Golden Dome: Overview of Midcourse and Boost Phase Ballistic Missile Defense

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Evolving goals for homeland missile defense

Congressional Missile Defense Act since 1999: defend against “limited” ballistic missile attack (whether accidental, unauthorized, or deliberate) but not to counter peer or near-peer strategic arsenals

2019 Missile Defense Review: defenses sized to defend the continental United States against limited offensive missile threats posed by states such as North Korea

2022 Missile Defense Review: additionally reassuring allies that the US will not be coerced, denying an adversary the ability to execute small scale demonstration strikes, complicating adversary decision making, mitigating damage to the US in case of an attack

2025 Golden Dome Executive Order: deter and defend population and critical infrastructure against ballistic, hypersonic, advanced cruise missiles, and other next-generation aerial attacks from **peer, near-peer, and rogue adversaries.** Prioritize boost-phase defense, space-based interceptors.

Golden Dome system plans

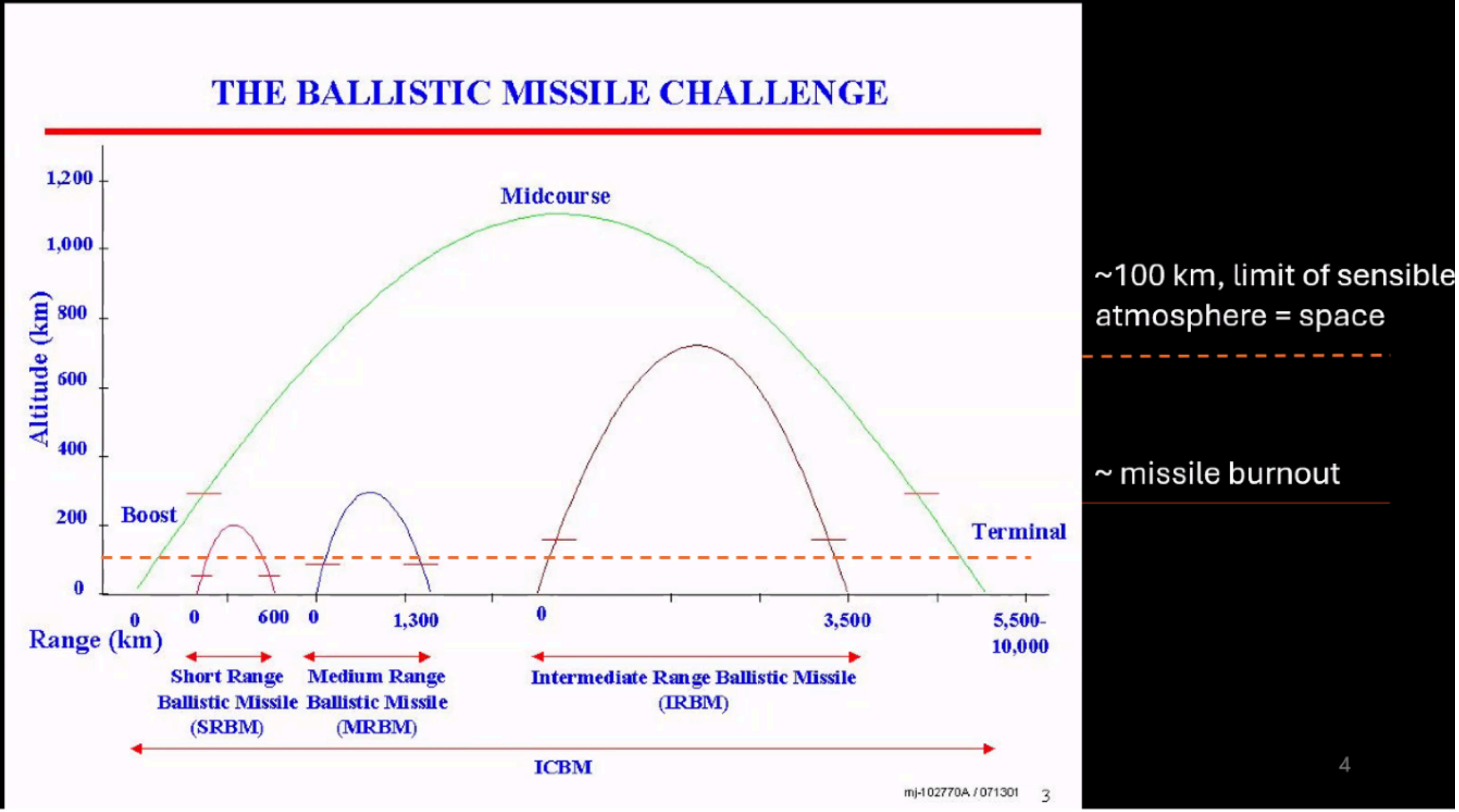
Mandates plans for defense of the US against ballistic, hypersonic, advanced cruise missiles and other next-generation aerial attacks from peer, near-peer, and rogue adversaries.

No public description of expected short-term or long-term architecture.

Will almost certainly include an expansion of midcourse defenses.

Mandates development of space-based boost phase interceptors.

Ballistic missile ranges and phases of launch



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Midcourse missile defense

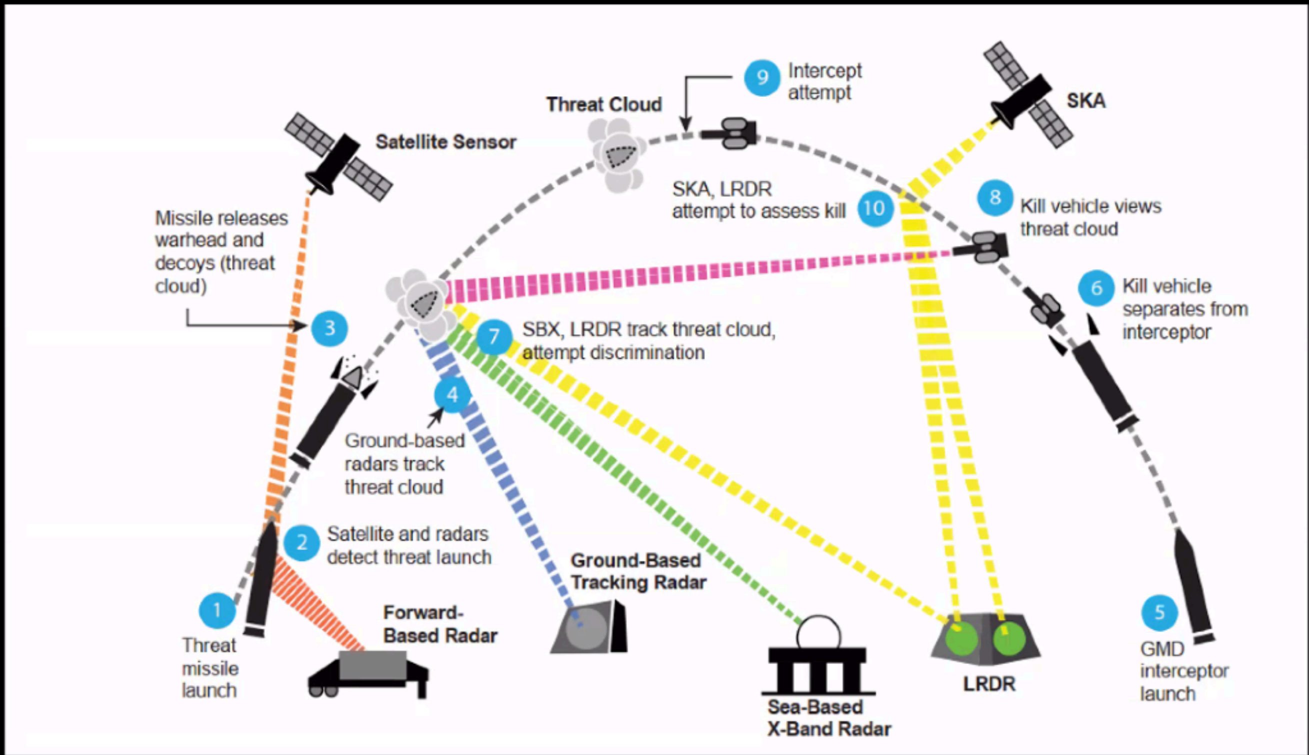
- Generous timeline, ~30-35 minutes, allows defense to be primarily in the defended area but not over populated areas, politically and practically simpler than boost phase.

- Will need to travel long distances quickly and this requires powerful interceptors, which can be based in silos.

- Missile is no longer a unitary target—may be multiple re-entry vehicles, launch debris, countermeasures including decoys, chaff, jammers.

- US Ground-based Midcourse Defense (GMD) system was fielded starting 2002 using technology developed in 1990s. We now have good data about how well it works.

Sequence of events in an attempted warhead intercept by the GMD system



GMD system comprises Interceptors: -40 in Alaska, 4 in California. 20 new generation interceptors will be added in 2028/9.

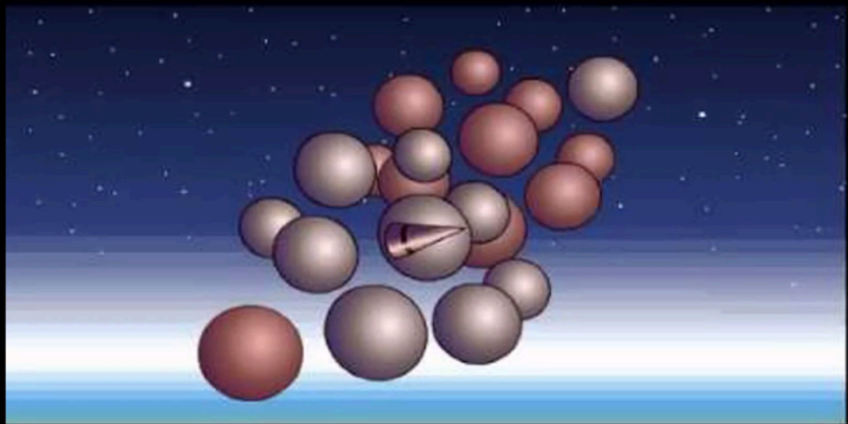
Sensors: space-based infrared and kill assessment, ground-based tracking and discrimination radars

Command and control

Threat cloud = warhead and associated objects, including launch debris and countermeasures
SKA = Space-based Kill Assessment
LRDR = Long Range Discrimination Radar
GMD = Ground Based Midcourse Defense system
SBX = Sea Based X-Band Radar

Image from "Strategic Ballistic Missile Defense: Challenges to Defending the United States." A Report by the American Physical Society Panel on Public Affairs. February 2025.

Midcourse countermeasures



From “Countermeasures”, Sessler et al. 2000
https://www.ucs.org/resources/countermeasures

Include, for example,

- Radar jammers, radar-reflecting chaff
- Lookalike decoys, anti-simulation (balloons with reflective and absorptive coatings, heaters, small weights to mimic warhead dynamics to create a scene with a diversity of signatures.)
- Blackout: high altitude nuclear detonation (may be salvage fused), confounds radar and IR sensors.

Ground-based Midcourse Defense System Intercept Tests

The Pentagon has consistently rated the GMD tests as low in operational realism. Even so, the system has failed as often as it has succeeded.

- only two tests have ICBM-range missiles as targets
- all successful intercept tests used similar lighting conditions/time of day
- no tests against salvos of simulated warheads
- appears to have never included complex countermeasures, e.g., use of target dynamics and penetration aids
- slow pace of tests, 20 in 24 years.

Test	Date	Designation	Kill vehicle
1	10/2/99	IFT-3	prototype
2	1/19/2000	IFT-4	prototype
3	7/8/2000	IFT-5	prototype
4	7/1/2001	IFT-6	prototype
5	12/1/2001	IFT-7	prototype
6	3/2/2002	IFT-8	prototype
7	10/14/2002	IFT-9	prototype
8	12/11/2002	IFT-10	prototype
9	12/15/2004	IFT-13c	prototype
10	2/14/2005	IFT-14	prototype
11	9/1/2006	FTG-02	CE-I
12	9/28/2007	FTG-03	CE-I
13	12/5/2008	FTG-05	CE-I
14	1/31/2010	FTG-06	CE-II
15	12/15/2010	FTG-06a	CE-II
16	7/5/2013	FTG-07	CE-I
17	7/22/2014	FTG-06b	CE-II
18	5/30/2017	FTG-15	CE-II Block 1
19	3/25/2019	FTG-11	CE-II, CE-II Block 1
20	12/11/2023	FTG-12	CE-II Block 1

Probability that at least one warhead survives in an attack of five with perfect discrimination, failures are uncorrelated.

n = number of shots on a given warhead
W = number of warheads in raid
P_{track} = probability of tracking warhead (set to 1.0)
K_W = kill probability against one warhead

$$K_W = P_{track}(1 - (1 - \mathrm{SSPK})^n)$$

And the probability that no warheads get through is:

$$P(0) = [P_{track}(1 - (1 - \mathrm{SSPK})^n)]^W$$

Probability is proportional to $P_{track}{}^{W}$ -important to get discrimination right

Adapted from Wilkening, D.A. 1999. "A Simple Model for Calculating Ballistic Missile Defense Effectiveness." Science and Global Security

Targeting scheme	Single shot kill probability	Probability at least one warhead survives
1-on-1	0.10	99.99%
2-on-1	0.10	99.98%
4-on-1	0.10	99.5%
1-on-1	0.25	99.90%
2-on-1	0.25	98%
4-on-1	0.25	85%
1-on-1	0.50	97%
2-on-1	0.50	76%
3-on-1	0.50	49%
4-on-1	0.50	28%
1-on-1	0.90	41%
2-on-1	0.90	5%
4-on-1	0.90	0.05%

Current status of homeland missile defense

Director of Operational Test and Evaluation: *when using complete, proposed architec*ture of sensors and command-and-control systems, "the GMD weapon system has demonstrated the capability to defend the U.S. homeland from a *small number* of ballistic missile threats employing *simple countermeasures* and with ranges greater than 3,000 kilometers" DOT&E 2024

Some improvements planned, including coming on-line of the Long-Range Discrimination Radar, and the Next Generation Interceptor being developed, described as having multiple kill vehicles. Potentially space-based sensor constellations for tracking and discrimination.

However, "*due to its fragility to countermeasures, and the inability to expand it readily or cost-effectively, the current midcourse intercept system cannot be expected to provide a robust or reliable capability against more than the simplest attacks by a small number of relatively unsophisticated missiles*" within 15 year time frame. Strategic Ballistic Missile Defense: Challenges to Defending the United States." A Report by the American Physical Society Panel on Public Affairs. February 2025.

Defeating Midcourse: direct & indirect attack, circumventing, overwhelming

- Attacking key sensors: radars, satellite-borne infrared early warning and tracking

- Radar and infrared blackout via nuclear detonation

- Circumventing defended corridors: e.g., sea-launched ballistic missiles, fractional orbital bombardment systems, maneuvering missiles, “long way around” ICBMs

- For a system that requires up to four interceptors per credible object and ten credible objects per real target, the defense could conceivably need to spend 50–150 times as much as the offense, interceptor to missile, to keep pace.
(Grego, Do technology advances allow missile defences to make up ground?. Journal of Strategic Studies, Feb. 2025)

Conclusions

- Key challenge for midcourse defense is vulnerability to countermeasures. Central unsolved issue is discrimination of threatening objects from nonthreatening.
- Developing the GMD system on a political timeline rather than on the basis of technical readiness led to costly failures. Repeating this approach is likely to do the same.
- Misunderstanding the capabilities of strategic missile defense systems can lead to poor or dangerous policy decisions.
- Longstanding US policy has been not to target Russian and Chinese strategic arsenals with defense. Development of strategic missile defense systems incentivizes adversaries to build weapons to counter them. Without the limits of New START, this may lead to an arms race.
- Development of strategic missile defenses can also lead to US and allies "taking eye off the ball"/ missed opportunities for more peaceful future including cooperative agreements to limit nuclear offensive and defenses.

Boost phase defense

Appears attractive because

- Can potentially defend a large geographical area (a whole country) from a relatively small basing area.
- Avoids countermeasures that make midcourse defense extremely challenging.

But has a key challenge

- “Reach vs time” – how far away can a defensive system be and still reach the launching missile in time with an interceptor or enough directed energy?

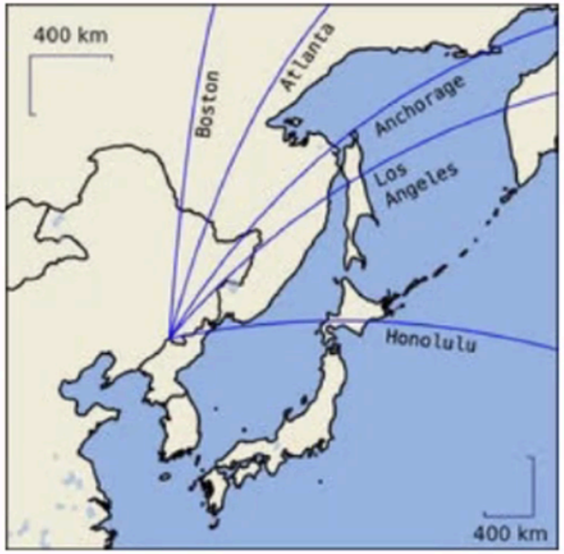


Figure 4 Map showing North Korea and adjacent countries and the initial ground tracks of ICBMs launched from north-central North Korea to five cities in the United States. ICBM ground tracks differ from great circles connecting the launch site to the target because of Earth's rotation. Cf. [APS 2003, Fig. 5.8].

Strategic Ballistic Missile Defense, American Physical Society, 2025

Boost-phase defense

- ICBMs boost phase lasts ~2-5 minutes, depending on technology. Solid-propellant missiles burn for a shorter time than liquid-propellant.
- Time window is compressed at beginning for detection and tracking, at end by need to keep missile from getting enough speed to reach defended territory. So more like 2-4 minutes available.
- This sets a practical limit to standoff distances from the path of the launching missile of hundreds of km, rather than thousands.
- This also provides almost no meaningful decision making time and drives the system toward automatic launch.
- For geographically large countries, boost phase defense from land, air, sea are not feasible. Would need to be from orbit. Exception is North Korea, where surface-based defense against some trajectories for some kinds of missiles may be feasible though very challenging.

Drone-based boost phase BMD even against a small country such as North Korea is very challenging

The reach-versus-time challenge

- ICBM boost phases are 4–5 min for liquids, 3 min or less for solids.
- Intercept points for ICBMs from North Korea are > 500 km from potential interceptor basing locations.
- Defense has short time to decide whether to fire and interceptors have little time to reach the ICBM (~ 100 to ~ 200 seconds).

Many other challenges must be met for a boost phase intercept system to be successful—hitting the final stage, defeating countermeasures such as programmed evasion, etc.

But *if a boost-phase defense cannot meet the reach-versus-time challenge successfully, all other issues are irrelevant—the defense will fail. Thus, the pursuit of space-based boost phase defense.*

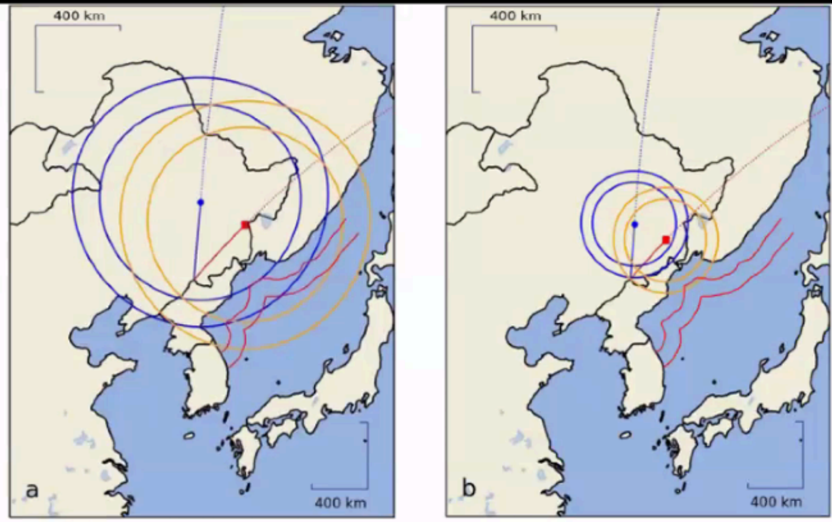


Figure 5 Basing areas that would allow the model interceptors discussed in the text to reach (a) the model of the liquid-propellant Hwasong-15 and (b) the model of the solid-propellant Hwasong-18 we used in time to prevent their warheads from striking targets in the continental United States, if they were launched from a site in north-central North Korea headed toward Boston or Los Angeles (see text for details). The model of the Hwasong-15 would have to be intercepted about 260 seconds after launch to defend the entire continental United States, whereas the model of the solid-propellant Hwasong-18 would have to be intercepted no later than 145 seconds after launch to do so. The slightly curved lines indicate the ICBM ground tracks from the launch site to the intercept points, which are indicated by a blue dot on the ground track for the Boston trajectory and an orange square on the ground track for the Los Angeles trajectory. The blue lines and circles are for ICBMs headed toward Boston; the orange lines and circles are for ICBMs headed toward Los Angeles. The smaller and larger circles indicate the kinematically allowed basing areas for interceptors with 4 km/s and 5 km/s burnout velocities, respectively. Both sets of basing circles assume the interceptors are fired as soon as a firing solution is available (zero decision time). The wavy red lines 100 and 200 km off the eastern coasts of North Korea and Russia indicate the distances beyond which on-station sea- and air-based interceptors would likely be safe. Adapted from [Wells 2024, Fig. 2].

Strategic Ballistic Missile Defense, American Physical Society, 2025

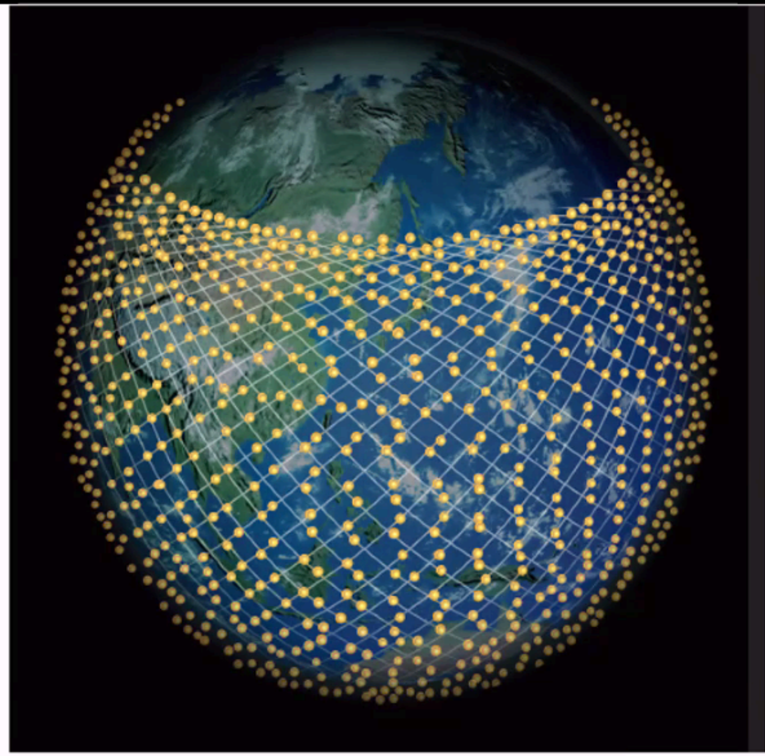
Space-based boost phase missile defense

Space-based boost phase defense

- National Academies 2012 study assessed boost phase defenses against a nominal North Korean missile system, recommended not spending a dollar. ("Making Sense of Ballistic Missile Defense" NAS, 2012)
- Constellation "heals" in around 200 s; two missiles launched in a salvo within this time frame would require roughly doubling the constellation. A salvo of ten in this timeframe in the same geographical area would require constellation times ten.
- Even with lighter components and lower launch costs this becomes quickly unsustainable.
- The critical issue, though, is that the systems are relatively straightforward to counter by overwhelming or by "punching a hole" in the constellation with an anti-satellite weapon. Unlikely to be left unchallenged during assembly.

Space-based boost phase missile defense

- To defend against a salvo of 4 slow, liquid-propellant ICBMs from North Korea targeting middle- and lower-latitude US states would require at least 1,600 space-based interceptors (SBIs), see figure. Assumes automatic firing (no system checks) and only one SBI per ICBM.
- To defend against a salvo launch of 10 faster, solid-propellant ICBMs (or deal with spoofing) from North Korea, covering all the continental US requires about 40,000 SBIs.
- Countermeasures include:
  - Salvo or staggered launch of ICBMs
  - Decoy, cheaper missiles to confuse/deplete
  - Deploy the warhead before the final stage burns out
  - Rocket-propelled decoys, flares, jammers
  - Program the upper stages to fly evasive maneuvers



Source: *Strategic Ballistic Missile Defense*, APS 2025

Costs of space-based missile defense

Congressional Budget Office (May 2025)

- The decrease in launch costs from ~ $10,000 per lb. in 2012 to ~ $1,000 per lb. now could reduce the 20-year costs of the various SBI constellations by 30%–40%.

- Hence for the constellation of 2,000 SBIs (using NAS 2012 methodology) that would be needed to theoretically defend against 1 or 2 liquid-propellant ICBMs launched by North Korea, assuming only one SBI per ICBM, the estimated 20-year cost is now $542 billion, down from $830 billion.

American Physical Society (March 2025)

- For the 40,000 SBIs needed to theoretically defend against a salvo of 10 solid-propellant ICBMs launched by North Korea, again assuming only one SBI per ICBM, the construction and initial launch cost could be ~ $1 trillion.

- In this case, to counter 1 additional ICBM the defense would need to spend ~ 1,000 times the cost of that ICBM.

Also see Harrison, 2025. Build Your Own Golden Dome: A Framework for Understanding Costs, Choices, and Trade-offs. AEI.

Likely destabilizing responses

China and Russia appear to have been preparing for the US to make a Golden Dome-like move since the US withdrew from the Anti-Ballistic Missile treaty in 2002.

- Development of weapons systems that can evade, overwhelm, or directly attack strategic missile defenses: for example, Chinese "MIRVing" of missiles, development of medium-range hypersonic glide vehicles, fractional orbital bombardment systems, anti-satellite weapons. Russian development of nuclear-armed nuclear-powered cruise missile, underwater nuclear drone, maneuvering hypersonic missiles, anti-satellite weapons including a nuclear-armed weapon.

- China appears to be considering increasing launch readiness.

- Russia has consistently linked further nuclear reductions to limits on missile defenses, though US policy has been not to accept any legal limits on missile defenses. Both agree that offense and defense are linked but have different views on how.

- Both midcourse and boost-phase weapons would potentially serve as capable anti-satellite weapons, complicating the strategic environment in space and potentially accelerating a space arms race.

Conclusions

- Over the last 70 years the U.S. has spent more than $400 billion in 2021 dollars on technologies intended to intercept nuclear-armed long-range ballistic missiles in flight.
- We are now considering hundreds of billions to trillions of dollars more on this effort.
- This huge and costly effort has never produced a system that could defend the continental United States against nuclear-armed long-range ballistic missiles and there is no prospect of deploying such a system in the near future.
- Wishful thinking, ideology, ignorance, and efforts to seek political advantage have repeatedly led to programs that ignore scientific and technical realities.
- The pursuit of large-scale strategic missile defense is likely to be destabilizing.
- Misplaced faith in the current system is dangerous and impedes more realistic and effective efforts to improve our security