5. Systems Aspects of Anti-Tactical Ballistic Missile Defenses

This chapter deals with systems aspects of ground-based anti-tactical ballistic missile defenses, and of space-based defenses which utilize kinetic energy weapons. (Defenses using beam weapons in space are still in the developmental stage, and many aspects have already been analyzed in the SDI debate.) Footprints of ground-based ballistic missile defense systems are introduced and computed in 5.1. Space-based kinetic energy weapons systems are discussed in 5.2. Section 5.3 takes a short look at the tactics of preferential defense. Reaction times of ballistic missile defense systems are the subject of 5.4. Some aspects of command, control and communication are mentioned in 5.5.

5.1 Footprint Area of a Ground-Based Ballistic Missile Defense System

5.1.1 Concept of Footprint of a Ballistic Missile Defense System

In general, a ballistic missile defense system cannot intercept missiles flying arbitrary trajectories and directed at arbitrary targets. Interception is only possible for trajectories and impact points which are sufficiently close to the defense system. The set of all possible ground impact points of ballistic missile trajectories which could be reached in time by the intercepting weapons is called the footprint of the defense system. This area is sometimes loosely called the "defended" or "protected" area. These are misleading terms, however, since the footprint is a kinematic measure only; it includes all trajectories for which the defensive effect – considering the different flight and reaction times – could in principle be transported to the vicinity of the incoming warhead in time, i.e. while it is still at some "safe" distance. This does not guarantee that:

- the guidance system is sufficiently accurate in that the defensive weapon actually affects the incoming warhead;
- the probability of destruction of the warhead is sufficiently high;
- the incoming object is actually a warhead and not a decoy;
- the defensive system has an intercepting weapon available;
- the defensive system has sufficient computing power available to manage the launch, guidance and intercept. (The latter two conditions could be violated if high numbers of objects – not necessarily all of them warheads – were approaching.)

Some countermeasures of the attacking side can be included into the footprint calculation, such as the reduction of detection range by reentry vehicles with a smaller radar cross section or by radar jamming transmitters. Other countermeasures lie beyond the footprint concept, like fooling the detection and guidance systems or attacking the defense system itself.

Traditional anti-ballistic missile systems had interceptor missiles launched from the ground, and ground-based radars for the detection and the tracking of the incoming reentry vehicles.

Earlier versions of anti-tactical ballistic missile systems would use the same principles, but with mobile radars of reduced power and size. Intercepts by objects electromagnetically launched from the ground can be analyzed by using the same procedure.

In the process of defense against a ballistic missile, the following steps have to be taken: a solid angle has to be searched for incoming objects; if an object is detected, this is time zero for the following events: the object has to be classified as potentially threatening (if possible), and its trajectory has to be determined by consecutive measurements of its location; the future trajectory has to be predicted, and it has to be established if an intercepting weapon could kinematically reach the object at some point of its trajectory. Then a launch decision has to be taken and the launch procedure has to be effected. The sequence of events from detection to the actual launch of an interceptor introduces a time delay of a couple of seconds, which can be shortened by faster computers and faster launch procedures. But because of the necessity of observing the object at two sufficiently different positions, this delay cannot be shortened to zero. Of course, during the delay time, the incoming vehicle has continued on its path and has decreased the distance to its target. After launch, an intercepting missile is accelerated during a further couple of seconds (this time would be zero in case of objects accelerated in a gun-type system); the interceptor trajectory will be chosen such that it leads to the predicted interception point. Again, during the interceptor flight time, the incoming vehicle will further approach its target, and the question to be asked is: how far will the interceptor have flown when both meet? The answer depends mainly on the detection range, the delay time, and on the average velocities of both objects. In an extreme case of a small detection range, long time delay, and a fast reentry vehicle, the reentry vehicle could impact before the interceptor were even launched. The larger the detection range, the lower the time delay, and the faster the interceptor were, the greater the distance of interception from launching would be. In order to keep possible interception distances small, the ballistic coefficients of reentry vehicles have been steadily increased, so that the velocity remains high as long as possible down to the lower layers of the atmosphere.

Damage to targets on the ground will not occur if the attacking warhead is intercepted above a certain minimum altitude (the value of which depends on the hardness of the potential targets and the warhead type, see 5.1.4). Interception would be called kinematically successful if the point where both objects meet is above that minimum interception (or keep-out) altitude. Determining the footprint of a defensive system means to establish – in all directions around the defense system – the boundaries of the impact point area where the possible interception points lie above the minimum interception altitude. The shortest path for the interceptor is given if the vehicle is targeted directly at the defense launcher. If the possible interception altitude is already lower than minimum in this case, the defense system does not even have self-defense capability, and therefore the footprint is zero.

If interception is kinematically possible for impact at the defense position, then the footprint boundary in any direction can be found by successively shifting the impact points outward and calculating the respective interception altitude. Where this altitude crosses the minimum altitude, or interception becomes impossible at all, the footprint boundary has been reached.

5.1.2 Method of Footprint Calculation

In the theoretical case of constant velocities of both objects, an analytical determination of the footprint boundaries is possible (even so, discontinuities have to be taken into account).

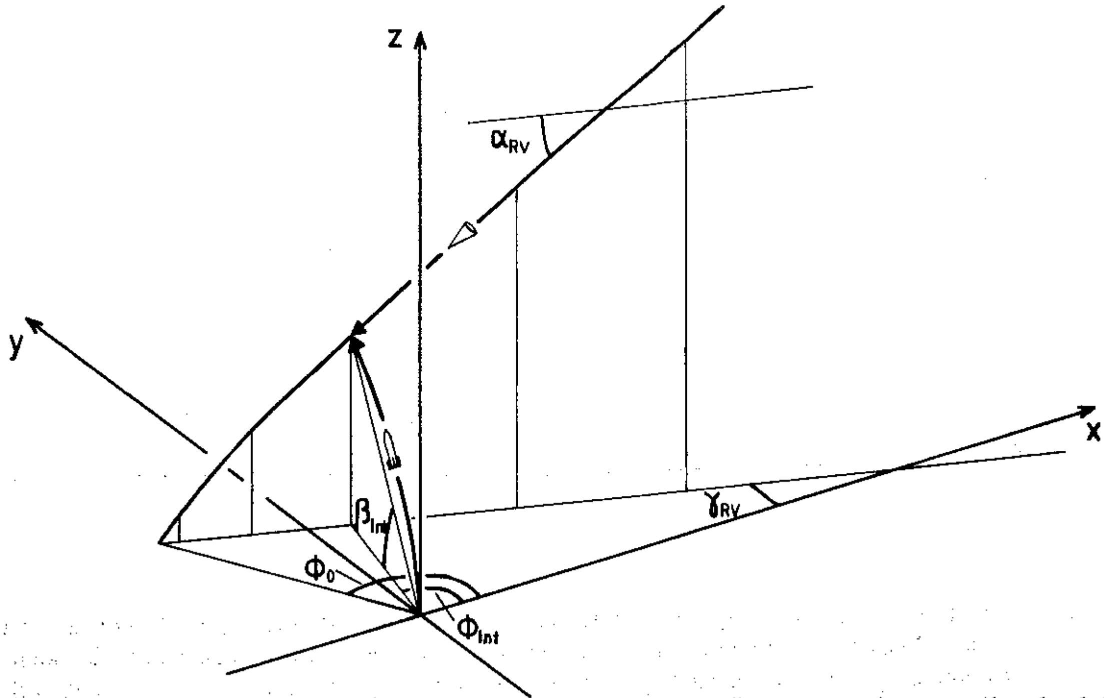


Fig. 5-1 Geometrical quantities in the interception process. The coordinate system is centered at the defense location; the x axis is horizontal, e.g. in some preferential direction of the radar (for the present model of circular symmetric defense, this direction can be chosen arbitrarily). The y axis is perpendicular and also horizontal, and the z axis is vertical. The incoming object approaches on a trajectory having an elevation angle α_{RV} with the horizontal, its ground projection has an azimuth angle γ_{RV} with the x axis. The impact point lies at an angle ϕ_0 with the x axis. After the object has been detected and the delay time for tracking, processing, and launch has passed, the interceptor is launched on a trajectory leading to the calculated interception point. Its elevation angle is β_{Int}, the ground projection has the angular direction ϕ_{Int}.

In reality, however, the reentry vehicle is strongly decelerated, while the interceptor first experiences acceleration, then deceleration. The time course of the interceptor velocity will also depend on the time course of its altitude. Therefore, the calculation of the footprint is regularly done using numerical methods.

Fig. 5-1 shows the geometry of the interception process and defines several quantities. In the present case, two simplifying assumptions are made. The first is circular symmetry around the defense location, namely that the radar detection range as well as the interceptor flyout trajectories do not depend on the azimuth angle. (This is fulfilled for the 360° coverage radars and vertically launched interceptors of traditional anti-ballistic missile systems, and will probably be true for anti-tactical ballistic missile defense systems of the future. It should be noted, however, that this does not apply to modern air defense systems which could be upgraded to some capability against short-range ballistic missiles. The U.S. Patriot system, e.g., has one radar antenna face only, and launch occurs in a forward direction.[1])

The next assumption is that, as long as thrust allows, the interceptor flies to the interception point on the shortest path, a straight line. After the boost phase, the interceptors follow a ballistic trajectory. For interception in space at long range, the boost trajectory is assumed vertical up to 25 km altitude and is then continued on a line of constant elevation. For a representative set of straight lines with elevation angles β from horizontal to vertical, the interceptor flight times to points on these lines are computed numerically and stored (Fig. 5-2). In order to gain an actual or hypothetical interceptor position at a given elevation angle β and a given time t, the stored values are interpolated bilinearly.

Given these properties of the defense system, the footprint depends on the reentry angle α_{RV} and velocity v_{RV} (i.e., the initial values of these quantities). (In case of non-circularly

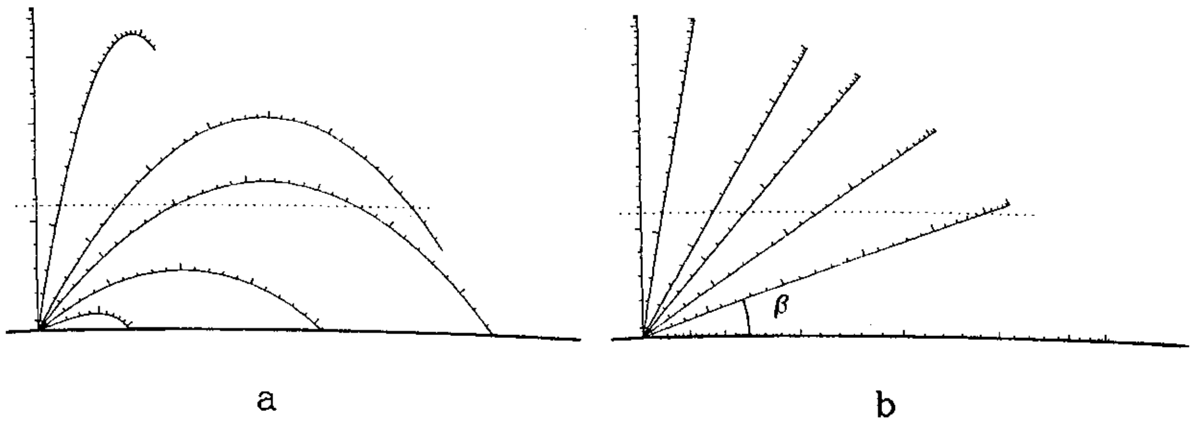


Fig. 5-2 Using the missile trajectory program described in the Appendix, interceptor flyout trajectories along straight lines during the boost phase are computed for several representative elevation angles β_{Int}; if a point in space can be reached by more than one trajectory, only the one with the shortest flight time is kept (a). By bilinear interpolation between these curves, for every point in space the time when an interceptor would arrive there can ge gained. Such hypothetical arrival times are stored along lines of constant elevation (b). Thus, for every elevation angle included, two linear arrays contain a sequence of times and the appropriate distances from the launch point. This is shown here by some examples. In order to obtain an actual or hypothetical interceptor position at an arbitrary time at an arbitrary elevation angle, the stored arrays are interpolated in a bilinear way. Since circular symmetry of the defense is assumed, the time course of the distance from the launch point for given elevation angle β_{Int} is identical for any interceptor azimuth angle ϕ_{Int}.

symmetric defense, it would additionally depend on the azimuth angle of the reentry trajectory γ_{RV}.) A representative reentry vehicle trajectory is computed numerically and stored, using given values of the reentry velocity v_{RV} and angle α_{RV}. An actual reentry vehicle trajectory leading to a specific impact point can then be gained by shifting all location coordinates by the same amount in such a way that the last point of the trajectory is at the impact location desired. Having thus fixed in space an actual reentry trajectory, one can – by working backwards from the impact point – determine the point in space where this trajectory crosses the detection boundary. This also gives the detection time, which afterwards is taken to be time zero for the interception process (Fig. 5-3 a). Then the tracking, decision, and launch delay time t_D is allowed to pass. Starting at the reentry vehicle position at interceptor launch time (i.e., at detection time zero plus time delay t_D), working forward in time, hypothetical interceptor positions on straight lines pointing to the actual reentry vehicle position are computed by interpolation from the stored array, (Fig. 5-3 b-d). The difference between the distances from zero of the reentry vehicle, and of the interceptor, respectively, is a measure of the possibility of interception. As the time increases, the straight lines point to changing positions of the reentry vehicle, and the hypothetical position of the interceptor approaches the respective actual position of the vehicle. At some point in time, the interceptor may have crossed past the reentry vehicle trajectory (Fig. 5-3 c). By suitable search, the actual interception point for this trajectory is then found where both objects meet at the same time (Fig. 5-3 d, e). The altitude h_{Int} of this earliest possible interception point is then compared with the given minimum interception altitude h_{min}. If the former is below the latter, the footprint boundary has already been crossed. The same holds, if on the whole reentry vehicle trajectory down to the minimum interception altitude the interceptor at its hypothetical positions does not arrive at the respective reentry vehicle positions. If, by working outward from zero along one direction, such an impact point has been found, then, by suitably searching along the impact point distance from zero, the boundary of the footprint area in this direction is determined where the interception altitude equals the given minimum value (or, under specific conditions, where any possibility of interception ceases to exist) (Fig. 5-3 f).

In such a way, the footprint boundary in several directions from forward to backward is established (Fig. 5-3 g). Due to the circular symmetry of the defense, when changing the azimuth direction γ_{RV} of the incoming vehicle, the footprint is rotated accordingly. The total footprint area is then given by the overlap area of all single-azimuth footprints (Fig. 5-3 h).

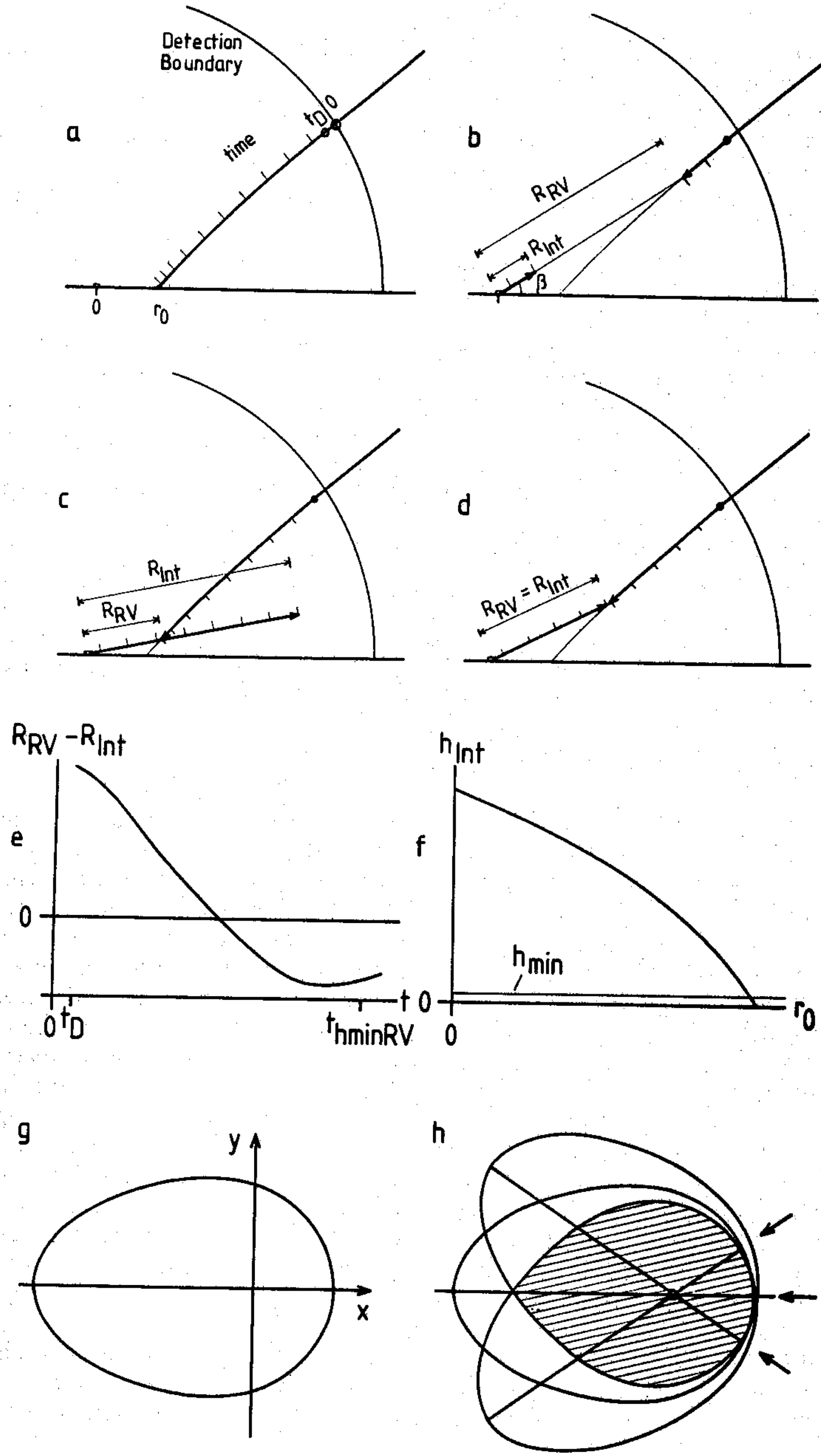
The process described starts for a reentry trajectory ending at the defense position (i.e., at zero). If, at this point already, interception is only possible below the minimum altitude (or even not at all), then the defense is said to not possess self-defense capability, and the footprint area is zero. (There may exist a backward area where interceptions are possible, but because an attack on the defense itself could not be prevented, this can be excluded from consideration for military reasons.)

Thus, the footprint of a ballistic missile defense system is a function of the reentry parameters: initial angle to the horizontal α_{RV}, initial velocity v_{RV}, and, for non-circularly symmetric defense systems, reentry azimuth angle γ_{RV}. On the side of the defense system, it depends on: the detection range R_{Det} (this also depends on the reentry velocity v_{RV}), the tracking, decision, and launch time delay t_D, the interceptor acceleration and velocity, and the minimum intercept altitude h_{min} required for prevention of damage on the ground. Section 5.1.5 gives several numerical examples for typical ground-based anti-tactical ballistic missile systems.

5.1.3 Two Types of Detection Boundary

Up to now, the detection range was assumed to be limited by the properties of the radar, working in the search mode (see 4.1.1.3). If no other early warning sensors are used, this provides an upper limit for the range where the tracking, decision, and launch sequence could start. In reality, a complication could arise. Ballistic missiles with ranges above several hundreds of kilometers travel outside of the atmosphere for a significant amount of their flight time. Because of the short times involved, the defense needs a radar detection range as large as possible, i.e. detection has to take place while the objects are still in space. This means that many light decoys could accompany the warheads, which could not reliably be discriminated by the detection capabilities of the search radar. Balloon-type objects would already be discernible by their lagging behind at altitudes of about 100 km. For tactical ballistic missiles, decoy research and development is likely to concentrate on new types that are capable of penetrating deeper into the atmosphere before significant lag occurs, say down to 50 or even 20 km altitude (see 6.1.2.5). This means that, in order not to waste expensive interceptors on decoys, the defense has to wait until the potentially threatening objects have descended to the appropriate discrimination altitude. At least part of the tracking and the total launch sequence could only occur after this time. This means that (as long as the discrimination altitude is less than the radar detection range) the time available for flyout is reduced, and the footprint area will shrink accordingly.

In the computations made here, this effect can be included by introducing a second effective detection criterion, which is fulfilled when the reentry vehicle crosses a specific detection altitude. Of course, this condition is only valid if the radar detection range has been



Detection Boundary
a
time
t_D
0
0
r_0
b
R_{RV}
R_{Int}
β
c
R_{Int}
R_{RV}
d
$R_{RV} = R_{Int}$
$R_{RV} - R_{Int}$
e
0
0
t_D
t_{hminRV}
t
h_{Int}
f
h_{min}
0
0
r_0
g
y
x
h

Fig. 5-3 Sequence of steps taken for determining the possibility of interception, and the interception altitude h_{Int}, for a given impact point of the reentry vehicle. For reasons of presentation, here a trajectory with zero azimuth angle γ_{RV} and an impact point in the x axis is chosen; in the actual computation impact points lying in any horizontal direction around the defense are used.

a) For a given impact distance r_0 and azimuth angle ϕ_0, the actual reentry trajectory is calculated by shifting the model trajectory accordingly. Then, by interpolation, the point is found where the reentry vehicle crosses the detection boundary (a radar detection distance or a discrimination altitude, see text). The corresponding time is taken as time zero for this impact point. After the defense time delay t_D, the interceptor is launched, and the reentry vehicle has proceeded further towards its impact point.

b) In order to find the conditions for collision, starting at interceptor launch time t_D, for several positions of the reentry vehicle a hypothetical interceptor position at that time on a straight line pointing directly towards the vehicle position is computed. At the time point shown, the interceptor distance from zero R_{Int} is less than that of the reentry vehicle R_{RV} – interception will only be possible at later times (if at all).

c) At some later time, the hypothetical interceptor distance from zero R_{Int} is larger than that of the reentry vehicle R_{RV}. This means that the possible interception time has passed already. (Note that for larger impact distances such a time may not exist.)

d) By search in time for the point where the hypothetical interceptor distance R_{Int} and the reentry vehicle distance R_{RV} are equal, the actual interception point is found. (Note that, for backward impact points and specific conditions, two such points may exist; in order to arrive at the maximum interception distance possible, the one earlier in time has to be taken.) The interception altitude h_{Int} can then be compared to the minimum interception altitude h_{min}. The boundary of the footprint in any azimuth direction ϕ_0 is reached where the possibility of interception ceases to exist, or where the interception altitude decreases below the minimum value. This boundary is gained by search in impact point distance at fixed impact azimuth angle ϕ_0.

e) Plot of the difference of reentry vehicle distance R_{RV} minus hypothetical interceptor distance R_{Int} versus the time t after detection for a given impact point. The actual intercept condition for determining the footprint boundary is reached where this difference becomes zero for the first time. (Note that under some conditions two zeroes, under others, none may exist.)

f) Plot of the intercept altitude h_{Int} versus the impact point distance r_0 for one azimuth angle ϕ_0. The footprint boundary in this direction is reached where this altitude crosses the minimum intercept altitude h_{min}. If, for specific conditions, the possibility of interception ceases to exist for some distance r_0, this is the boundary distance. This distance is found by working outward from zero and searching for the boundary. Should the intercept altitude be below the minimum value already at impact distance zero, the defensive system has no self-defense capability, and the footprint is zero.

g) By repeating this process in several impact point directions ϕ_0, the total footprint area is determined for the reentry angle α_{RV} and velocity v_{RV} chosen.

h) For circular symmetry of the defense, this area would rotate with the reentry azimuth angle γ_{RV} (otherwise, the area would decrease with the deviation from the optimum direction). If missiles could arrive from several directions, the total footprint is the overlap section of all single ones. If arbitrary azimuth angles were possible, the total footprint would become circular, with a radius equal to the single-azimuth footprint extension in the forward direction.

crossed earlier (see Fig. 5-4). Only if detection by other means, e.g. airborne infrared sensors, were provided, would the altitude criterion remain as the only one.

5.1.4 Estimation of the Minimum Intercept Altitude

In order to estimate the altitude at which a ballistic missile has to be intercepted so that the damage effects for ground objects can be negligable, one has to differentiate between the types of weapons.

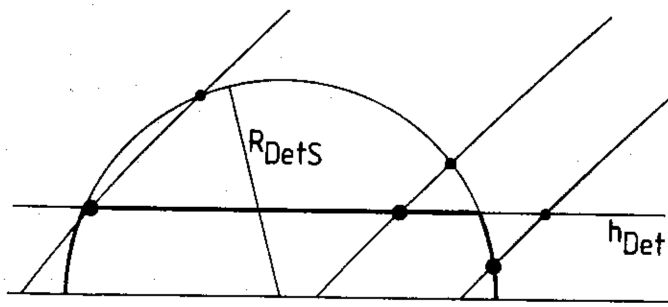


Fig. 5-4 If decoy discrimination by atmospheric drag is required, the effective detection boundary is the envelope of all points at which the distance is less than or equal to the radar detection range R_{DetS} and the altitude is less than or equal to the discrimination altitude h_{Det}. Effective detection takes place when both criteria have been met (big circles). (If earlier detection by other means is available, the altitude detection criterion will work for larger distances too.)

For *nuclear* warheads, the radii for damage due to overpressure to semi-hardened military objects in Europe are about 180 m, 350 m, 750 m, and 1.7 km for yields of 1, 10, 100 kt, and 1 Mt TNT, respectively (see Fig. 3-7). For a typical yield of a tactical ballistic missile, 100 kt TNT, a minimum intercept altitude of 1 km would avoid damage to hardened above-ground bunkers. If damage to lighter buildings is also to be avoided, 2 km is required. If explosions in the megaton range are feared, 5 km would be necessary. Roughly the same altitude is necessary in case of a 1 Mt explosion to avoid damage to hard material by thermal radiation (however, ignition of tinder materials could still happen at explosion altitudes of 15 km).[2] For a rough estimate, 5 km seems a plausible value for the minimum intercept altitude. The figures given also explain that the defense can use nuclear explosions of the kiloton-class, without having to fear immediate damage on its ground. (Of course, the distribution of radioactive fallout would take place according to the actual release and weather conditions. If the explosion of the incoming warhead with about 100 times the defense yield could really be reliably prevented, the total fallout damage would be less by about the same factor. This, however, is only theoretical, because chances for near 100% interception probability are quite small, see 6.2.)

For *chemical* warheads, the interception altitude required to prevent lethal concentrations on the ground is more difficult to assess. This will strongly depend on the interception mechanism; if total decomposition by thermal effects of nuclear radiation could be relied upon, an altitude at which the nuclear explosion effects were acceptable on the ground would suffice, i.e. about 1 km. If a portion of the poisonous gases will remain undestroyed, which is more than likely, everything will depend on the release process. If the gas or liquid were outside of a container, it would probably rapidly decelerate, would diffuse in a somewhat lower layer of air, and would slowly precipitate. The higher the diffusion altitude, the slower the chemicals would reach the ground, the larger the contaminated area would be, and the lower the resulting concentrations would be. It may well be that to prevent lethal concentrations on the ground, a missile carrying several hundred kilograms of nerve gas would have to be intercepted at 10 kilometers, or even higher. If, on the other hand, a portion of the chemicals were protected by (remnants of) a container during part of the reentry, transport to lower altitudes, and faster distribution over a smaller area, would follow. Therefore, even if 10 km intercept altitude could be guaranteed, one could not rely on preventing lethal concentrations on the ground.

For *conventional* weapons, two types have to be analyzed. In case of unitary explosive warheads, even damage to non-hardened objects does not extend beyond 100 m for 1 t of explosive (see Fig. 3-8); in case of fuel-air explosives, damage radii of several hundred meters are possible. Therefore, for these cases minimum interception altitudes of 500 m to 1 km would suffice. If, however, the tactical ballistic missile carries submunitions, the interception would have to take place before their release. Due to weight and cost reasons, submunitions are unlikely to be equipped with thermal protection against reentry themselves, as required for ranges above several 100 km. For these ranges, the submunition release can only happen after the reentry vehicle has passed through the altitude region of maximum deceleration. This altitude depends on the initial velocity (i.e., on the missile range), and on the ballistic coefficient of the vehicle, and is between 2 and 10 km for typical tactical and intermediate-range missiles (see Figs. 3-3 and 3-4). Another consideration is the intended scattering radius of the submunitions. If this is to be small, and submunitions are not provided with target recognition and maneuvering capabilities by themselves, the release altitude may be further limited. As an estimate for the minimum intercept altitude, one could use 2 km and keep in mind that under some circumstances even 5 km could be necessary.

5.1.5 Examples of Footprint Areas for Typical Ground-Based Anti-Tactical Ballistic Missile Systems

5.1.5.1 Type 1: Upgraded Air Defense Systems Against Conventional Short-Range Missiles.

Upgrading of modern air defense systems is planned as a near-term option for defense against tactical ballistic missile. In NATO, the Patriot system will be used in this way. Because the Patriot radar has one fixed face looking in the general direction from where aircraft or missiles are expected, one radar cannot guide interceptors to backward positions; this leads to a footprint area which is shorter in the backward than in the forward direction.[3] (360° azimuth coverage, and a roughly circular footprint area, can be achieved by appropriately combining multiple Patriot units.) The next upgrade of such a system could include several radar faces to have a more comprehensive radar coverage; in addition, the interceptor launch direction could be changed to vertical in order to allow equal interception capabilities in all azimuth directions, and side thrusters could be added to allow trajectory control above altitudes of 25 km. For an analysis of the footprint area of such a solution, the basic radar and missile parameters are taken to be similar to those of the Patriot system (see Table 5-1).

Defense footprint areas of such a Type 1 system have been computed for ballistic missiles of several ranges, and for several defense parameters. Fig. 5-5 shows the flyout trajectories and the curves of equal arrival time.

As a standard case, it is assumed that the radar cross section of the incoming object is 0.01 m^2 (this corresponds to reentry vehicles of current longer-range ballistic missiles). The resulting radar search detection ranges are listed in Table 5-2. Further, in the standard case no atmospheric discrimination is needed, and the minimum interception altitude is 2 km, as required for defense against conventional ballistic missiles. (For the effects of variations of these parameters, see below, and Section 6.1.1.) Fig. 5-6 shows the resulting footprint areas for several ballistic missile ranges. The reduction with increasing range (i.e. with increasing

Tab. 5-1 Standard parameters of the Type 1 anti-tactical ballistic missile defense system used in the calculations. Basic quantities are similar to the U.S. Patriot system; modifications are: the radar is assumed to be able to cover the whole hemisphere; the interceptor trajectory is linear (constant elevation angle) during the burn time, and the launch elevation is equal to that respective angle; side thrusters allow guidance even after burnout and at altitudes above 25 km. For the interceptor data used as program input, see Appendix.

Radar	
Average power P_{av}	10 kW
Effective antenna area A_{eff}	4.5 m^2
Noise reference temperature T_0	290 K
Noise factor F_n	3
Loss factor F_L	5
Search solid angle Ω (90° by (20 to 70)°)	0.94 sterad
Pulse integration factor Q_i	0.9
Ratio for distance traveled during frame time δ	0.042
Ratio for search detection range ρ	0.155
Incoming missile/reentry vehicle	
Radar cross section	0.01 m^2
Interceptor missile	
No. of stages	1
Launch mass m_0	910 kg
Fuel mass m_F	640 kg
Warhead mass	70 kg
Burn time t_B	12 s
Actual burnout velocity (depending on elevation)	2.1 – 2.4 km/s
Defense system	
Identification, tracking, and launch delay time t_D	5 s
Minimum interception altitude h_{min}	2 km

reentry velocity, and thus decreasing detection range) is clearly seen. Whereas for short ranges, the footprint margins are dozens of kilometers away, the forward boundary is at 21 and 12 km for missiles of 1,000 and 2,000 km range, respectively. Against ballistic missiles of 5,000 km range, 2 km forward, and 12 km backward footprint extension seems to provide coverage for one extended military installation, but this possibility vanishes with simple countermeasures or a greater minimum interception altitude (see below).

Next, the influence of variations of several parameters will be demonstrated. Fig. 5-7 shows the footprint areas which result if the identification, tracking, and launch delay time t_D varies from 2 to 5, and 8 seconds. Note, that with 8 seconds, any possibility to reach a 5,000 km range reentry vehicle at the minimum intercept altitude of 2 km has vanished. Whereas the forward footprint margin for 500 km range missiles changes only from 30 to 28 km, this effect is more pronounced with the faster missiles: for 2,000 km range, e.g., the forward margin shrinks from 12 to 8 km. Conversely, in case the defense could manage to launch interceptors only 2 seconds after detection, the increase in footprint area is greatest for the longest ranges. In case of a delay time slightly above 10 seconds, interception of 2,000 and even

Tab. 5-2 Radar search detection ranges of a Type 1 anti-tactical ballistic missile system for missiles of different ranges, after (4-11) and (4-13), using standard parameters (see Table 5-1). The radar cross section value of $\sigma = 0.01\ m^2$ is that of reentry vehicles of current long-range ballistic missiles, and could be considerably reduced.

Range, km	100	200	500	1,000	2,000	5,000
Reentry velocity, km/s	0.6	0.8	1.8	2.8	4.0	5.8
Search detection range, km	142	129	99	85	76	67

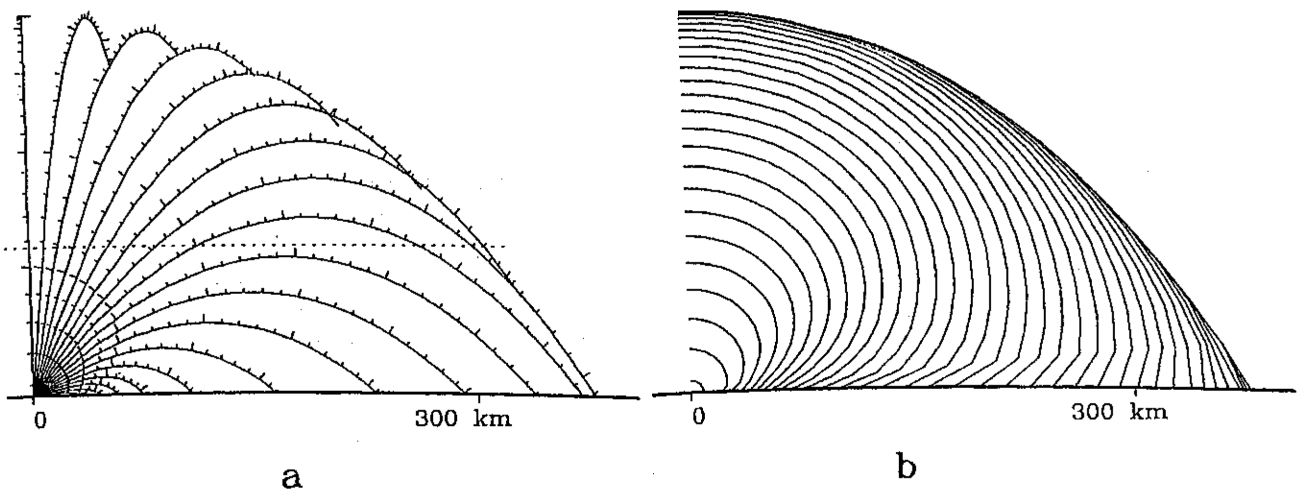


Fig. 5-5 Flyout characteristics of Type 1 interceptor missile.
a) Trajectories have constant elevation angles β during burn time (5° steps); they are shown only until they cross the next lower one. One tick corresponds to 10 seconds. The altitude 100 km is indicated.
b) Curves of equal arrival time; one curve is drawn every 10 seconds.
For circular symmetry of the defense, these curves can be rotated around the vertical at zero.

1,000 km range missiles would become impossible; should the launch decision be delayed by more than two minutes, interception of even the slowest missiles would be excluded. The technical preconditions for interceptor launch within 5 or 10 seconds exist; for the consequences this may have on political control and crisis stability, see 5.4 and Ch. 7.

In Fig. 5-8, the radar search detection ranges have been modified by a factor of two in both directions. Because the parameters of the radar and the reentry vehicle enter the search detection range under the cubic root (see (4-11) and (4-13)), an increase by a factor of two could e.g. be the result of simultaneous increases by factors of two in radar power and antenna area each, and a decrease by a factor of two in the search solid angle. This may well transcend the capabilities of mobile radars. If such increase were feasible (and the discrimination problem outside the atmosphere could be neglected), significantly larger footprint areas would ensue. Even for 5,000 km range, the forward footprint boundary would increase to 17 km. On the other hand, a reduction of the search detection range by a factor of two could be achieved by reducing the radar cross section by a factor 8, which should not prove extremely difficult (note that the theoretical lower limit is a factor of about 30 below the standard value of $0.01\ m^2$ used here, see 4.1.1.2). In this – more realistic – case, the footprint areas shrink drastically, most pronounced for the longer ranges. Against 5,000 km range missiles, no capability remains at all; against 2,000 km range ones, the capability is just marginal. For 500 km range missiles, the footprint area decreases by more than a factor of four.

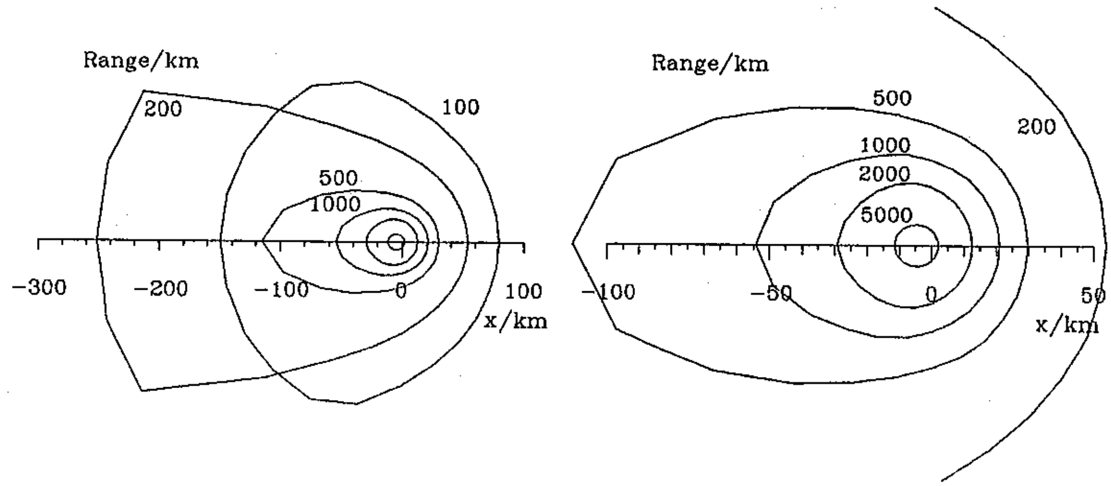


Fig. 5-6 Footprint areas of a Type 1 defense system against tactical ballistic missiles, coming from the right from several ranges, as indicated (two scales). Standard parameters (see Table 5-1). For short range (100 km), the launch point is within the detection radius. Here the effective detection time is taken at burnout, after which trajectory prediction becomes possible. In a real military situation with a defined front, the defense would be located behind the front, and no missiles would be launched from positions to the left of it. Thus, those backward parts of the short-range footprints lying further than the missile range (100 or 200 km) from the defense position could not be hit anyway.

The influence of variations of the keepout altitude is shown in Fig. 5-9. Because 2 km is at the lower limit of what can be plausibly be expected, additional footprints are computed for the higher values of 5 and 10 km (5 km would be required for nuclear warheads up to several 100 kilotons TNT, 10 km would be used for yields above 1 megaton TNT or against chemical warheads). In the case of 5 km minimum altitude, the 5,000 km range missiles can no longer be reached in time; for 2,000 km, the forward margin shrinks from 12 km to 6 km. The lower ranges are less affected. If even 10 km minimum interception altitude would have to be guaranteed, 2,000 km range missiles would also be out of reach, and the forward footprint margin for 1,000 km missiles would decrease from 21 km to 9 km.

If atmospheric decoy discrimination has to be used, effective detection has to wait until the incoming reentry vehicles have arrived at some altitude. Fig. 5-10 gives the footprint areas if this altitude is 100, 50, and 20 km. Here it is assumed that detection of incoming objects has already taken place at arbitrary distance, before the effective detection altitude is reached. Because typical reentry angles are between 30 and 50°, this implies detection at ranges larger than 1.4 to 2 times the detection altitude from the impact points, which could either be done by large fixed radars, or by infrared sensors on board aircraft or satellites. A detection altitude of 100 km would apply to traditional balloon-type light decoys. Of course, every type of decoy could only be effectively used by ballistic missiles with a ceiling markedly above the respective discrimination altitude, therefore this type could only be used by missiles of range above 500 km. New types of heavier decoys would penetrate to 50 or even 20 km, before significant lag could be measured. In the model calculation detection is assumed to be independent of the distance from the defense position, therefore the fooprint areas are extended much more in forward directions. With 100 km detection altitude, the forward footprint margin is 25 km for 5,000 km range missiles, and 68 km for 500 km ones. Both 100 and 200 km missiles are detected already at burnout, therefore the 200 km footprint is larger in this case.

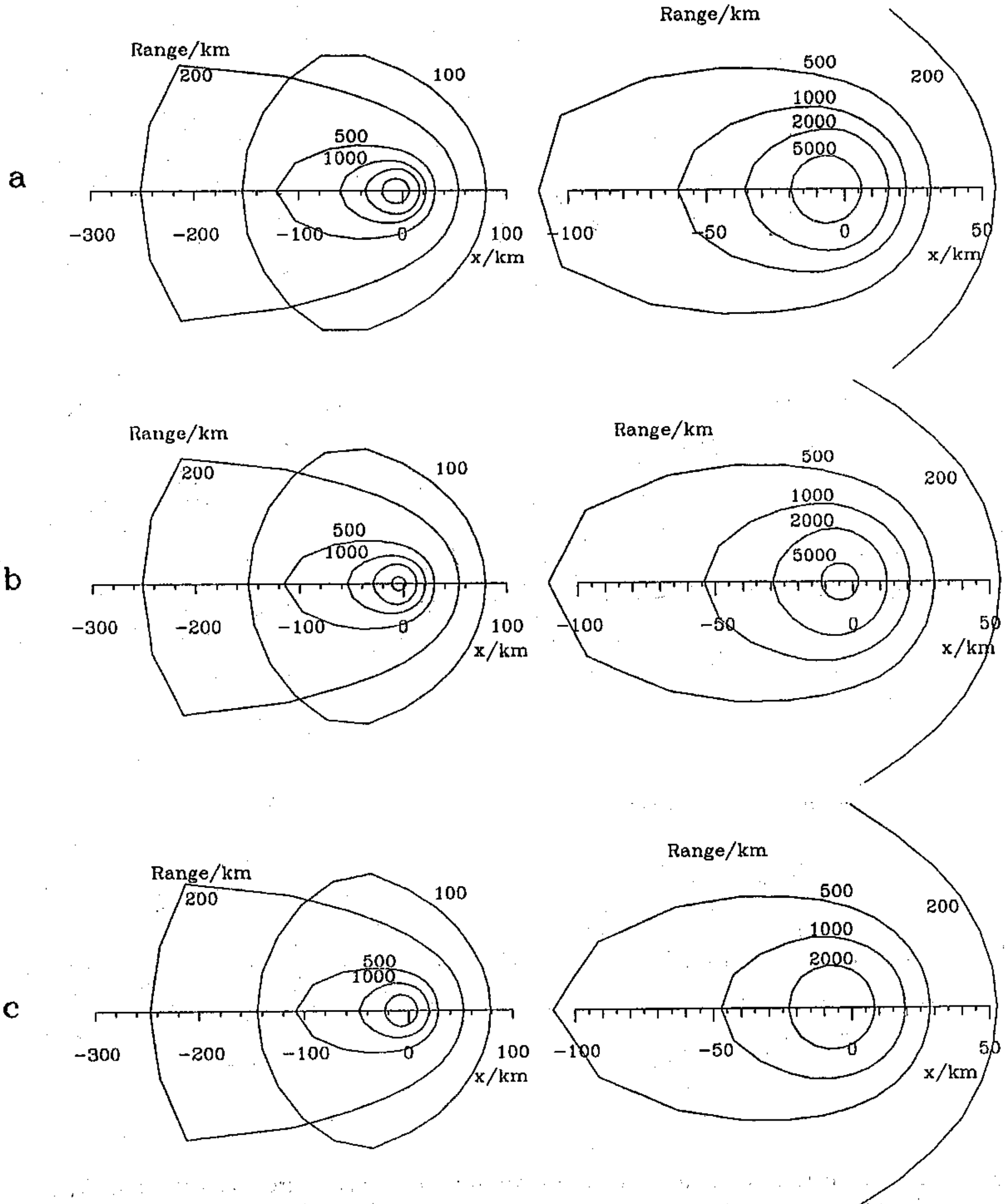


Fig. 5-7 **Influence of the identification, tracking, and interceptor launch delay time t_D on the defense footprint areas, two scales.**
a) $t_D = 2$ s. The main increase is with ranges from 1,000 km up.
b) $t_D = 5$ s (i.e., identical to the standard case of Fig. 5-6).
c) $t_D = 8$ s. The main decrease is with ranges from 1,000 km up. Note that the footprint against 5,000 km range missiles has vanished.
Other parameters as in Fig. 5-6.

With 50 km detection altitude, the 5,000 km forward margin decreases to 11 km, the 500 km one to 32 km. Now, only the 100 km missile stays below the detection altitude during its total flight. If decoys penetrating to 20 km altitude before discrimination could be developed, footprint areas would shrink drastically. For ranges of 2,000 km and higher, any interception

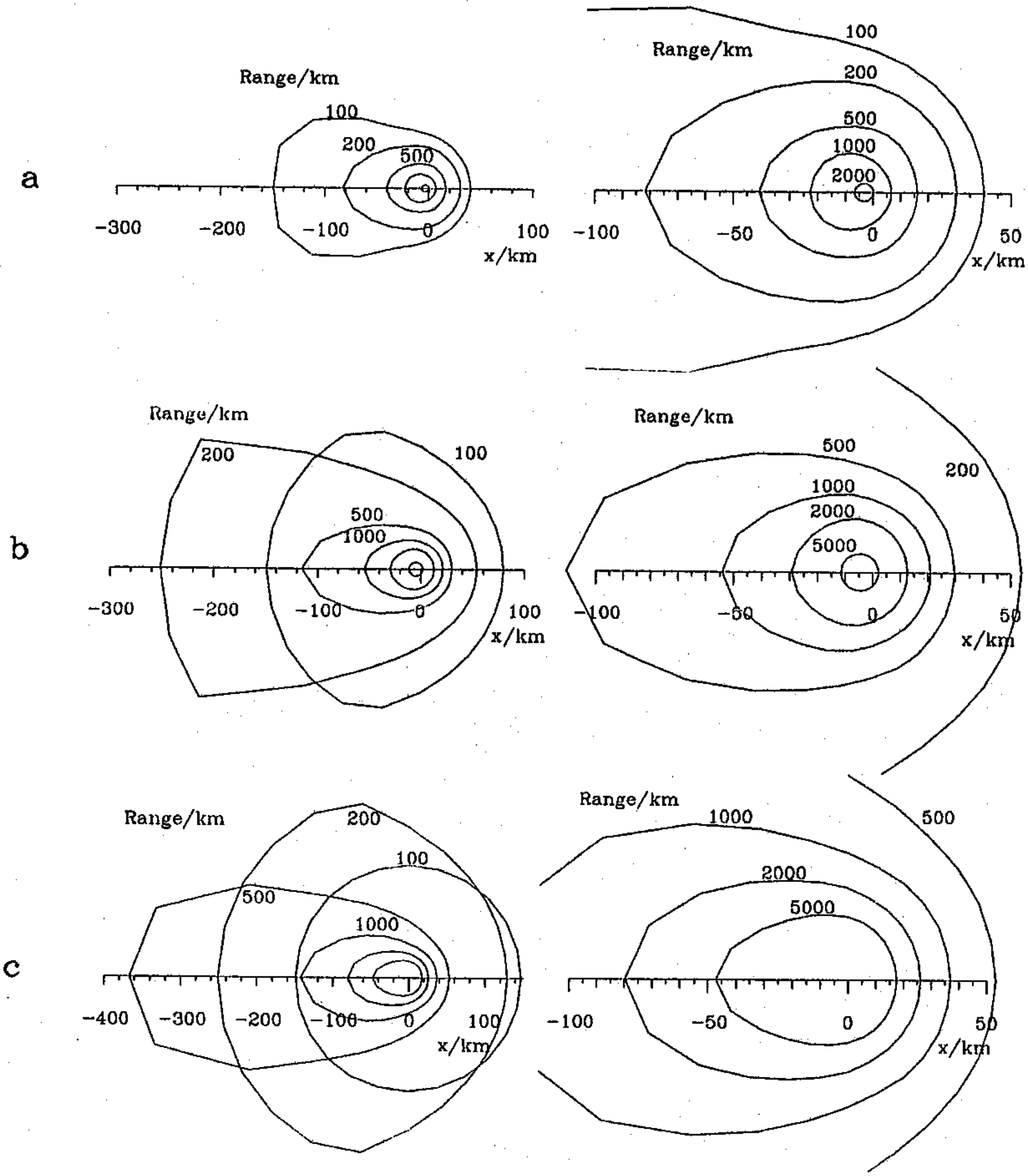


Fig. 5-8 Defense footprint areas in case of strong variations of the radar search detection range R_{DetS}. Note that variation by a factor two requires a factor of eight of the product under the cubic root of (4-11). Standard values of the search detection range are contained in Table 5-2.
a) Search ranges are 0.5 times the standard ones. Such a variation could without much difficulty be achieved by an eightfold reduction of the radar cross section (see 6.1.1). Note that the 5,000 km footprint is zero.
b) Search ranges as in the standard case (Table 5-2 and Fig. 5-6; of course, appropriate combinations of other radar and reentry vehicle parameters could give the same values).
c) Search ranges are 2 times the standard ones (changed scale on the left). The defense would have great difficulties achieving this; it may well be beyond the capabilities of mobile radars.
Other parameters as in Fig. 5-6.

would be impossible. For 1,000 km range, the forward margin would be 2 km, for 500 km it would amount to 11 km. In the near future, search will only be possible by mobile radars. Their detection range is limited, and has to be included in a realistic calculation. The com-

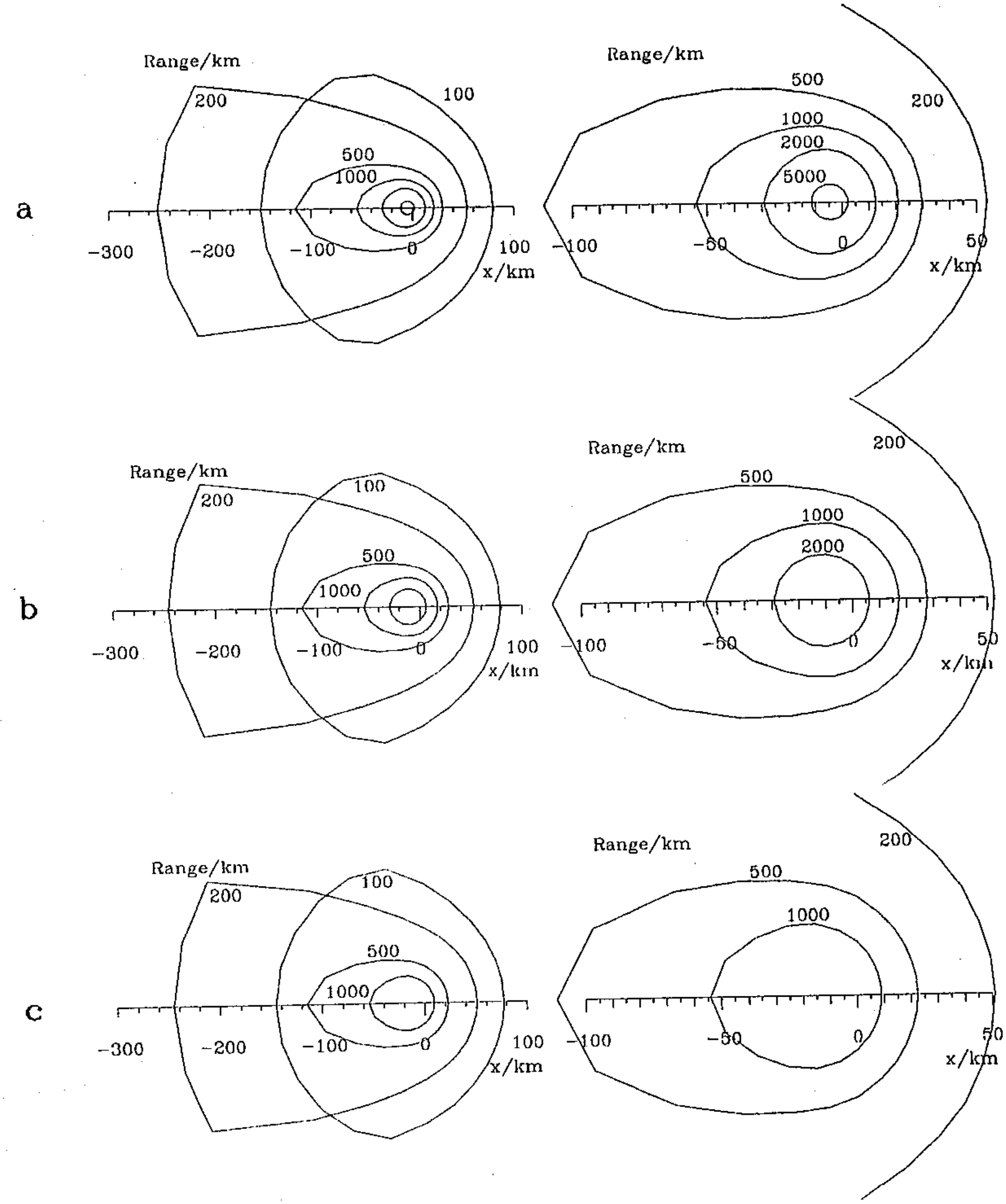


Fig. 5-9 Defense footprint areas for different values of the minimum intercept altitude h_{min}, two scales.
a) $h_{min} = 2$ km (identical to the standard case of Fig. 5-6).
b) $h_{min} = 5$ km (such a value could be necessary for defense against nuclear warheads). Note that the possibility to reach a 5,000 km warhead in time has vanished.
c) $h_{min} = 10$ km – this might be required if high yield nuclear weapons, chemical warheads or early release of conventional submunitions are to be countered. (The latter possibility would, for ranges above about 500 km, require thermal reentry protection of individual submunitions as well as more elaborate guidance methods, see 6.1.2.4.) Note that even a 2,000 km warhead could not be reached before it arrived at the keepout altitude.

bined footprint area can be obtained from calculations using search detection ranges on the one hand, and minimum detection altitudes on the other hand, by taking the respective lower extension value in any azimuth direction.

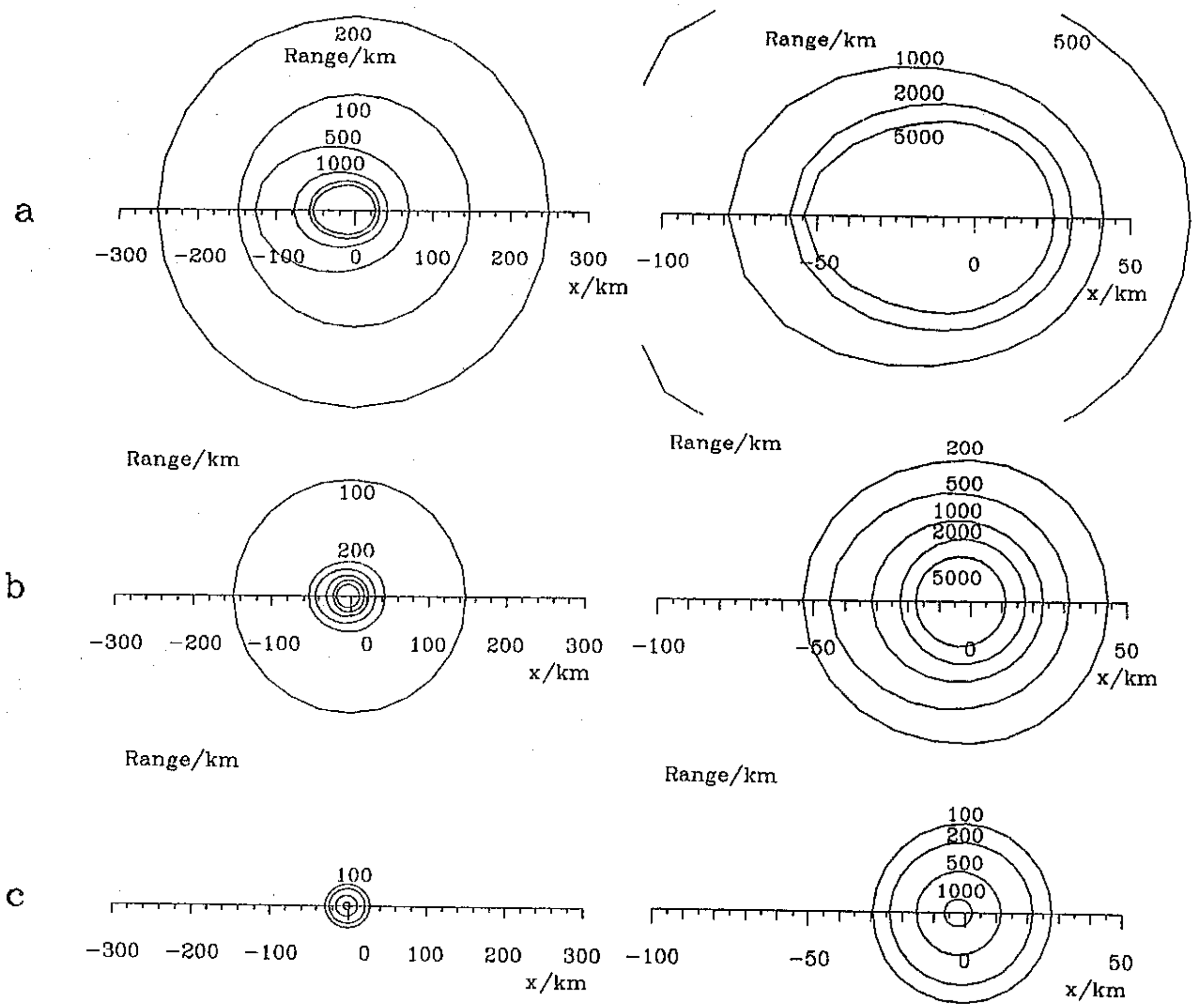


Fig. 5-10 Influence of an effective detection altitude h_{Det} on the footprint areas. In this case, detection is assumed to be independent of the distance from the defense system, therefore footprint areas are extended much more in forward directions. (Note that the left hand scale has changed from that of Figs. 5-6 to 5-9.)

a) h_{Det} = 100 km. Because the reentry angles are typically between 30° and 50°, this implies detection ranges of several hundreds of kilometers, which is clearly impossible for mobile radars against missiles of ranges from 500 km upward (see Table 5-2). Because for backward directions and low missile ranges the detection altitude is crossed near the sphere of radar detection in the standard case, the corresponding footprint extensions are similar to those of Fig. 5-6. Because 100 and 200 km range missiles remain below 100 km altitude for their total trajectories, detection is assumed to happen already at burnout time; no decoys being discriminated at 100 km could be used.

b) h_{Det} = 50 km. Now only the 100 km missile stays below the detection altitude all the time; the 200 km missile could already use decoys which are separated at 50 km.

c) h_{Det} = 20 km. Decoys penetrating like warheads to such low altitudes could be carried by missiles of all ranges. Note that the 5,000 and 2,000 km footprints have vanished.

5.1.5.2 *Type 2: Fast Ground-Launched Missiles for Low Endoatmospheric Intercept (Nuclear and Non-Nuclear)*

A fundamentally new interceptor missile which is being developed within the U.S. SDI program, but has also been recommended for use against tactical ballistic missiles, has been called FLAGE (formerly SRHIT). This one-stage missile weighs only one fourth of the Patriot missile, and accelerates and burns out much faster. A missile of such a kind is modeled here by Type 2 (Table 5-3). A Type 2 interceptor is to be used in the low atmosphere as a last resort, during the very last seconds of reentry. Therefore, only very little time is available, and fast flyout at short distance is of maximum importance. Thus, the acceleration is high (mean value 600 m/s^2), and the burnout velocity is a secondary criterion. As a consequence, the maximum interceptor range is lower than with Type 1. In order to match the more pressing time line, here a detection-to-launch delay of only 2 seconds is used (which could be achieved using powerful computers). In the present case, guidance to a direct hit is assumed, therefore a light warhead and a light missile are possible. If a conventional explosive or a nuclear warhead of about 100 kg mass would have to be used, the mass of the missile would be more than ten times higher (e.g., about 2,500 kg) for equal flyout characteristics. For detection, the data of the Type 1 mobile radar system are used (Tables 5-1 and 5-2). Fig. 5-11 shows the flyout trajectories and curves of equal arrival time.

Tab. 5-3 Parameters of the Type 2 anti-tactical ballistic missile defense interceptor used in the calculations. Basic quantities are similar to the U.S. FLAGE missile. (Other defense system parameters as in Table 5-1.) For program input data, see Appendix.

Interceptor missile	
No. of stages	1
Launch mass m_0	230 kg
Fuel mass m_F	80 kg
Burn time t_B	2 s
Actual burnout velocity (depending on elevation)	1.1 – 1.2 km/s

Fig. 5-12 shows the calculated footprint areas for a minimum interception altitude of 2 km, for several values of the radar cross section. Because of the cubic root dependence of (4-11), reduction from the standard value of 0.01 m^2 by a factor of 10 to 0.001 m^2 roughly corresponds to the decrease in search detection range by a factor of two which was used in Fig. 5-8 a) for the Type 1 interception system. Reduction to 0.0003 m^2 would result in an additional factor of 1.5. Table 5-4 gives the search detection ranges used. Comparison of Fig. 5-12 a) with Fig. 5-8 b) shows that the shorter launch delay time and higher acceleration overcome the higher burnout velocity of Type 1 only for the faster ballistic missiles – with 0.01 m^2 cross section, the Type 2 forward footprint extension becomes about equal for 2,000 km range, and gets larger than Type 1 for a greater range. With 0.001 m^2 cross section and the correspondingly reduced detection distances and time spans, breakeven is achieved at about 1,000 km range. The footprint against 2,000 km range missiles is significant only here (forward extension 4 km versus 0.1 km for Type 1), and becomes marginal at least for 5,000 km range (1 km versus 0 for Type 1).

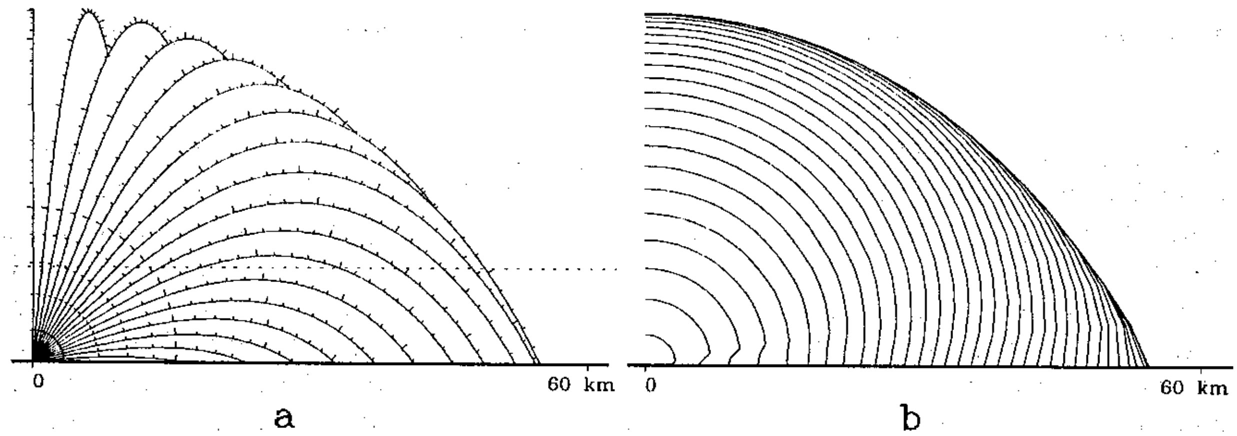


Fig. 5-11 Flyout characteristics of Type 2 interceptor missile.
a) Trajectories have constant elevation angles β during burn time (5° steps); they are shown only until they cross the next lower one. One tick corresponds to 4 seconds. The altitude 10 km is indicated.
b) Curves of equal arrival time; one curve is drawn every 4 seconds.
For circular symmetry of the defense, these curves can be rotated around the vertical at zero.

Fig. 5-13 gives the corresponding footprint areas in the case of a minimum intercept altitude of 5 km (as required against nuclear warheads). With the standard cross section value of 0.01 m^2 (Fig. 5-13 a)), most footprint areas are smaller than those of Type 1 (cf. Fig. 5-9 b)); for 2,000 km range, they are roughly equal. Against 5,000 km range missiles, the Type 2 interceptor, like Type 1, has no capability. With 0.001 m^2 cross section, even a 2,000 km range missile cannot be reached in time. A further reduced cross section would even remove the possibility of attacking 1,000 km range missiles. Because missiles above 1,000 km range are mostly nuclear, use of terminal phase interceptors will drive the requirements on detection distances upwards, to values which could not be guaranteed by mobile radars. Instead, either large stationary early warning radars or infrared detection schemes wiill be neccessary.

Fig. 5-14 illustrates – for a minimum intercept altitude of 2 km – the footprint areas which would result if detection were feasible at larger distances, but initiation of the identification-tracking-launch sequence could only start after the warheads had penetrated to a certain discrimination (or effective detection) altitude. For 100 and 50 km effective detection altitude, the areas are smaller than those of Type 1 (cf. Fig. 5-10 a), b)), approaching identical values with 50 km altitude and 5,000 km range. Only in the case of 20 km effective detection alti-

Table 5-4 Search detection ranges of a Type 1 radar for missiles of different ranges having three different radar cross sections. Calculation after (4-11) and (4-13), using standard parameters (see Tables 5-1 and 5-2). Note that because of the high reentry velocity, the lowest cross section value may not be attainable with 5,000 km range.

Missile range, km	100	200	500	1,000	2,000	5,000
Radar cross section, m^2	Search detection range, km					
0.01	142	129	99	85	76	67
0.001	66	60	46	40	35	31
0.0003	44	40	31	26	24	(21)

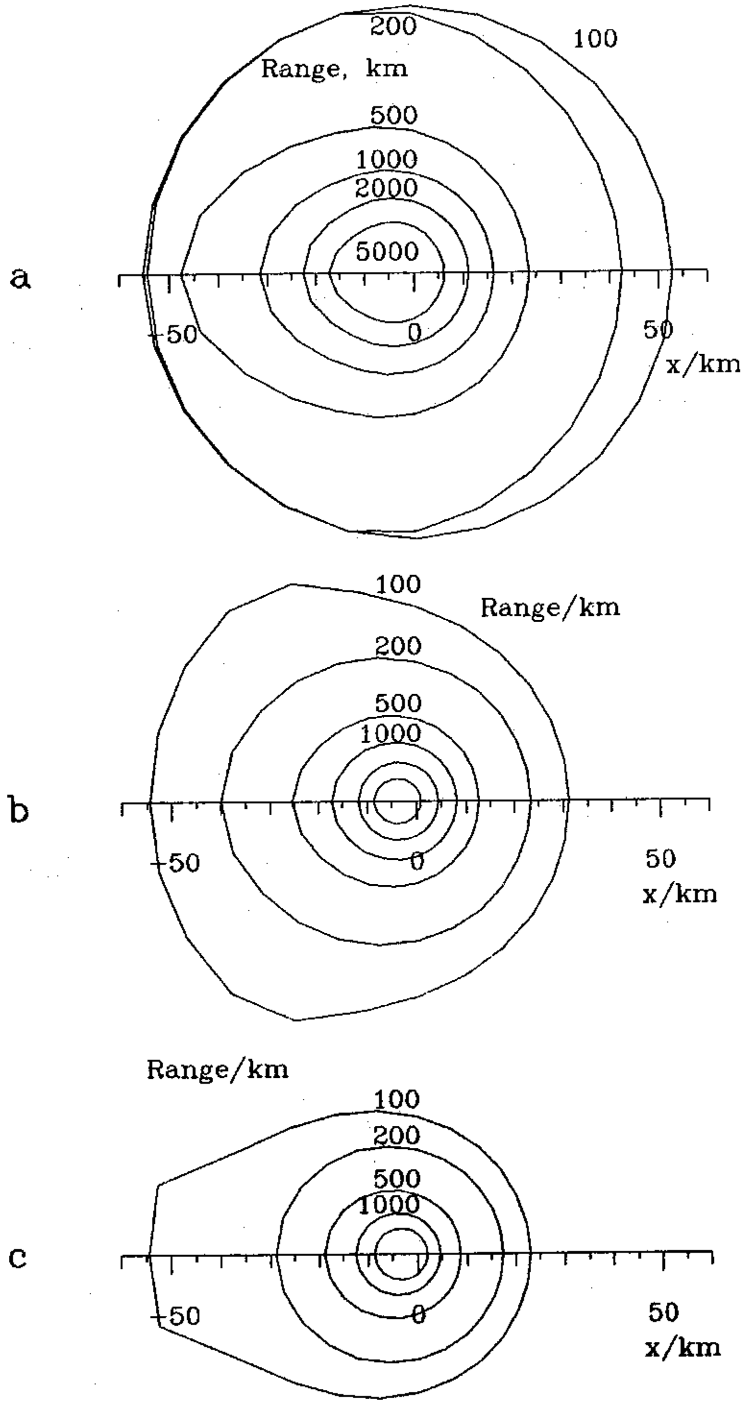


Fig. 5-12 Footprint areas of a Type 2 interceptor against tactical ballistic missiles approaching from the right from different ranges (as indicated), using a minimum interception altitude of h_{min} = 2 km (i.e., against conventional warheads). Radar characteristics as with Type 1. Search detection ranges are listed in Table 5-4.
a) Radar cross section $\sigma = 0.01\ m^2$ (typical value of present reentry vehicles of strategic ballistic missiles, standard case).
b) Radar cross section $\sigma = 0.001\ m^2$ (intermediate value, detection ranges reduced by a factor 2.2).
c) Radar cross section $\sigma = 0.0003\ m^2$ (lower limit, detection ranges reduced by a factor 3.1; may not be attainable for 5,000 km range missiles).

tude (i.e., for very short remaining time to impact), would the fast reaction and flyout of the Type 2 interceptor have a noticeable effect: here the 1,000 km footprint is larger than for

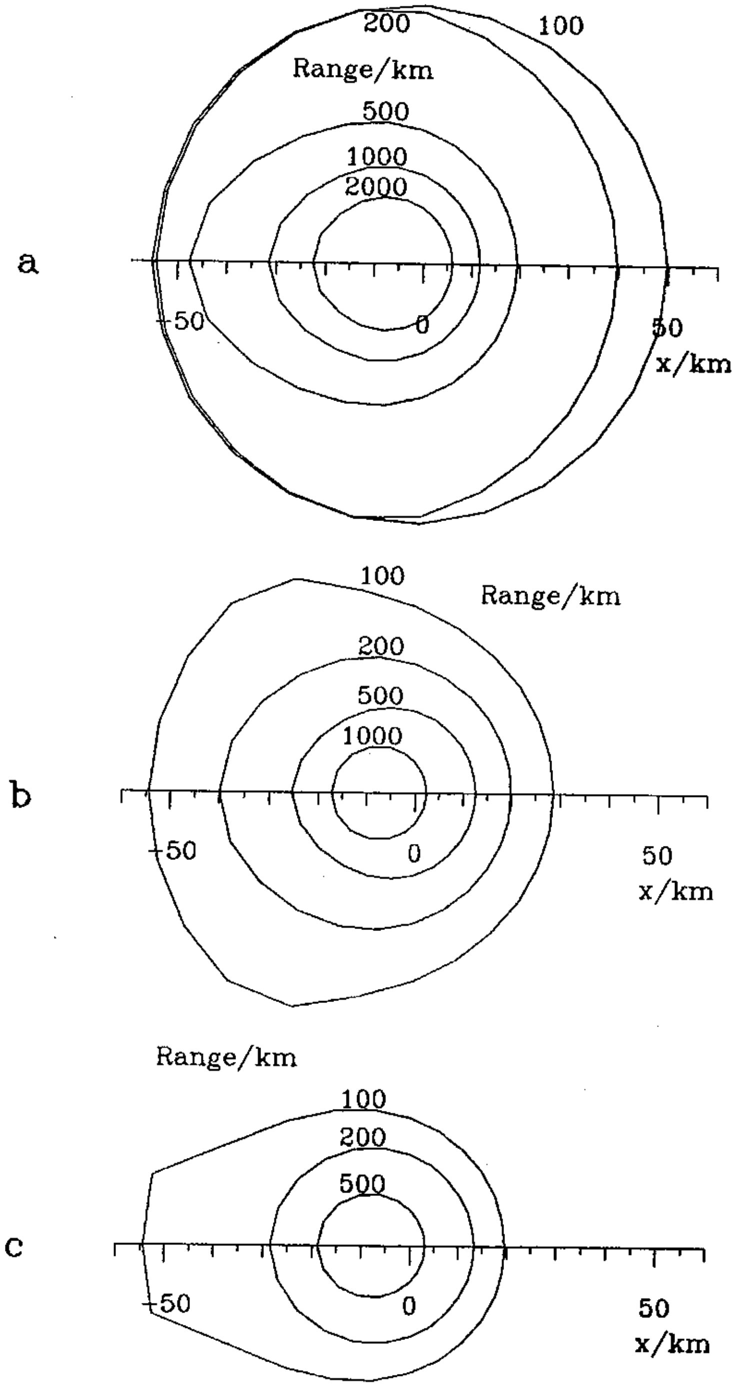
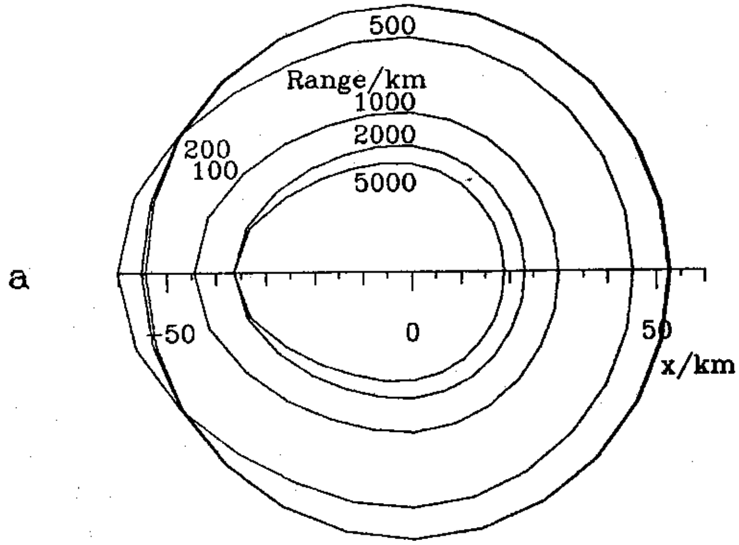
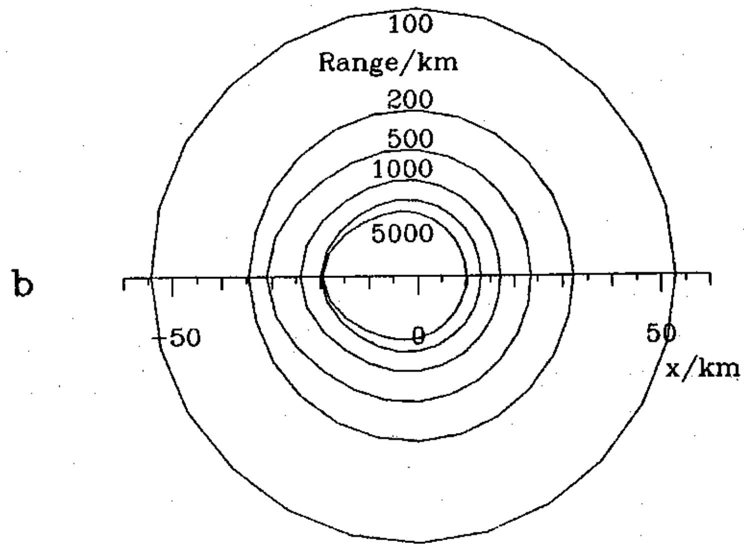


Fig. 5-13 Footprint areas of a Type 2 interceptor using a minimum interception altitude of $h_{min} = 5$ km (i.e., against nuclear warheads). Radar characteristics as with Type 1. Search detection ranges are listed in Table 5-4.
a) Radar cross section $\sigma = 0.01\ m^2$ (typical value of present reentry vehicles of strategic ballistic missiles, standard case).
b) Radar cross section $\sigma = 0.001\ m^2$ (intermediate value, detection ranges reduced by a factor 2.2).
c) Radar cross section $\sigma = 0.0003\ m^2$ (lower limit, detection ranges reduced by a factor 3.1; may not be attainable for 5,000 km range missiles).

Type 1, and the possibility to attack missiles above 1,000 km range is accomplished, whereas it is non-existent with Type 1 (see Fig. 5-10 c)).





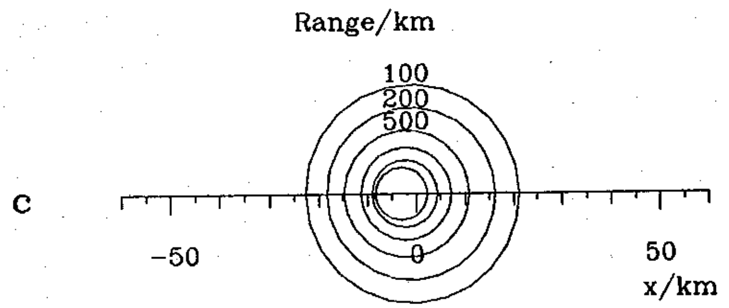


Fig. 5-14 Footprint areas of a Type 2 interceptor using an effective detection altitude h_{Det}, i.e. detection is assumed to be independent of distance. Minimum interception altitude h_{min} = 2 km (i.e., against conventional warheads).
a) h_{Det} = 100 km. This altitude would apply for discrimination of present balloon-type decoys. Missiles of 100 and 200 km range remain below 100 km during their total flight time; effective detection is assumed to happen at burnout.
b) h_{Det} = 50 km. This altitude could apply to new types of heavier decoys. Only 100 km range missiles cannot use decoys of this type, because they remain below this altitude for their total trajectory.
c) h_{Det} = 20 km. This altitude could apply to future heavy decoys with matched ballistic coefficient.

5.1.5.3 *Type 3: Ground-Launched Missiles for Late-Midcourse Intercept (Nuclear and Non-Nuclear)*

Another interceptor being developed in the U.S. SDI program is the Exoatmospheric Reentry-Vehicle Interceptor System (ERIS). With respect to its range, it resembles early exoatmospheric ABM systems; with terminal phase guidance using infrared sensors, however, the warhead would be much lighter (e.g., 20 kg) than the megaton class hydrogen bombs used formerly (e.g., 1,000 kg). Whereas plans call for a direct-hit non-nuclear warhead, a conventional shrapnell-type explosion or even a kiloton-class nuclear warhead could also be used in principle; in this case, the warhead mass would be on the order of 100 kg. Because of the lower warhead mass, a much smaller missile would suffice. A missile of such a kind is modeled here by the Type 3 interceptor (Table 5-5). An actual burnout velocity of nearly 5 km/s provides sufficient momentum for reaching altitudes above 1,000 km. Because midcourse interceptors have to be launched very early, it has to be assumed that detection and tracking of warheads in space is done by long-range systems like large ground-based radars and/or by infrared sensor systems carried on board high-flying aircraft or low-flying satellites. Since here only a qualitative assessment of the footprint area is intended, the detection range is fixed at 2,000 km (as above, detection of missiles of shorter range is assumed to occur at burnout). In order to demonstrate the basic kinematic capabilities of such a system, it is further assumed that the identification, tracking, and interceptor launch sequence can begin immediately after detection. This means that it is unrealistically assumed that no stealth techniques are used, and that decoys are either not present, or can be reliably discriminated. Because for late midcourse interception there is more time available, in this case again a less demanding defense system delay time of 5 seconds is used. By the same token, the burn time chosen is longer (40 seconds total), and the minimum interception altitude is assumed to be 5 km (2 km would not change the results significantly).

Fig. 5-15 shows the flyout trajectories and the curves of equal arrival time for the Type 3 interceptor. For the specific data set used here, this missile could reach altitudes up to 1,400 km, and could achieve surface-to-surface ranges of more than 2,700 km. Figures like this would be typical of a real midcourse interceptor, but of course variations are to be expected.[4] Defense footprint areas of a Type 3 interceptor system have been computed for tactical ballistic missiles of ranges from 500 to 5,000 km, where a significant midcourse phase exists. Fig. 5-16 shows the results. Since the detection range was assumed fixed in this case, and because of variations in the interceptor characteristics, the footprint margins shown only give typical values. If early detection and, above all, discrimination could be guaranteed, then midcourse interceptors could provide quite large footprint areas, reaching from more than 500 km in the forward direction, to several 1,000 km in the backward direction. To cover a country like the Federal Republic of Germany, a handful of such defense systems would suffice (of course, hundreds of interceptors would have to be available at each position); for the USA, some 10 or 12 Spartan sites had been discussed in the sixties.[5] This explains why efforts for ballistic missile defense will tend to include long-range detection systems and long-range interceptors. As a consequence, several problems arise: one is the possible use of decoys to negate warhead discrimination. Acknowledgement of this possibility was instrumental for halting countrywide ABM systems and concluding the ABM Treaty. Another grave problem, specific of defense against tactical ballistic missiles, is that interception would take place

Tab. 5-5 Parameters of the Type 3 ballistic missile defense interceptor used in the calculations. A similar missile could be used for the U.S. ERIS late-midcourse interceptor. Part of the fuel on board the warhead is used for further acceleration. Search and tracking is assumed to be done by fixed large radar and/or infrared sensors on board aircraft or low orbit satellites, and decoys are neglected. A fixed detection distance is used (for lower range missiles, detection is assumed to take place at burnout). For program input data, see Appendix.

Search	
Detection range (independent of ballistic missile range)	2,000 km
Interceptor missile	
No. of stages	2 + 1
Launch mass m_0	690 kg
Warhead mass (with fuel)	40 kg
Total burn time t_B	40 s
Actual burnout velocity	4.6 km/s
Defense system	
Identification, tracking, and launch delay time t_D	5 s
Minimum interception altitude h_{min}	5 km

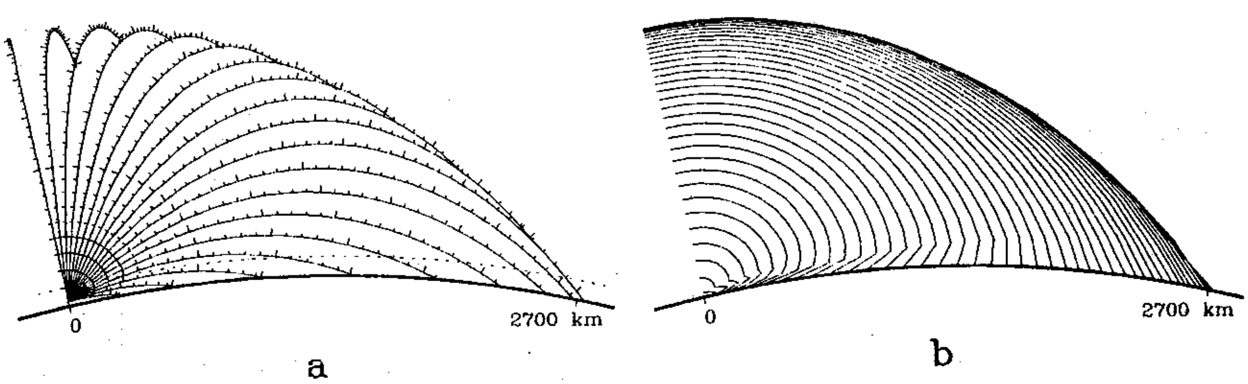


Fig. 5-15 Flyout characteristics of Type 3 interceptor missile.
a) Trajectories start with a vertical ascent of 25 km, changing to constant elevation angles β during the rest of the burn time (5° steps); they are shown only until they cross the next lower one. One tick corresponds to 20 seconds. The altitude 100 km is indicated.
b) Curves of equal arrival time; one curve is drawn every 20 seconds. For circular symmetry of the defense, these curves can be rotated around the vertical at zero.

above the territory of the other side and that interceptors could reach surface areas thousands of kilometers within that territory.

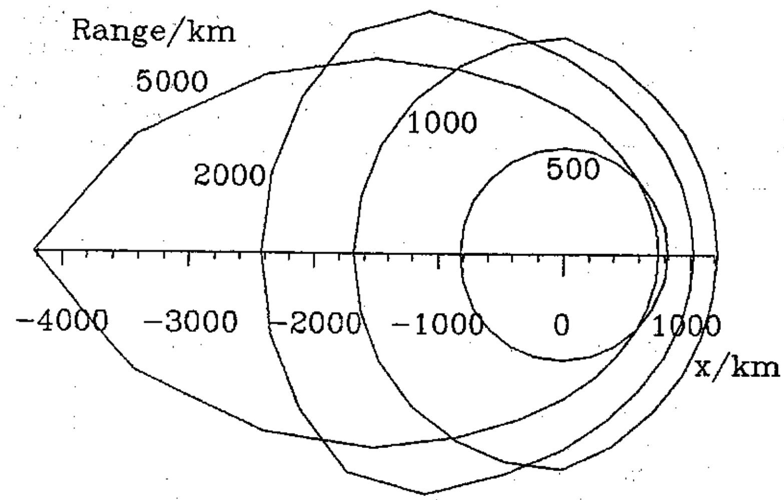


Fig. 5-16 Footprint areas of a Type 3 defense system against tactical ballistic missiles from 500 to 5,000 km range, as indicated, coming from the right. A fixed detection range of 2,000 km and reliable discrimination of warheads in space are assumed. For launch within the detection range, the burnout time is taken as the detection time.

5.1.5.4 Evaluation of the Examples

Table 5-6 is a summary of the basic properties for the three interceptor types. *Type 1*, an upgraded air defense missile of moderate acceleration and considerable burnout velocity serves as a reference point. Using a mobile radar such as the radar of the U.S. Patriot system for search, this interceptor can provide footprint areas against short-range missiles (100 to 500 km range) extending over dozens of kilometers. For intermediate ranges (1,000 to 5,000 km), footprint extensions are degraded from less than 20 km to a few kilometers; under some conditions, at greater ranges footprint areas can even become zero. In reality several conditions working against the defense can be combined; reduced detection range because of low radar cross section, low effective detection altitude because of heavy decoys, and the requirement for a higher minimum interception altitude (e.g. 5 km) because of nuclear warheads. If only a mobile radar is available, the defense cannot significantly counteract – perhaps the radar power-aperture product could be increased by a factor of two. Thus, as Table 5-7 shows, such a combination would preclude interception of nuclear ballistic missiles above 1,000 km range, and of conventional ones (with 2 km minimum interception altitude) above 2,000 km range.

Type 2, a smaller missile for low endoatmospheric interception, is launched with shorter delay, accelerates faster, but achieves only half the burnout velocity of Type 1. Its footprint areas are smaller than those of Type 1 in most cases, except for detection at short distances and interception of fast missiles, then its quick reaction and high acceleration can have their effects. In the absence of countermeasures, considerable footprint sizes against intermediate-range missiles can be achieved with a mobile radar. If, however, the same combination of adverse conditions (and a twofold increase in radar power-aperture product) is used, then nuclear ballistic missiles cannot be intercepted if the range is above 1,000 km (conventional ones are only out of reach if their range exceeds 5,000 km) (see Table 5-7). The results for both interceptor types emphasize a weak link, namely the limited detection range of a mobile

Table 5-6 Basic properties for the three interceptor types used in 5.1.5.

Interceptor for flight phase	Type 1 total reentry	Type 2 late reentry	Type 3 midcourse
Launch delay, s	5	2	5
Burn time, s	12	2	40
Mean acceleration, m/s^2	190	600	120
Burnout velocity, km/s	2.2	1.1	4.6
Max. altitude (vertical launch), km	260	40	1,400
Max. surface-to-surface range, km	400	55	2,700

radar. This explains the efforts to augment ground-based ballistic missile defense systems with other larger ranging search mechanisms, such as large fixed early warning radars or air- and space-based infrared detection.

The long-range, high-altitude *Type 3* interceptor could theoretically achieve very large footprint areas (sizes measuring from several 100 kilometers to several 1,000 km) against intermediate-range missiles above 500 km range, if discrimination during midcourse could be done. (It could not feasibly be used against shorter-range missiles which do not leave the atmosphere.) It would provide another, earlier layer of defense, after which Type 1 and/or Type 2 interceptors could have a second (or even third) try.

As a whole, the results of this section underscore two tendencies which exist with defense against tactical ballistic missiles: one is the tendency for earlier detection, the other is the tendency to include earlier interception. Because short-range missiles cannot effectively be attacked using midcourse interceptors, terminal phase interceptors will have to be present anyway. In addition, a layered system with several interceptors functioning at successive

Table 5-7 Upper missile range limits where footprint areas of interceptors using a mobile radar shrink to zero in presence of multiple offensive countermeasures and one defensive counter-countermeasure.
Deviations from the standard case (see Table 5-1):
Offense:
Radar cross section reduced by factor 10 to $\sigma = 0.001\ m^2$;
Effective detection altitude $h_{Det} = 50$ km;
Minimum interception altitude $h_{min} = 5$ km (nuclear); 2 km (conventional).
Defense:
Radar power-aperture product increased by factor 2 to $P_{av} \cdot A_{eff} = 90\ kWm^2$.

Interceptor Type	Upper missile range limit where defense could be kinematically possible, km: against nuclear missile	against conventional missile
Type 1	1,000	2,000
Type 2	1,000	5,000

flight phases and altitudes will tend to increase the total effectiveness against missiles of longer ranges. Even though midcourse discrimination will probably continue to present insurmountable difficulties, it can be expected that these tendencies for detection and interception at far forward positions would come to bear over time under conditions where a full spectrum of tactical ballistic missile ranges is present, and defense against those missiles has become a major goal.

5.1.6 Methods for Enlarging the Footprint Areas of Ballistic Missile Defense Systems

As was demonstrated in 5.1.5, the footprint area of mobile ground-based ballistic missile defense systems is rather limited. The main reason for this is that incoming vehicles are detected only late in their trajectory, and that the interceptors can thus meet them only at a modest distance from the defense location. Therefore, in order to enlarge the footprint area, one has to provide a means for earlier detection. This could be achieved by large early warning radars, by long-wave infrared sensors placed on board high-flying aircraft or low-orbit satellites, or by short-wave infrared sensors placed on high-orbit satellites.

If early warning radars are to achieve significantly larger search detection ranges, their average power and their antenna area have to be increased significantly, so that they can no longer be land-mobile. For the problems associated with this approach, see 4.1.1.4.

Long-wave infrared sensors carried by aircraft or low-orbit satellites would detect reentry vehicles after the boost, and possible post-boost, phase. This means that, given appropriate tracking capabilities, the course of the trajectory could be predicted with good accuracy. If reliable communications to the ground-based interceptor launch systems were available at all times, and if the decoy discrimination problem were solved, determination of the impact area could immediately be followed by assignment and launch of an appropriate interceptor. Depending on the remaining flight time of the reentry vehicle and on the interceptor velocity, interception could in principle take place at several hundred kilometers distance from the intended target, and footprint areas could extend over more than 1,000 km in any direction (for ballistic missiles of comparable range, i.e. of sufficiently long flight time). The ultimate limit would be given by the maximum range of the interceptor achievable during the remaining flight time of the reentry vehicle.

At most, this is a remote possibility. It may well be that the discrimination problem will remain unsolved by use of passive or active countermeasures; if these had arrived at their limits, offensive attacks at the sensor platforms would then call discrimination into question. For the foreseeable future, however, several other conditions mentioned will likely remain unfulfilled. One is the problem of tracking from one sensor platform (triangulation using two or more platforms is very complex and requires extensive communication). Another is the complexity of a communication and decision system involving several sensor carriers and several hundred launch locations. For the next decade, one would expect that sensor systems would only relay information on the detected objects to the ground posts. This would constrain the possible attack corridors, and the respective ground radars would begin a search in a substantially reduced solid angle region. Only if a local defense system had detected, tracked, and classified as an approaching object coming in range, would an interceptor be launched.

For an estimate of the increase in radar detection range, let us assume that the search solid angle could be confined to 5° by 5° in azimuth as well as elevation. The solid angle is then 0.008 steradian, which is a factor 120 below the typical value for an independent search radar used in 4.1.1.3. Since, according to (4-11) and (4-13), the search detection range varies as the inverse third root of the solid angle, it would rise by a factor of 5, which is a substantial increase. For a Patriot-type radar, e.g., detecting an object approaching with 3 km/s velocity, i.e. from 1,000 km range, the detection range would thus increase from 80 to 400 km. This would increase the forward footprint boundary of a Type 1 interceptor (using standard values) from 21 to 90 km; in the backward direction, the footprint margin would increase to several hundreds of km.

Satellite-borne boost phase detectors could contribute to another footprint area increase. Because they would have difficulties determining the further trajectories, and predicting the impact points, tracking would still have to be done by the other sensors mentioned. Integrating information from different carriers and forming an integrated decision network is even more complicated than in the case of airborne sensors. The satellite information on launch regions could alert airborne infrared sensors, and the search solid angle of ground-based radars could possibly be constrained at an earlier time.

The ultimate increase of the footprint area would be theoretically possible with space weapons capable of shooting down ballistic missile during their boost phase. If these weapon satellites were distributed globally in such a way that sufficient firepower were always present above potential missile launch regions, the footprint area could extend to the whole globe (for weapons not able to shoot at arbitrarily low atmospheric layers, excluding a small circle around every launcher of a short-range missile). With space-based weapons of global coverage, the footprint concept looses its utility. The probability of interception, the amount of protection, and the consequences on strategic stability have to be assessed in another framework. For kinetic weapons, the next section will cover some of these aspects. For laser and particle beam weapons, see section 4.3.3 and the references cited there.

5.2 Ballistic Missile Defense by Space-Based Kinetic Energy Weapons

5.2.1 Basic Properties of Space-Based Kinetic Energy Weapons

For an early deployment of ballistic missile defense weapons in space, only kinetic energy weapons accelerated by chemical rockets can be used. Several small rockets would be carried on board a satellite (numbers in the tens have been mentioned)[6]. Similarly to beam weapons on satellites, deployment would have to guarantee that sufficient firepower is above the ballistic missile launch regions for boost phase defense, or in the region of the free flight trajectories for midcourse defense. Different from beam weapons is the relatively long time to target – typical velocities being 5 or 10 km/s instead of 300,000 km/s for beam weapons.

Any type of kinetic kill vehicle is accelerated for a short time (seconds with chemical rockets, milliseconds with electromagnetic launchers) to a velocity of several km/s on a course leading to the predicted impact point with the target object. After that, the projectile coasts on a free-fall trajectory through space for a relatively long time (tens of seconds up to minutes). Course changes have to be made by thrusters, as the relative movement of both objects becomes better to observe with a reduced distance, or, if the target object is still accelerating, as the actual time course of its velocity vector becomes known. As the projectile approaches the target, sensor systems have to acquire the target in order to guide the projectile on a (near-)collision course. The lowest interceptor mass is possible, if a direct hit can be achieved; the probability of hitting could be increased by unfolding of a net- or web-like structure (as was done in the U.S. Homing Overlay Experiment)[7]. If a shrapnel-like explosive warhead would be required as in the atmosphere, significant increases in projectile mass – and thus the total mass lifted to satellite orbits – would result. Target acquisition and homing guidance in space can be performed by a cooled long-wave infrared sensor; as shown in 4.1.3, detection distances of more than 100 km (depending on the optics size) are possible. In the vacuum of space, no window would be needed in front of the detector/mirror. This detection scheme would, however, break down in the atmosphere. (Note that the U.S. HEDI missile for interception at 15 to 50 km altitude uses a shroud and a cooled window, and that optical distortion causes severe problems.[8]) With light-weight projectiles with open optics, interception in the atmosphere at less than 50 km is totally impossible.

In order to uniformly cover the regions of interest, and to proliferate the number of possible targets for offensive countermeasures, satellites with kinetic energy interceptors would be deployed in many orbits, and in high numbers (several hundreds have been mentioned)[9]. For boost phase attack the targets are below the satellites; the same holds for midcourse defense against tactical ballistic missiles of shorter ranges. Because of the finite flight time to the collision point, one would try to choose as low an altitude as possible. This is limited by the drag of the residual air; numbers of 500 to 800 km have been mentioned.[10] For a conservative estimate, I assume that the satellites are deployed at 300 km altitude; this would result in a lifetime below one year without compensatory maneuvers.

Estimates on the effort and cost of such schemes can be derived from the masses which have to be transported to satellite altitudes, and to be accelerated to orbital velocities. For the additional acceleration which is needed to move the projectile to the collision point on the target trajectory, energy supplies would have to be on board. In case of chemical rockets, the amount of fuel required per projectile mass can be estimated by (3-13). Neglecting the mass of the rocket housing etc. and assuming an exhaust velocity of 3 km/s, for a velocity increment of 5 km/s the launch mass has to be 5.3 times the projectile mass. In order to achieve 10 km/s, this factor increases to 28. Because of the high cost of transporting mass into orbit (numbers vary between 1,500 and 3,000 $ per kg),[11] one understands the efforts of the SDI Organization to reduce the projectile mass, which has to include a miniature inertial measuring unit, an optics system, a cryogenically cooled infrared detector, a computer, a communications unit, a power supply, and lateral thrusters with fuel (possibly, a structure to be unfolded may also be required). Projections call for a mass of 5 kg to be achieved in 1990, and 2 kg later.[12] If one assumes a velocity increment for the first type of 5 km/s, and 10 km/s for the later one, the total mass of one space-based interceptor missile is about 30 or 60 kg, respectively. (Note that the SDI Organization strives to achieve a mass of 110 kg.[13])

With electromagnetic acceleration, the fuel can be spent on board the satellite, and thus does not need to be accelerated with the missile. In the earliest achievable types, chemical fuel would be burnt in one way or the other, producing electrical from thermal energy at some energy efficiency η_{el}. The electrical energy – possibly after storage (in flywheels, in superconductors etc.) – would then be converted to kinetic energy of the projectile with a second efficiency η_{kin}. In order to derive the mass of fuel per projectile mass needed to provide a velocity v, one can equate the kinetic energy per projectile mass gained from the chemical energy to the kinetic energy per mass needed:

$$\frac{E_{kin}}{m_P} = \eta_{el}\,\eta_{kin}\frac{E_{chem}}{m_P} = \frac{v^2}{2} \qquad (5\text{-}1)$$

From this, the ratio of the fuel mass m_F needed to the projectile mass m_P accelerated is

$$\frac{m_F}{m_P} = \frac{v^2}{2} \frac{1}{\eta_{el}\,\eta_{kin}} \frac{m_F}{E_{chem}} \qquad (5\text{-}2)$$

A projectile of v = 10 km/s velocity has a kinetic energy per mass of E_{kin}/m_P = 50 MJ/kg. A typical value of liberated energy per fuel mass is E_{chem}/m_F = 10 MJ/kg.[14] Using efficiency values for the energy conversion processes of η_{el} = 0.3 and η_{kin} = 0.5, one derives that about 33 kg of fuel is required to accelerate 1 kg of projectile. This is about the missile mass in the case of rocket propulsion – electromagnetic acceleration becomes more mass-efficient than rocket propulsion only with final velocities above 10 km/s.[15] This conclusion would not hold, if nuclear reactors would be used for the production of electrical energy, because here the energy produced per fuel mass is several orders of magnitude higher; but nuclear power supply of such satellites is probably further away than electromagnetic acceleration.

Taking a projectile mass of 100 kg as a baseline, assuming that every satellite would contribute another 100 kg per interceptor, and a cost per mass to orbit of 1,500 $/kg, lifting one interceptor into orbit would cost $ 300,000.

5.2.2 Boost Phase Properties of Tactical Ballistic Missiles

In order to assess whether projectiles from low satellite altitude are able to reach tactical ballistic missiles during their boost phase, one needs to know how long the boost phases are, and at what altitudes burnout occurs. For the notional missiles used in this study, which have burn times of 50 seconds per stage, different quantities of their boost phases are listed in Table 5-8. It is evident that even with modest acceleration (and, accordingly, long burn times), ballistic missiles of up to 500 km range burn out below 50 km altitude. It should be possible without overwhelming effort to produce missiles of 1,000 and 2,000 km range which have reduced burn times and higher acceleration, and thus also burn out at altitudes below 50 km (cf. the data of the Type 1 interceptor missile in Table 5-8). For 5,000 km range missiles, one could take the figures for fast-burn intercontinental missiles (10,000 km range): if a 25% reduction in payload is tolerated, burn times of less than 60 seconds and burnout altitudes of 90 km can be achieved.[16]

5.2.3 Is Boost Phase Defense Against Tactical Ballistic Missiles Possible?

If one optimistically assumes that detection of a tactical ballistic missile launch occurs immediately at the beginning of the boost phase, and that prediction of the further missile trajectory is possible to an extent sufficient for an interceptor launch decision, then the first question is: can the interceptor descend to the burnout altitude in time, i.e. before burnout?

The minimum distance that the interceptor must move at its additional velocity is the altitude difference between the satellite altitude of 300 km and the burnout altitude of less than 50 km for missiles of up to 2,000 km range. It is obvious that with chemical rockets which provide a projectile velocity of 5 km/s, the distance of at least 250 km cannot be covered in less than 50 seconds time.

The task could in principle be achieved by projectiles having significantly higher velocity, say, 10 km/s (as provided by electromagnetic acceleration, or by a chemical rocket more than

Table 5-8 Quantities of the boost phase for typical tactical ballistic missiles of different ranges (computed with the data and program described in the Appendix). To give an idea on how much the burnout altitude could be reduced, the data for the Type 1 solid-fuel interceptor missile of 5.1.5.1 is included. For comparison: gravity acceleration at sea level is 1 g = 9.81 m/s^2.

Range km	No. of Stages	Burnout time s	Burnout velocity km/s	Burnout altitude km	Max. acceleration m/s^2
100	1	50	1.0	18	33
200	1	50	1.3	23	53
500	2	100	2.0	49	51
1,000	2	100	2.8	70	69
2,000	2	100	3.9	87	121
5,000	3	150	5.5	260	85
Type 1 Interceptor					
380	1	12	2.4	10	330

28 times heavier than the projectile). But here the atmospheric effects come into play. As stated above, space interceptors with open optical systems cannot function at altitudes below about 50 km; therefore, any tactical ballistic missile which burns out below 50 km cannot be attacked for fundamental reasons, irrespective of the projectile velocity. As stated above, this burnout altitude can be achieved for missiles of up to 2,000 km range at least. (To get an idea about longer ranges, one should look at the analyses done for intercontinental ballistic missiles, which are also not very promising for the defense.[17]) The conclusion therefore is that space-based kinetic energy weapons cannot be used for boost phase defense against tactical ballistic missiles.

5.2.4 Midcourse Defense Against Tactical Ballistic Missiles

Space-based kinetic energy weapons are better suited for the task of attacking missiles or reentry vehicles while they coast through space at altitudes above 50 or 100 km. As Table 3-1 shows, this excludes ballistic missile of short ranges (100 or 200 km). Missiles from 500 to 5,000 km range can be attacked, and the available time varies between 2 and more than 15 minutes. The most demanding task is posed by the missiles with the shorter flight times; for 500 to 1,000 km ranges, which in Europe could be launched from an area of roughly 1,000 by 1,000 km^2 (1 Mm^2), the time is 2 to 6 minutes (such missiles are now banned from the U.S. and Soviet arsenals by the INF Treaty). This assumes that tracking for trajectory prediction and the launch decision are completed immediately after burnout (and decoys are reliably discriminated). In 2 minutes, a projectile with 5 km/s velocity covers a distance of 600 km; neglecting the vertical component due to different altitudes of satellite and missile, one projectile on one satellite could cover a circular projection on the ground with that radius, i.e. with an area of 1.1 Mm^2. The area density of interceptors required can be derived from the requirement that at least one interceptor is available per missile/reentry vehicle at the midcourse region during the midcourse flight time. In two minutes, the satellites at 7 km/s travel 840 km, slightly less than the diameter covered by one satellite; therefore, the area density of projectiles needed momentarily can be reduced by a factor of about two. Because the launch/midcourse region is smaller than the area covered, the required area density of interceptors is related to the latter area. Assuming a mass launch of 1,000 warheads, 1,000 interceptors have to be present in an area of 1.1 Mm^2 during 2 minutes, i.e. about 500 at any given time: the interceptor density has to exceed a value $N_{Int}/A = 440/Mm^2$. From this, the total number of interceptors N_{tot} to be deployed around the globe can be calculated according to a formula which originally was derived for the number of beam weapons needed to cover ICBM launch fields:[18]

$$N_{tot} = 4\pi R_E^2 \frac{N_{Int}}{A} \frac{1}{y}, \text{ where} \tag{5-3}$$

$$y = \frac{2}{\pi} \frac{\arcsin(\sin\lambda_2/\sin i) - \arcsin(\sin\lambda_1/\sin i)}{\sin\lambda_2 - \sin\lambda_1}. \tag{5-4}$$

Here, $R_E = 6.37$ Mm is the earth radius, i is the inclination of the satellite orbits, and the covered region is bounded by the geographical latitudes λ_1 and λ_2 (i being equal to the larger of the two for optimum coverage). For Mid-Europe, $i = \lambda_2 = 60°$ and $\lambda_1 = 50°$; thus, $y = 3.1$. With $N_{Int}/A = 440/Mm^2$, the total number of interceptors becomes 73,000, which translates to 3,000 to 7,000 satellites of 10 or 20 interceptors each. (Note that for 10,000 reentry vehicles of intercontinental ballistic missiles with significantly longer midcourse durations, a total number of 40,000 interceptors of 8 km/s velocity has been estimated.[19])

If a higher velocity of 10 km/s can be achieved, within 2 minutes a distance of 1,200 km, and an area of 4.5 Mm^2 can be covered. Because the diameter is now larger versus the distance traveled by the satellites during the same time, overlap is insignificant. Postulating that 1,000 interceptors can reach the relatively small launch/midcourse region means that the interceptor density is $N_{Int}/A = 220/Mm^2$. The total number becomes 36,000; still several 1,000 satellites are needed if each carries not more than 20 interceptors.

If the requirement to engage 500 km range missiles could be dropped, things would seem easier. Within the 6 minutes midcourse phase of a 1,000 km range missile, a 10 km/s interceptor could cover an area of 40 Mm^2, without an overlap factor. Now, a total number of 4,000 interceptors on 200 to 400 satellites would theoretically be sufficient.

Summarizing, one must state that tactical ballistic missiles of ranges of 100 or 200 km are out of reach for space-based kinetic energy weapons. Defense against missiles of the 500 km range requires tens of thousands of interceptors on thousands of satellites. Only when the task is reduced to ballistic missiles of 1,000 km range and higher, do the satellite numbers drop to hundreds.

In reality, it is improbable that missiles with ranges below 1,000 km would be neglected by defense planners; moreover, motives would exist to exceed the number of warheads by a factor of at least two, to make up for misses and for interceptors hitting decoys (as well as for other losses). Certainly, reliable detection of warheads in the presence of countermeasures will remain questionable (see 6.1.2.5). Another problem is the possibility of mass attack on the satellites by ground-based anti-satellite missiles (or, for that matter, ground based interceptors for late-midcourse defense against tactical as well as strategic ballistic missiles). The biggest problem would be presented by a second system of kinetic energy weapons satellites belonging to the other side, which would probably be deployed at a similar altitude, say 50 to 100 km higher. In this case, interceptors would take only 5 to 20 seconds to reach the other side's satellites, and the systems could attack each other globally with much greater efficiency than they could defend against ballistic missiles.

5.3 Preferential Defense

A defending side can drive the costs for the attacker upward, if one defensive system can cover several targets, and if not all targets need to be protected. In this case, some targets are willingly sacrificed by concentrating the defense on a portion of the targets only. Because an attacker cannot know in advance which targets will be defended heavily, he will have to spend an equally high number of missiles or warheads on every target, if he really needs to destroy all of them. (If he were only interested in damaging a portion of the target, the tactics of preferential defense would not impede his aim.) Usually, these conditions are thought to apply to a silo field of intercontinental ballistic missiles with a terminal defense system.[20] Here, a successful nuclear first strike hitting all silos could be made very difficult by heavily defending only a few silos; even if only a small portion of the missiles remain, this second-strike capability produces a strong deterrence against such an attack. (In reality, a sufficient number of uncertainties would be connected with a nuclear first strike, so that even without any defense no side could reliably destroy the land-based missiles of the other. In addition, there are bombers and submarine-launched missiles which could also be used in a second strike.[21])

If the two conditions mentioned are not fulfilled, preferential defense is of no use: This holds for targets of which every single one is of high importance, and none could reasonably be sacrificed (like cities e.g.). It also holds for defense at an early time, when the trajectory does not permit prediction of which warhead will hit at which target, and therefore no selection between warheads to be attacked or warheads to be left unimpeded, can be made. This means that preferential defense of single missile silos of a field of some 10 km size is only possible by terminal-phase defense systems.

Against tactical ballistic missiles, preferential defense practically cannot be used. For nuclear missiles targeted against cities, the same argument as above applies. For nuclear missiles targeted against military installations, the area of damage would reach out to 1 to 2 kilometer, with corresponding increase in difficulty for the defense. In addition, military targets in Europe are more than 20 km apart on the average, so that one defense system could cover only one target. Finally, the military effectiveness of the side being attacked would decrease significantly with every target hit. Because conventional tactical ballistic missiles will remain relatively inefficient in a military sense (see 7.2), it is not necessary to analyze whether and how the preferential defense concept could apply to them.

5.4 Reaction Times of Anti-Tactical Ballistic Missile Defense Systems

Anti-tactical ballistic missile defense systems have to react quicker when the the incoming ballistic missile is faster, when the interceptor is launched later in the missile flight time, and when the distance to the interception point is greater. (For boost-phase intercept similar short reaction times as for terminal phase defense would apply, but this is only a theoretical possibility, see 5.2.3.). Any increase in the actual launch delay over the minimum value (which was used in the calculations of 5.1) reduces the distance that can be flown by the interceptor during the remaining time to target of the ballistic missile; thus, the footprint area is decreased. If the launch is delayed too long, reaching the incoming missile before it has arrived at the minimum interception altitude becomes impossible – the footprint area will then be zero.

In case of endoatmospheric interceptors using a local mobile radar and/or a minimum detection altitude for discrimination, the additional delay which can be allowed without losing self defense capability ranges from a few seconds against intermediate-range missiles to one or two minutes for short-range missiles of low velocity.

Ground-based exoatmospheric interceptors, against intermediate-range ballistic missiles in their midcourse phase, would provide more latitude; in principle, the allowable delay is equal to the time difference between the first and the last possibility of intercept. The former is given by the first detection time plus the durations needed to discriminate (if at all possible) and track the reentry vehicle, plus the flight time of the interceptor; the latter is an intercept just outside the atmosphere, before reentry begins. Depending on the missile range, the possible delay in time can amount to several minutes, shrinking to several times 10 seconds for a range of 500 km. For an approximation, one can assume equal velocities of missile and interceptor, and launch at missile burnout. Because both objects move in roughly opposite directions, the earliest possible intercept is at half midcourse time. Therefore, the allowable delay is approximately half the time spent at altitudes above 100 km (see Table 3-1).

For space-based kinetic energy projectiles, the allowable delay depends on the ballistic missile trajectory and the density of the interceptor-carrying satellites. As above, it is figured by the difference between the first and the last possible intercept times. Since satellites would be nearer than interceptor launch positions on the ground, the delay could be even longer. As an upper limit, one can use the total flight time at altitudes above 100 km, minus an average projectile flight time. Thus, the additional time delay could range from zero at 500 km range to about 20 minutes at 5,000 km range. (Of course, this requires – besides discrimination – a multitude of satellites; any single one would be within range of a missile trajectory for a few minutes only.)

5.4.1 Multiple Consecutive Interception Attempts

If a defense system provides sufficient time between the first and the last possibility of intercept, the so-called "shoot-look-shoot" tactic can be used. This means that if an interceptor is launched early, the relative approach of the ballistic missile and the interceptor is observed up to the intercept point; the process of interception is evaluated and the damage to the incoming missile is assessed. If interception fails, a second interceptor is launched for another try. (If sufficient time is available, this process could be repeated several times.) The possibility of doing this depends on the detection (and discrimination) range, the time needed by the interceptor to reach the missile trajectory at the appropriate point, and the remaining time to target. For kinetic energy projectiles in space with 5 km/s velocity and on average 200 km range to cover, about one minute is spent on each interception attempt. For missiles of 5,000 km range, more than ten consecutive trials are possible (of course assuming that discrimination would work and a sufficient number of projectiles were available). For 500 km range missiles, only one projectile could be used in space. An endoatmospheric terminal phase defense (with e.g. discrimination at fixed altitude) provides independent, additional chances of interception.

For ground-based interceptors (alone or in addition to an exoatmospheric overlay), the number of successive interception attempts possible has been calculated, as has the footprint

Table 5-9 Calculated possibilities of consecutive interception attempts if earlier attempts have failed, for tactical ballistic missiles of various ranges and a Type 1 defense system with standard parameters (see Table 5-1). Detection is assumed to take place at 100 km altitude, independent of the distance from the defense position (as earlier, for missiles staying below 100 km, detection is assumed to occur at burnout). The minimum interception altitude is h_{min} = 2 km (the value used for conventional missiles). The first interceptor is launched after a delay time of t_D = 5 s, the later ones are launched without delay at the time of interception by the respective previous one. (This is achieved in the program described in the Appendix by setting the respective consecutive detection range equal to the previous interception range and using a launch delay of zero.)
The first result row gives the number of consecutive interceptions possible if the missile is targeted at the defense itself. The third row gives the forward footprint margin if two consecutive interceptors are required; for comparison, the margin for one interceptor is given in the second row (see also Fig. 5-10 a)).

Missile range, km	100	200	500	1,000	2,000	5,000
Number of consecutive interceptions possible for missile impact point at zero distance	7	7	4	3	2	1
Forward footprint margin for one interceptor R_{FF}, km	148	249	69	41	31	26
Forward footprint margin for two interceptors R_{FF2}, km	55	70	28	16	6	-

extension if two consecutive trials are required for interception. The footprint program described in the Appendix was used with Type 1 interceptors. Discrimination by an effective detection altitude of h_{Det} = 100 km was assumed (i.e., no new types of decoys), and the detection range was not limited (i.e., more capable search means are used than mobile radars). For the second and later interceptors, the launch delay was set to zero; the next one was thus launched at the time of interception by the preceeding one, no additional time for damage assessment was included. Table 5-9 gives the results.

It is evident that for slow, short-range ballistic missiles several consecutive shots within the atmosphere are possible; the number decreases as the range increases. For 5,000 km range, a shoot-look-shoot procedure is no longer feasible. The footprint area for two shots is considerably smaller than for one; the relative reduction being most pronounced at longer ranges.

5.4.2 Consequences on Military and Political Decision-Making

As can be seen from the considerations of 5.4.1, in many cases the defense may be able to wait for some time after the first detection without immediately endangering its survival. The possible additional delay times range from several seconds to several minutes. A defense will, however, feel pressures to use the earliest intercept possible in order to achieve a higher probability of interception by providing time for another try. Thus, it is safe to state that in most cases a launch decision would have to be made within one minute (the more so, since prospects for the longer delay times in space through midcourse discrimination are dim); for fast ballistic missiles and terminal-phase defense, the decision will be required within less than ten seconds.

Whereas for the former period a launch decision by a human operator will be possible, it seems plausible that for the latter automatic launch procedures will be preferred by military commanders. In any case, there is not a possibility to include high levels of military command, let alone political leaders, in the decision-making process. In order to keep high-level control, a centralized battle management organization may be created. But also in this case, in times of a crisis, authority for launch would have to be predelegated to lower command levels, if the defense is to be effective. Whether such predelegation and the associated possibilities of false launches enhance the likelihood of preemptive strikes, will strongly depend on the range of the interceptors, as well as the overall structure of missile defense systems (e.g. on the use of nuclear or non-nuclear warheads) (see Ch. 7).

5.5 Aspects of Command, Control and Communications for Anti-Tactical Ballistic Missile Systems

As has become obvious in the preceding sections, a defense system against ballistic missiles needs to receive and process large amounts of information under a strong time pressure. Possibly threatening objects have to be detected as early as possible at large distances; attempts to discriminate the warheads from the decoys have to be made; the trajectories of the objects have to be determined and predicted; combat priorities have to be set; defense units and interceptors have to be assigned to individual targets; interceptors have to be guided and the engagement has to be observed and evaluated. Organizing the appropriate flow and processing of information, especially under war conditions when some nodes and lines may be destroyed, is an enormous task which cannot be discussed in any detail here.

Whereas a first defense capability against short-range ballistic missiles can be brought about by upgrading air defense systems, inclusion of longer ranges can no longer rest on the existing air defense command, control and communication (C^3) system. On the contrary, a qualitatively new C^3 system is needed.[22] In laying out the informational structure of anti-tactical ballistic missile defenses, two opposite tendencies will be at work. One is centralization. This begins with the cooperation of local mobile radars over distances of some 10 kilometers in order to divide the search volume and to increase the detection range. Making use of the relatively few longer-range detection systems (infrared detecting aircraft, possibly satellite-based detectors or large fixed radars) automatically necessitates a centralized structure with links over hundreds or even thousands of kilometers. Organizing intercepts in space at several 100 km from the defense positions also requires coordination over comparable distances. Finally, the political and military requirements for control of weapons which could cross the border or are even linked to strategic systems provide strong incentives for a centralized structure.

On the other hand, several arguments push for decentralization. One is the extraordinarily short time frame. Only with high effort in computing systems and communication lines may a centralized structure be able to react within seconds (of course, some long-range sensor and weapon systems cannot function at all in a decentralized way). Another argument is the prospect that under war conditions parts of the command, control and communications system will be destroyed, jammed or otherwise out of function. The higher the degree of centralization is, the more vulnerable will the C^3 system be. To prevent total dependence of defense positions on central information, some degree of autonomy will be required at least for emergency cases.

In European anti-tactical ballistic missile defense systems the C^3 structure will certainly contain elements of both, centralized and decentralized control. The degree of centralization will rise if flying infrared sensors or large fixed radars are to be integrated. Adding space-based sensors will further increase this tendency. If space weapons were to be included, a completely new area of mostly automated warfare would be opened, the C^3 aspects of which have not yet been fully analyzed in the SDI debate.

Notes and References to Chapter 5:

1 For a calculation how these facts reduce the Patriot footprint against tactical ballistic missiles targeted at backward points, see: H. van Gool, D. van Houwelingen, E. Schoten: Assessing ATBM, Appendix E, Boerderijcahier 8703, Enschede: University of Twente, Center for the Study of Science, Technology, and Society 'de Boerderij', 1987.

2 S. Glasstone, P. J. Dolan, The Effects of Nuclear Weapons, Washington DC: U.S. Department of Defense and Energy Research and Development Administration, 1977, p. 288-291.

3 van Gool et al. (note 1).

4 One notional midcourse interceptor concept published in the trade press could reach altitudes in excess of 1,500 km and ground ranges of more than 3,000 km; see the figure on p. 52 in: C. A. Robinson, Jr., Panel Urges Boost-Phase Intercepts, Aviation Week & Space Technology, pp. 50-61, December 5, 1983.

5 See: R. L. Garwin, H. A. Bethe, Anti-Ballistic Missile Systems, Scientific American, vol. 218, no. 3, pp. 21-31, March 1968.

6 For defense against strategic ballistic missiles, the G. C. Marshall Institute proposes 5 to 10 interceptors per satellite, for a total number of 11,000 interceptors, deployed in 500 to 800 km altitude: J. Gardner, E. Gerry, R. Jastrow, W. Nierenberg, F. Seitz, Missile Defense in the 1990s, p. 37-39, Washington DC: G. C. Marshall Institute, 1987. An SDI official has tentatively given figures from 6 to 24: SDIO on Verge of Producing Kinetic Kill Vehicle, Aviation Week & Space Technology, p. 24, February 9, 1987.

7 C. A. Robinson, Jr., BMD Homing Interceptor Destroys Reentry Vehicle, Aviation Week & Space Technology, pp. 19-20, 18 June 1984; See also: Report to the Congress on the Strategic Defense Initiative, prepared by the Strategic Defense Initiative Organization, Washington DC: U.S. Department of Defense, April 1987, p. VI-D-3.

8 High Endoatmospheric Defense Interceptor, Aviation Week & Space Technology, pp. 75-77, November 23, 1987.

9 Requirements for 5,000 to 10,000 interceptors, with 10 or 20 per satellite, translate to satellite numbers of 200 to 1,000. See: Report to the Congress (note 7).

10 Report to the Congress (note 7).

11 H. A. Bethe, R. L. Garwin, New BMD Technologies, Appendix A in: Weapons in Space, vol. II: Implications for Security, Daedalus, vol. 114, no. 3, Summer 1985; see also: R. M: Hord, CRC Handbook of Space Technology: Status and Projections, Boca Raton FL: CRC Press, 1985, p. 5.

12 T. M. Foley, USAF Center Develops Lightweight Projectiles for SDI Applications, Aviation Week & Space Technology, pp. 46-47, November 2, 1987.

13 SDIO on Verge ... (note 6).

14 For rocket propellants, this can be derived from the kinetic energy per mass of the exhausts, 4.5 MJ/kg for v_e = 3 km/s, and the internal efficiency, typically about 0.5. For TNT, the energy of explosion is 4.8 MJ/kg, see: G. F. Kinney, K. J. Graham, Explosive Shocks in Air, New York etc: Springer, 1985, pp. 23-24, 31-32.

15 See also: Bethe/Garwin (note 11).

16 Martin Marietta Denver Aerospace, Short burn-time ICBM characteristics and considerations, Denver CO, 20 July 1983, cited in: G. Field, D. Spergel, Cost of Space-Based Laser Ballistic Missile Defense, Science, vol. 231, pp. 1387-1393, 21 March 1986; Bethe/Garwin (note 11).

17 Bethe/Garwin (note 11).

18 R. L. Garwin, How many orbiting lasers for boost-phase intercept?, Nature, vol. 315, pp. 286-290, 23 May 1985.

19 Bethe/Garwin (note 11).

20 See: A. B. Carter, BMD Applications – Performance and Limitations, in: A. B. Carter, D. N. Schwartz (Eds.), Ballistic Missile Defense, Washington DC: Brookings, 1984.

21 See: M. Bunn, K. Tsipis, Ballistic Missile Guidance and Technical Uncertainties of Countersilo Attacks, Report no. 9, Cambridge MA: Program in Science and Technology for International Security, Department of Physics, MIT, August 1983; Report of the President's Commission on Strategic Forces, 11 April 1983 (Excerpts), Survival, vol. XXV, no. 4, pp. 177-186, July/August 1983.

22 The State Secretary at the West German Ministry of Defense called for unity of command, control and communications for the defense against aircraft and against missiles; he acknowledged that creation of such a system "with an instant reaction capability" is a major challenge. See: L. Rühl, A NATO European Anti-Missile Defence, NATO's Sixteen Nations, pp. 28-33, April 1986. J. P. Wade, U.S. Deputy Undersecretary of Defense for Research and Engineering, argued for a "NATO counter-air command center" for organising passive and active defenses as well as attacks agaist missile launchers, "something that does not necessarily exist today": DoD eyes Satellites to Warn NATO of Tactical Missile Attack, Aerospace Daily, pp. 97-98, November 18, 1983.

23 See e.g.: Report of the Study on Eliminating the Threat Posed by Nuclear Ballistic Missiles (U), vol. V, Battle Management, Communications, and Data Processing (U), J. C. Fletcher, Study Chairman, February 1984; D. L. Parnas, Software Aspects of Strategic Defense Systems, American Scientist, vol. 73, pp. 432-440, 1985; Eastport Study Group, Summer Study 1985 – A Report to the Director, Strategic Defense Organization, December 1985; D. A. Bella, Ballistic Missile Defense and the Possibility of Catastrophic Mistakes, IEEE Technology and Society Magazine, pp. 4-9, March 1987; B. Rauschenbach, Nuclear War Through SDI – Why the Star Wars Idea is Destabilizing (in German), in: J. Altmann, B. Gonsior (Eds.), Welt ohne Angst – Naturwissenschaftliche Konzepte für den Ausstieg aus dem Rüstungswettlauf, Hamburg: Rasch und Röhring, 1987.