defence or air to air missiles. However, since these decoys are intended to fool incoming missiles, rather than the sensors employed by the launch system, it is actually better to model these as air defence missiles. Thus, we set D=0 and A=10, assuming that the patrol aircraft does not carry additional air to air weapons. We will assume that the decoy has a pretty decent chance of fooling the missile, and so set $P_K=0.6$. Since we are modelling the decoys as defensive missiles, it is P_K that corresponds to the probability of successful deception. We also assume that the plane has some tolerance for hits, since by luck missiles could hit less vital parts of the plane. Thus, we set H=1.1, which means one in ten planes will survive a direct hit.

With this we have defined all parameter of the model, and we can calculate the expenditure as

$$M = 1 \cdot 1 \cdot 1 \cdot (1.1 + 0.6 \cdot 10)(5 - 3 + 0) = 7.1 \cdot 2 = 14.2.$$

Thus, in this case we find that about 14 missiles will be enough to achieve a significant reduction in coverage.

However, in this case the model is considerably less suited, since some of its basic assumptions are violated. First of all, in this case the purpose of the attack is not really to reduce capabilities, but rather to create risk for surveillance aircraft, and thereby to deter surveillance activity. Secondly, the derivation of the model assumes that all targets will be available simultaneously, which is not the case here, since only one plane will be on patrol at a time. Accordingly, though the results of the model might still serve as a rough estimate, we will not use it to consider improvements in this case. Instead we note this example as one that should be kept in mind when considering possible generalizations of the model.

5.2.4.3 Manoeuvring army units

In this example we will consider an attack on army units operating in the field. We will consider a fairly large unit consisting of 100 platforms of various kinds, including personnel acting as infantry. We assume that the attacker's goal is to reduce the size of the unit down to some level L, which we will keep undetermined for now. Manoeuvring army units have ample options for hiding, so we will assume P_H=0.5. We will also set P_E=0.2, and we will assume the unit is somewhat dispersed, but that individual components are still close enough for each missile hit to cover three platforms. Accordingly x=3. With this we can estimate how many targets can be destroyed. We find

$$N - L + R \leq x(1 - P_E)(1 - P_H)N = 3 \times 0.8 \times 0.5 \times 100 = 120.$$

Accordingly, all 100 platforms can be destroyed if sufficient numbers of missiles are expended. In addition to the actual operational platforms, we assume that the army unit is employing D=40 decoys of various types, and that these are quite effective at deceiving the attacker, so that we can set P_F=0.4. Further, we assume that some platforms are armoured, and that some are not, so that on average H=1.3 missile hits are required to destroy one platform. We also assume the unit to be covered by air defence platforms that are able to fire a total of 160 defensive missiles. Thus, A=160/N=1.6. Like in the previous examples we assume P_k=0.6. Thus, we estimate the missile expenditure to be

$$M = \frac{1}{3} \cdot \frac{1}{0.8} \cdot \left(1 + \frac{0.4}{0.5} \cdot \frac{40}{100}\right)(1.3 + 0.6 \cdot 1.6) \cdot n = \frac{1.32 \cdot 2.26 \cdot n}{3 \cdot 0.8} = 1.24 \cdot n,$$

where n = N – L + R is the number of platforms destroyed. Accordingly, an expenditure of about 1.2 missiles is required per target. To determine a reasonable value of L, this expenditure must be compared to the value of reducing the army size to L, as perceived by the attacker. A comparison of this sort is illustrated in the figure below, where the red curve shows missile expenditure as a function of L, and the blue curve is intended to illustrate a potential relationship between L and the perceived value/utility of the attack. In this particular example, only attacks reducing the number of platforms to a value between about 15 and 90 will be worthwhile. Attacks eliminating less than 10 platforms are too small to achieve a sufficiently valuable effect, while the additional benefit of eliminating more than 85 platforms is too small to justify the extra expense. The optimal attack size according to the figure is one where a little less than 60 platforms are eliminated, expending about 80 missiles. In order to successfully deter the attack, the defender must either increase the recovery capacity R or the expenditure M/n to such an extent that the orange curve no longer intersects the blue one.

When it comes to the suitability of the model, this seems quite good except for one major flaw, which is that the individual platforms must in this case be expected to be too close together for it to make sense that each platform is covered by only one air defence platform. This causes the cost of small attacks to be drastically underestimated. The problem can be fixed by generalizing the model to include long range air defence.

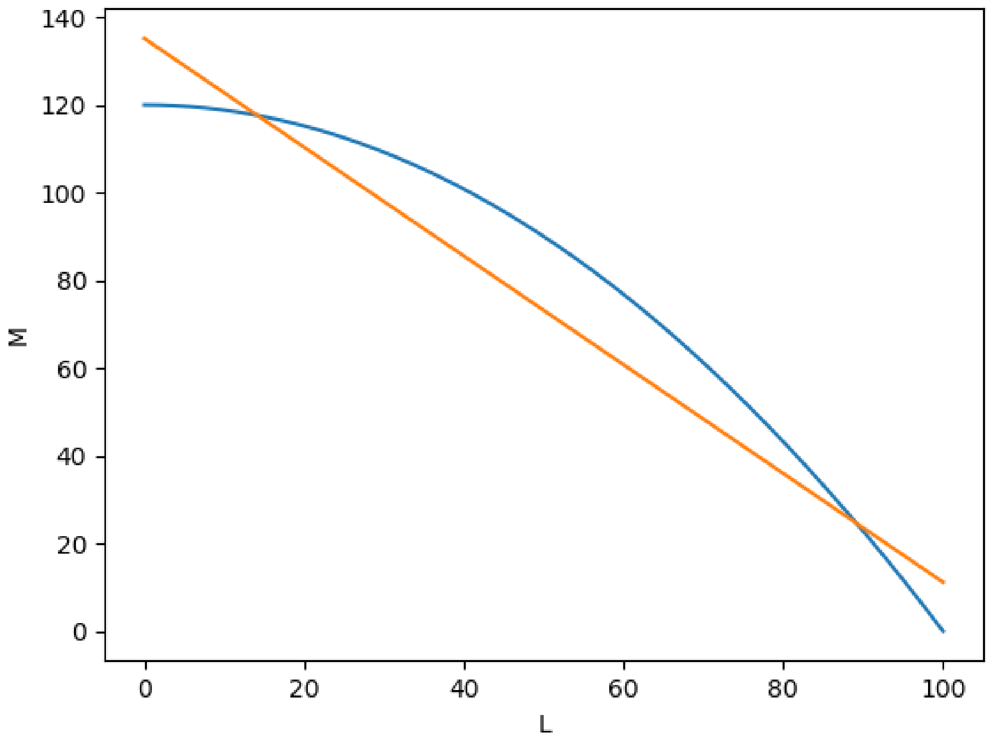

Figure 5.5 Example of value vs expenditure.

An obvious defensive measure in this case is to increase the dispersal of the unit, in order to reduce x to1. This reduces the maximal number of platforms that can be destroyed to $(1\text{-}P_E)\ (1\text{-}P_H)\ N = 40$, and also increases the cost per destroyed platform to 3.7 missiles. In the table below we consider some more options for improving the defence. The results are also shown in figures 5.6–5.8, which have the same format as Figures 5.2–5.4.

Table 5.3 Defensive improvements, Army units.

Measure	**Assumed effect**	**Destroyed platforms**	**Estimated expenditure M/n**
None		100	1.24
1. Increasing dispersal	Reduces x to 1	40	3.73
2. Improve early warning system	Increases P_E to 0.4	90	1.66
3. Better camouflage	Increases P_H to 0.6	96	1.32
4. Improving quality of decoys	Increases P_F to 0.5	100	1.32
5. Doubling number of decoys	Increases D to 80	100	1.54
6. Armouring all units	Increases H to 3	100	2.18
7. Doubling size of air defence	Increases A to 3.2	100	1.77
All of the above	All of the above	24	16.4

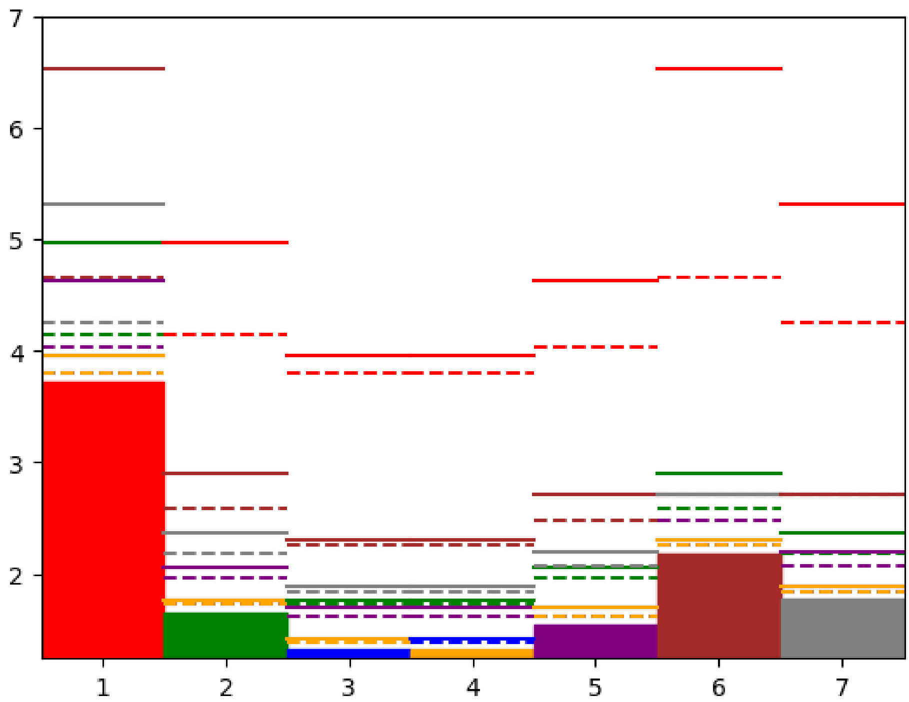

Figure 5.6 Defensive improvements, Army units.

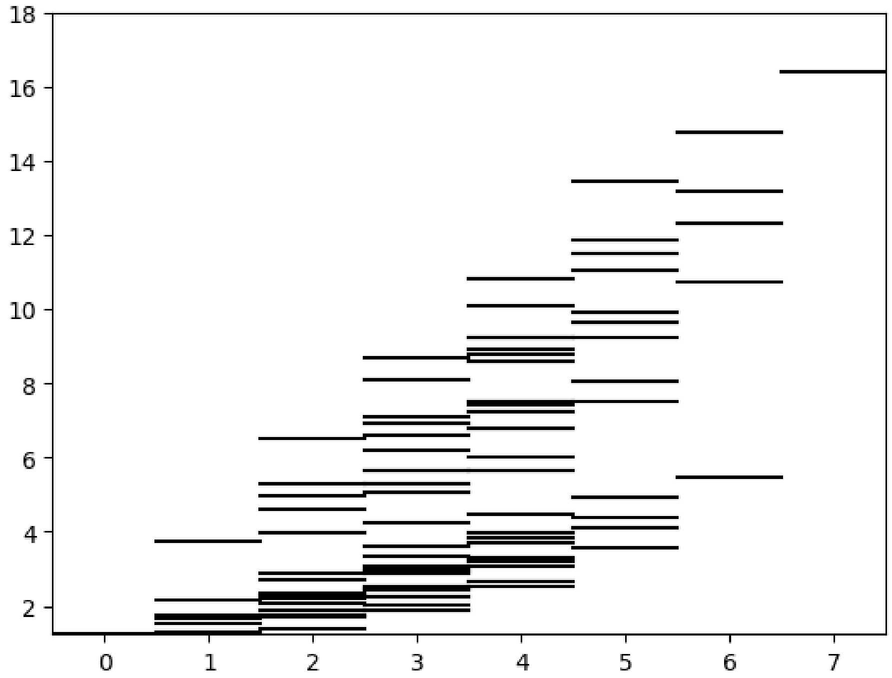

Figure 5.7 Effect vs number of combined measures.

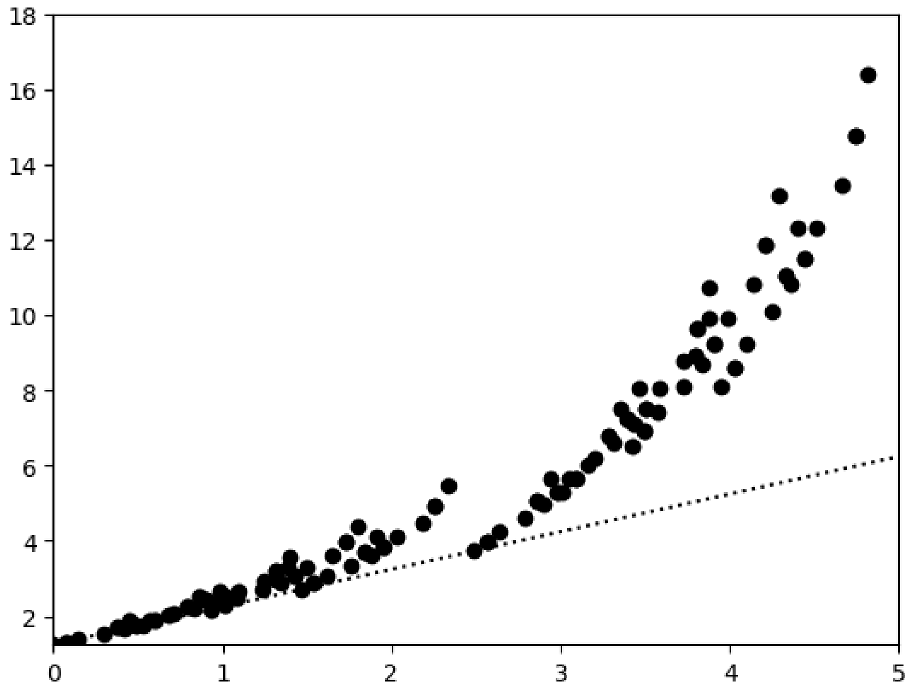

Figure 5.8 Effect vs linear combination.

5.2.4.4 *Operational headquarters*

The final example we will consider is an operational headquarter. We assume there is only one such headquarter, which is immovable and well known. Then N = x = 1 and $P_E = P_H = 0$. We will also assume that if the headquarter is destroyed, then some of its capabilities can be rapidly restored through various means, so that the tasks of the headquarter is still being executed at 25 % of the original capacity. Thus, effectively R = 0.25, and the largest effect the attacker can hope to achieve is to reduce the capability associated with the headquarter to L = 0.25. This can also be seen from the model, which says that in order for the attack to be possible we must have

$$N - L + R = 1 - L + 0.25 \leq x(1 - P_E)(1 - P_H)N = 1 \times 1 \times 1 \times 1 = 1.$$

In this case there are no decoys, so D = 0. Further, we will assume that the headquarter can be rendered inoperable through H = 4 missile hits, and that it is defended by an air defence system capable of firing A = 20 missiles at an incoming barrage. As before we assume P_k=0.6. Then the expenditure estimated by the model is

$$M = 1 \cdot 1 \cdot (1 + 0)(4 + 0.6 \cdot 20) \cdot 1 = 16.$$

In the table below we again consider various options for improving the defence of the headquarter.

Table 5.4 Defensive improvements, Operational headquarter.

Measure	**Assumed effect**	**Estimated expenditure M**
None		16
One additional headquarter	Increases N to 2	32
Moving headquarter to secret location	Increases P_H to 0.01	16
Creating a decoy headquarter	Increases D to 1, Increases P_F to 0.1	18
Replacing headquarter with movable systems	Increases P_E to 0.1	18
Doubling air defence	Increases A to 40	28
Reducing structural vulnerabilities	Increases H to 10	22
All of the above	All of the above	79

Also in this case, the suitability of the model is highly questionable. One particularly important concern is that the derivation of the model assumes a large number of targets, which is likely to make it less accurate when applied to situations where there are only a few of these, and particularly ill-suited in situations like the one considered here, where there is only one single target. This problem originates from the fact that we are expressing the model in terms of averages rather than full probability distributions.

When it comes to the particular values calculated above, some of these do still make sense. In particular, the base value M = 16 obtained without defensive improvements, seems sensible, as do the improvements obtained by modifying the parameters N, A and H. However, it is not clear that the values obtained by changing P_H, D, P_F and P_E have any sensible interpretations. Thus, it is precisely those parameters that are connected to collective defensive effects which are not correctly accounted for by the model. Obviously, it is also of interest to consider ways of generalizing the model to situations where there are only a small number of targets.

6 Summary and conclusions

In this final section, we briefly summarize some of our most important conclusions from this work.

6.1 What is A2/AD?

It is important to keep in mind that the term A2/AD can refer both to a particular military capability, and to a strategy/military concept. When used in the first sense, A2/AD should be understood as describing the ability to limit the operations of certain enemy systems within certain regions. These regions may be geographical or virtual, but must be of strategic consequence. When used in the second sense, the term A2/AD should be understood as a spectrum of strategies employing these capabilities.

In both senses A2/AD describes a spectrum, ranging from a weaker variant denoted AD, to a stronger variant denoted A2. In the capability sense, AD describes merely the ability to limit or suppress operations, whereas A2 describes the ability to keep systems outside of the region in question. When used in the strategic sense, AD could be understood as another name for a strategy of deterrence by denial, where the idea is to impose costs by stretching the conflict out, and continuously suppressing and endangering enemy operations and employment. At the opposite side of the spectrum, A2 should be understood as a strategy aiming to impose total control over a region, and to deny all enemy access.

A2/AD capabilities can be usefully classified according to the means by which they suppress enemy access. Above we have divided these into physical barriers, local means of incapacitation, and short and long range means of incapacitation. Only the last of these four categories describe something that is really new, and it is this category, consisting of fairly modern technologies, which makes A2/AD into such a hot topic. This category, long range means of incapacitation, can again be divided into three components: information warfare, long range electromagnetic warfare, and long range precision missiles. Information warfare is further divided into the two components of influence campaigns and cyberwarfare, while the long range precision missile threat consists of ballistic missiles, land attack and anti-ship cruise missiles, and long range air defences.

6.2 Russian A2/AD capabilities

For Norway's purposes, the currently greatest concern related to foreign A2/AD capabilities, is that Russia may decide to set up an A2/AD zone which covers part of Norwegian territory. Thus, we have attempted to paint a picture of current Russian capabilities related to A2/AD. We have focused on long range capabilities, since this will be required to project A2/AD zones over Norway from Russian soil. In this study we have also limited our overview to missile capabilities, since particularly a discussion of information warfare is deemed to be outside the scope of this report.

As can be seen from Tables 3.1–3.3 and the maps of Section 3.3, Russia has a substantial number of different missile systems that may contribute to the projection of an A2/AD zone, although not necessarily with great numbers of each individual missile type. Further, many of the mentioned missiles are likely to be in storage, and not currently operational. Nevertheless, one must expect the total collection of these systems to be able to inflict considerable losses on, and accordingly to create substantial risk for Norwegian and allied elements within the projected zone. Some of these weapons also have ranges which extend way beyond the borders of Norway, and puts large parts of Europe at risk.

The greatest imposed risk will be to elements on land, and particularly to stationary infrastructure. This risk originates in two different components: ballistic missiles and land attack cruise missiles. As can be seen from Figures 3.1–3.5, the potential warning time associated with these two different threats differs substantially, suggesting that defence against them should also be approached differently. The current range within which ballistic missiles may be used tactically is difficult to ascertain, due to uncertainty in the range of the Kinzhal missile. Obviously, a situation where the Kinzhal's range is comparable to that of the Iskander, from which it is supposedly derived, is entirely different from one where the Kinzhal has a range extending up to the largest estimates of 2000 km. However, with the dissolution of the INF treaty, the existence of Russian IRBMs with ranges in the 2000 km area is in any case likely to soon become a reality.

The risk to naval elements is as of yet smaller than to those on land. Most anti-ship missiles have ranges that are considerably shorter than those of high end land attack missiles, and in addition, it is questionable what chances even a moderately ranged missile has of hitting a moving target at its maximum range. In fact, there is currently a discussion in the literature whether current Russian anti-ship missiles and coastal defences are effective at all when fired at targets beyond the horizon [14]. In any case, this ability must be expected to grow in the future.

At present, the smallest A2/AD threat is that faced by aircraft. As discussed in the literature, there is some uncertainty concerning whether Russia has yet deployed its longest range anti air missile, the 40N6 [21] [12] [14]. And even if this missile is now operational, only a quite small region of Norwegian territory can be reached from launch platforms on Russian soil (see Figure 3.9). Further, as seen from Figure 3.10, this region can be made even smaller by utilizing stealth technology, or by flying at lower altitudes near the border. Finally, the literature questions the ability of these missiles to make course corrections before the target is inside their own active radar range [12] [14]. Thus, as with anti-ship missiles, it is questionable whether long range SAMs have particularly good chances of hitting targets at their maximum range, even if these targets are within radar coverage of the launch system.

6.3 Defence measures

Defensive measures are summarized in Table 4.1, while Sections 4.2–4.5 go into details, respectively related to naval and airborne units, and movable and stationary land based elements. The following are some main points:

- Airborne and naval units are generally less vulnerable than elements on land, but are considerably more vulnerable when on the ground or at port.

- Movable land units are those that have the greatest potential benefit from measures related to manoeuvres and physical dispersal.

- Stationary infrastructure is the most vulnerable element. This is both because manoeuvring is completely excluded as a defensive measure, and because deceptive measures have a significantly reduced probability of success.

- Better airspace surveillance and increased warning time will be highly beneficial in multiple different ways. This will give movable units the opportunity to manoeuvre on warning. Stationary elements will have time to evacuate personnel, as well as its most valuable materiel and equipment. Long range area defences will have much better chances at shooting down missiles before they reach their target. And finally, with sufficient warning times, missiles may even be intercepted by fighter planes. However, this measure cannot be expected to significantly improve defence against ballistic missiles, since the earliest possible warning time will in any case be very short (see Figures 3.3–3.6).

6.4 Quantitative modelling

Very often defensive measures work by imposing a cost upon the attacker. Thus, we have developed a model which gives a rough estimate of the cost associated with an attack, measured in terms of the number of expended missiles. The predictive value of the model is quite limited, both because of the inclusion of several numerical parameters which are difficult to estimate, and because of aspects of the models derivation, which limit its realism. In particular, these aspects are related to the measurement of costs in terms of missile numbers, the formulation of the attacker's goal and target selection, the effect of dispersal on losses, limitations in the description of air defence, and finally the expression of estimates in terms of averages rather than distributions. A more thorough discussion of these limitations is provided in Section 5.2.3.

Even with these limitations, the model does have some limited predictive value, in the sense that it does provide rough order of magnitude estimates of missile expenditures. In addition, the model has considerable illustrative value: It quantifies defence as imposed costs, and illustrates both the effect and the mechanism of different defensive measures. Finally, it illustrates the synergy between different defensive measures, i.e. the way in which they combine in a nonlinear way to create effects that are larger than the sum of individual effects.

The limitations related to the derivation of the model means it must be validated on a case by case basis, since the assumptions of the derivation cannot be expected to fit all situations equally. Above we have assessed the suitability of the model in four different example cases. Of these, the first example, where we considered an attack on radar stations, seemed like the one where the model is best suited. In all of the other examples, considering attacks on patrol aircraft, operating army units, and operational headquarters, at least one poorly fitting element of the derivation could be identified. A few learning points can be gathered from these examples, concerning which cases the model can be expected to be well suited:

- The purpose of aggression should be capability reduction, not deterrence.
- All targets should be available for attack simultaneously.
- Targets should be far enough apart that each air defence unit can only cover one target.
- The number of potential targets should be rather large. If there is only one, or some other very small number of targets, many aspects of the model will still be useful, but results related to collective defence effects will not be meaningful.

It should however be noted that many of these limitations can be removed by introducing fairly simple generalizations of the model. Thus, the presented model should be regarded as a starting point rather than a fully developed model.

Appendix

A Overview of Russian long range missile systems

A.1 Ballistic Missiles

A.1.1 9K720 Iskander-M short range ballistic missile

The **9M723-1**, often referred to as the 9K720 Iskander short range ballistic missile, is a ballistic missile with a burn out velocity of about Mach 6, and a probable operational range of 500 km, right at the limit of the former INF-treaty [46] [47] [48]. This would give it a maximal flight altitude of about 100 km and a maximal flight time of about 5 minutes. The Iskander is able to take some counter measures against anti-ballistic missile defences, by manoeuvring or making use of depressed trajectories [46], and possibly also by releasing decoys [49] [48]. It reportedly also has a low radar cross section [46] [47] [48].

The missile uses INS for navigation, possibly in combination with GLONASS or GPS. During the terminal phase it also has a self-homing capability, making use of radar or optical target recognition. When this is employed it reportedly achieves a circular error probable of about 5 m [46] [49] [47] [48]. It is unknown whether the missile can be retargeted during flight [46].

The warhead comes in multiple variants, with referenced weights being either 700 or 480 kg [46] [47] [48] [3]. There may also exist a nuclear variant of the warhead [46] [49] [48]. It is important to note that the referenced 500 km range depends upon the weight of the warhead, as the range decreases with the weight of the missile. It is unknown which warhead the 500 km range statements refer to [46].

Estimates have the Russian military operating a total of about 500 Iskander missiles [50].

A.1.2 Air-launched ballistic missiles

The **Kh-15** is an air-launched ballistic missile with a range of 150 km when launched from altitude [51]. The Kh-15 dates from about 1980, and relies on inertial navigation. The accuracy can be significantly improved by utilizing active radar homing during final approach, as is done by the anti-ship version of the missile. The purely INS based missile carries nuclear weapons, which reduces the accuracy requirements. The missile can be carried by Su-33, Su-34, Tu-95, Tu-22M and Tu-160, but its operational status is uncertain [52].

However, Russia has just recently fielded a new air-launched ballistic missile known as the **Kh-47 Kinzhal**, which is likely to be an air-launched version of the Iskander [46] [53] [54] [55]. The Kinzhal probably has an accuracy similar to the Iskander, and carries a somewhat lighter warhead at 500 kg [55]. The lighter warhead together with the fact that the missile is air-launched means that the range will be somewhat longer than that of the Iskander. Official claims have the range at 1500-2000 km [53] [54], but this is implausible unless it has either been significantly upgraded or the original Iskander has considerably longer range than what has been reported. The missile is launched from MiG-31K and Tu-22M3 [53] [55]. It may also be intended as an anti-ship missile [53] [54].

A.1.3 Rocket artillery systems

Russia also has considerable fire power in the form of various rocket artillery systems, such as the **Grad, Uragan** and **Smerch**. While the Grad and Uragan are shorter range systems, the Smerch system can fire missiles up to distances of 120 km. The most recent and modernized versions of these systems have all been dubbed **Tornado** (Respectively Tornado-G, U and S). The Tornado artilleries can reportedly fire guided missiles that use the GLONASS system for navigation, giving them significantly improved accuracy over the older systems. Estimates have the Russians operating several hundreds of the shorter range Grad and Uragan systems, and approximately 100 Smerch artillery. Of the latter, at least 20 are of the modernized Tornado variant. Over time, all of the older artilleries are to be replaced by their respective Tornado counterparts [56] [57] [58] [59] [60].

A.1.4 Short range systems that are retired or scheduled for replacement

The **Tochka** missiles are an older set of tactical ballistic missiles that have a range of 70, 120 and 185 km in the case of Tochka-A, B and C respectively [61] [60] [62]. The Tochka C seems to never have finished development [61]. The Tochka missiles also use inertial navigation, and are estimated to have accuracies on the order of 100 meters. Some missiles also have a passive radar capability, and can be used for anti-electronic operations. The warhead can be nuclear or conventional [61] [60] [62]. In total, Russia is estimated to currently be operating about 200 Tochka missiles. However, all Tochka missiles were scheduled for replacement with Iskander by the end of 2020, and according to recent reports this process was completed in March that year [46] [62].

Russia also has an older selection of short range ballistic missiles known by NATO as the **Scud** missiles. These are believe to be decommissioned, but may still be in storage. They have a range of 180 and 300 km in the case of Scud-A and B respectively [63] [60] [64] [65]. In addition to these, development was started on a Scud-C and a Scud-D missile. The purpose of the Scud-C was to extend the range of the Scud-B to 500 km, but the project was abandoned due to problems with achieving sufficient accuracy. The Scud-D on the other hand, was primarily intended to improve the accuracy of the Scud-B by utilizing optical target recognition. While the Scud-D seems to have finished development, it was apparently never deployed [63] [65]. The estimated accuracies are 3000, 450, 700 and 50 m in the case of Scud-A, B, C and D respectively. Again, the warheads can be nuclear or conventional [63] [64].

A.1.5 ICBMs

Russia operates a host of different ICBMs, with ranges between 5000 and 16000 km [60] [66] [67]. Most of these are older, and make use of INS in combination with stellar navigation. Accordingly, these are unlikely to have very high accuracy. The newer missiles probably make use of the GLONASS network. Still, even the newest operational missile is estimated to have an accuracy only in the range of a few hundred meters [68]. It is in any case unlikely that any of these missiles are armed with anything but nuclear weapons, which makes an accuracy of 100 m adequate for most purposes. Current estimates place the total number of ICBMs operated by Russia at about 500, of which about 150 are launched from submarines [60] [67].

A.2 Land attack cruise missiles

A.2.1 Air-launched land-attack missiles

Many of Russia's air-launched land-attack missiles are derived from the **Kh-55**. The Kh-55 itself is a subsonic nuclear armed missile with a range of 2500–2800 km [69] [70] [71] [60]. It makes use of TERCOM navigation, and reportedly achieves an accuracy of 25 m [69] [71]. All of its derivatives are also subsonic, but have differing range and accuracy. The **Kh-55SM** is a simple modification of the Kh-55, which extends its range to 3000 km. The slightly newer **Kh-555** is a conventionally armed version with improved stealth properties and a more modern navigation system [69] [70] [71]. It is estimated to have a range of 3500 km [69] [71], and also to improve upon the accuracy of the Kh-55 [71].

The **Kh-101** seems to be Russia's newest operational air launched cruise missile, and may also be partially derived from the kh-55 [70]. The Kh-101 is supposed to achieve a high degree of stealth, and makes use of TERCOM navigation, possibly in combination with the GLONASS system, to achieve an accuracy in the range 6-20 m [72] [70] [73]. It also has a terminal phase homing capability, making it effective against moving targets [70] [73]. If the Kh-101 carries a nuclear warhead, it is denoted **Kh-102** [72] [70] [73]. Moderate estimates place the range of the Kh-101/102 in the range of 2500-2800 km [73], while higher estimates extend as far as to 4500 km [72] [70] [73]. The large variation in range estimates may be related to a dependency on warhead weight [70].

The Kh-55 and Kh-555 are carried by the Tu-95MS, Tu-142M and Tu-160 [70] [71]. As of 2006 it was estimated that Russia had 872 of these missiles operational [71]. However, modernization efforts are under way, and Russia is replacing an increasing number of these with Kh-101 and Kh-102 [73], which are carried by Tu-95MS, Tu-160, Tu-22M and Su-34 [70] [73]. This process is intended to be completed by 2023 [70].

In addition to these long-range derivatives, there were also efforts to develop shorter range versions of the Kh-55. These include the **Kh-50** and the **Kh-65**, which were supposed to have ranges between 300 and 1900 km. However, these missiles seem to never have entered service [70].

Another important missile family is based on the **Kh-59**. The Kh-59 itself is a short range missile with a maximum range of 90 km [74], but it has several longer range derivatives. The **Kh-59M** replaces the solid rocket motor of the Kh-59 with a turbojet engine, thereby extending its effective range to 115 km [75] [76]. Beyond this range the effectiveness of the missile would be limited by its TV-guidance seeker, which requires a datalink to the launch platform. Thus the **Kh-59MK** replaces this with an active radar seeker, which extends its effective range to 285 km and makes it effective as an anti-ship missile [77] [76]. Finally, the **Kh-59MK2** is outfitted with a TERCOM navigation system similar to those employed by the Kh-55 class missiles, probably in combination with satellite navigation. This makes the missile into a long range precision weapon well suited for land attack missions [77]. The full range of the missile is unclear, but some sources quote as much as 550 km [76].

Just like the Kh-55 derived missiles, the Kh-59 class is subsonic. But unlike the Kh-55 class, which is launched by bombers, the lighter Kh-59 class missiles can be carried by smaller fighter and attack planes, such as the MiG-27 and the Su-17M, 22M, 24M, 25, 30 and 57 [76].

A.2.2 Naval land-attack missiles

Among Russia's many naval cruise missiles that are currently in use, two stand out as intended specifically for land targets. These are the **S-10 Granat** and the **3M14 Kalibr**. The S-10 Granat is the submarine launched version of an earlier land based missile, the Rk-55 Relief/Granat, which was decommissioned due to the INF treaty [78] [79] [80]. The S-10 can also be referred to as RK-55 Granat. It is subsonic [78] [80], has an estimated range of 2400 km [79] [80] [60], and an estimated accuracy of 150 m [79] [80]. It uses INS in combination with TERCOM for navigation [78] [80], and was originally intended to carry both conventional and nuclear weapons [79] [78] [60]. However, it seems that the nuclear variant of the missile has been decommissioned [79]. Estimates of the number of missiles in service range from 36 [50] to 180 [80]. The large span between estimates could be due to increasing numbers of S-10 being replaced with Kalibr [80].

The 3M14 Kalibr, also known as the 3M14 Biruyuza [39] is a modern derivative of the S-10/RK-55, and comes in two variants, the 3M14K which is launched from submarines, and the 3M14T which is launched from surface ships [39] [50]. The missile is subsonic like the S-10. Official statements concerning its range vary between 1500 and 2500 km, and from operations in Syria it is known that it must be at least 1800 km [40] [39] [81] [49] [50] [60]. The Missile combines inertial, TERCOM and satellite navigation with terminal phase ARH, and reportedly achieves an accuracy of 3-5 m [40] [39] [49]. It is estimated that Russia currently operates a total of 76 3M14K and 100 3M14T [50].

A.2.3 Land based land-attack missiles

The **9M728** and the **9M729** are launched from a slightly modified Iskander-TEL system, known as the **Iskander-K**, and are among the most recent cruise missile deployments of the Russian military. Fairly little seems to be known with certainty about these missiles, as there is speculation that they may be new members of the Kalibr family, some other derivative of the Rk-55 Relief, or even land based adaptions of the Kh-101 [46] [48] [47] [82] [78]. In either case, this would likely make them subsonic missiles with long range and high accuracy. The 9M728 is the older of the two, and is reported to have a range of 500 km [46] [48]. The 9M729 is reportedly very similar, and according to Russian official sources has the same range as the 9M728, and just fields a larger warhead and upgraded avionics [46] [48]. However, according to American intelligence the 9M729 has been tested at ranges beyond 500 km, in violation of the INF treaty. In fact, this was the triggering cause for the dissolution of the treaty in 2018 [82] [47]. These sources estimate the maximal range of the 9M729 at 2500 km [82], which also fits with the theory that it is a derivative of the Kalibr, Relief or Kh-101 missiles. According to recent estimates, Russia had at the time fielded 48 operational 9M729 missiles [50].

Possibly, Russia also operates an older land based land attack missile, the **S-35**, which is based on the earlier naval P-35. It is subsonic like the other land attack missiles, but has a shorter range of 450–1000 km, and a considerably poorer accuracy of about 3000 m. It makes use of an older guidance system based on INS together with TV-guidance, and ARH or IRH for terminal phase homing [83] [84].

A.3 Anti-ship cruise missiles

A.3.1 Air-launched anti-ship missiles

Russia is operating several air-launched cruise missiles that are intended primarily for an anti-ship role. The **Kh-35** is a subsonic missile with a range of 130-300 km, where the largest values refer to an upgraded version [85] [86]. The **Kh-31** is a relatively short range missile, but is supersonic with a top speed around Mach 3. Most versions have a maximal range of 110-160 km, but the most recent anti-radiation version may have a range of up to 250 km [87] [88]. The **Kh-22** is also supersonic, and seems to have a range in the region of 200–600 km, and a top speed between Mach 3.5 and 4.6 depending on the model [89] [90] [50]. A modern version of the Kh-22, the **Kh-32**, seems to have traded increased range for a smaller warhead, and is said to have a range of 800 km [89], with some estimates extending up to 1000 km [91]. Another supersonic missile is the **Kh-41,** which is an air launched version of the naval Moskit missile to be described below. Current indications are that the air launched missile was never fielded, and as such, little information is available. It is estimated that it has a range of 250 km and a top speed of Mach 3 [92] [93]. Some sources also mention an air launched version of the naval Oniks missile, referred to as **Kh-61** [94]. All of the mentioned missiles make use of INS for navigation and ARH for terminal phase homing [85] [86] [87] [88] [89] [90] [91] [92] [93]. Then newest version of the Kh-35 may also be using satellite navigation [85].

As mentioned, the Kh-59MK can also be employed as an anti-ship missile. It is described above under air-launched land attack missiles, as part of the Kh-59 class. The Kh-15, which is also an air-launched anti-ship missile, is ballistic and described in Appendix A.1.2.

A.3.2 Naval anti-ship missiles

Many of Russia's naval anti-ship missiles are derived from the **P-500 Bazalt** missiles system, which was itself derived from the now decommissioned P-5 and P-35 missiles [95]. The derivatives include the **P-700 Granit**, the **P-800 Oniks** and the **P-1000 Vulcan** [96] [97] [94]. The P-500 itself has an estimated range of 550 km, and a top speed of Mach 2.5. It uses ARH and SARH for terminal homing [95] [96] [50]. The P-1000 is only a moderate upgrade and very similar to the P-500 itself, although it seems to have a somewhat longer range. The typical estimate seems to be 700 km, but some go as far as 1000 km [95] [96] [97]. The P-700 is a new design, but has similar performance to the P-500. Range estimates vary from 550 to 625 km, while the top speed is thought to be Mach 2.5 [95] [97] [50]. It uses INS together with Legenda satellite navigation, and ARH and passive radar for terminal homing [97]. Also the P-500/1000 may have used the Legenda system at some point [95].

The P-800 Oniks has an estimated top speed of about Mach 2, and is usually stated to have a maximum range of 300 km [94] [98] [99]. There are however claims that this refers to the export version, and that the domestic missile has twice that range at 600 km [94] [50]. This distinction may not be of great importance, since the Russian navy has in any case not fielded the missile in great numbers [99]. It is estimated that no more than 36 Oniks missiles are operational, vs respectively 32 of the close to decommissioned P-500/1000 and 164 of the P-700 [50]. The P-800 makes use of INS together with ARH and passive radar [94] [99], and possibly an IR seeker [98]. The P-500 and all of its derivatives can be launched both from submarines and from surface ships [50] [96].

In addition to the P-5/7/800 series of missiles, the **3M54 Kalibr**, a relative of the 3M14, is a more modern and very capable anti-ship missile. Most sources operate with a 660 km range estimate [100] [39] [50]. Supposedly, the missile carries a combat stage, which is contained within and fired from the cruise stage once the target is sufficiently close [100]. While the cruise stage is subsonic like its land attack relative 3M14, the combat stage performs a sea skimming terminal flight at Mach 3 [39] [100]. The missile uses INS for mid-flight navigation, and ARH for terminal phase homing [39] [100] [101]. There are also claims that it may use satellite navigation [101]. It comes in two variants, the 3M54T which is launched from submarines, and the 3M54K which is launched from surface ships [39] [50]. Reportedly, there also exists versions without the terminal combat stage, which can be recognized by their shorter length [100]. As of 2019 it was estimated that Russia had fielded 20 3M54T and 16 3M14K [50].

Russia also operates two naval anti-ship systems in the lower end of the capability spectrum, the **P-120 Malakhit** and the **Uran**. The P-120 is subsonic, guided by ARH or IRH in its terminal phase, and has a range estimated at 70-120 km [102] [103]. The Uran is the naval version of the Kh-35. As such, it is subsonic, has an estimated range of 130-300 km depending on the version, and is guided by INS and ARH as well as possibly satellite navigation in the case of the upgraded version. It seems to be deployed only on surface ships [86] [104]. Finally, the **P-270 Moskit** is the naval version of the Kh-41. It can be launched from both submarines and surface ships, and has a range of 250 km and a top speed of Mach 3. It uses INS and ARH [92] [93].

A.3.3 Land based anti-ship missiles

Russia has two mobile long-range coastal defence systems. These are the **Bal** system and the **Bastion-P** system, which are, respectively, coastal versions of the Uran/Kh-35 and the P-

800/Kh-61 [86] [104] [105] [98] [99]. The Bal system seems to be a straightforward TEL based implementation of the Uran, and as such its specifications are most likely identical. I.e. it fires a subsonic missile with a range of 130-300 km [86] [3] [104]. The Bastion-P comes in both TEL-based and stationary variants [99]. It is reported to have a top speed of Mach 2.5 and a range of 350 km [105] [50] [3]. There are no indications whether the difference in specifications between the Bastion-P and the P-800 are due to modifications of the missile or just due to the fact that the estimates are uncertain in the first place. Russia has reportedly fielded a total of 2048 operational Bal missiles [86] and 196 operational Bastion-P missiles [50].

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List of acronyms

A2	Anti access
A2/AD	Anti-access/Area denial
AAM	Air to air missiles
AD	Area denial
ARH	Active radar homing
ASW	Anti-submarine warfare
CC	Command and control
C3	Command, control and communications
CEC	Cooperative engagement capability
EW	Electronic warfare
FFI	Norwegian Defence Research Establishment
FOI	Swedish Defence Research agency
GPS	Global Positioning System
ICBM	Intercontinental ballistic missile
IIR	Imaging infrared
INF	Intermediate nuclear forces
INS	Inertial navigation system
IRBM	Intercontinental ballistic missile
IRH	Infrared homing
ISR	Intelligence, surveillance and recognisance
LPV	Long distance precision weapon
RCS	Radar cross section

RV	Re-entry vehicle
SAM	Surface to air missile
SARH	Semi active radar homing
Satnav	Satellite navigation
SRBM	Short range ballistic missile
TEL	Transporter erector launcher
TELAR	Transporter erector launcher and radar
TERCOM	Terrain comparison
TRBM	Theatre range ballistic missile

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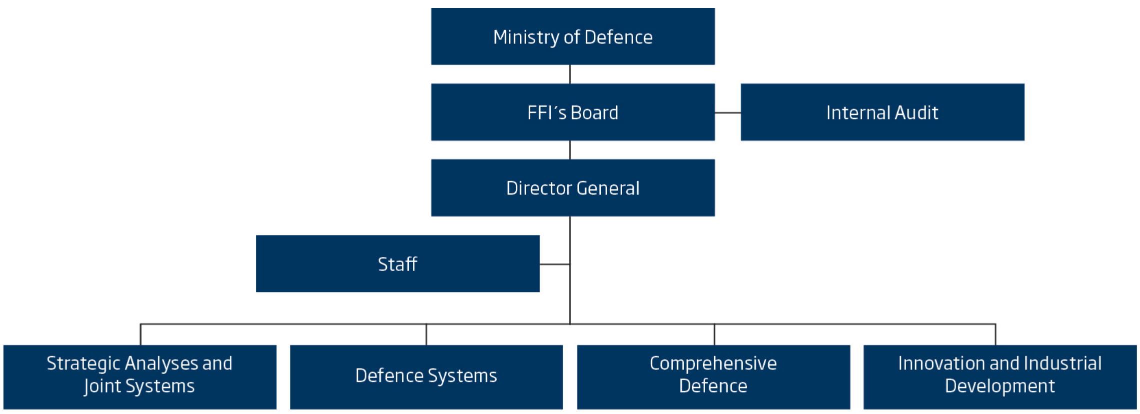

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