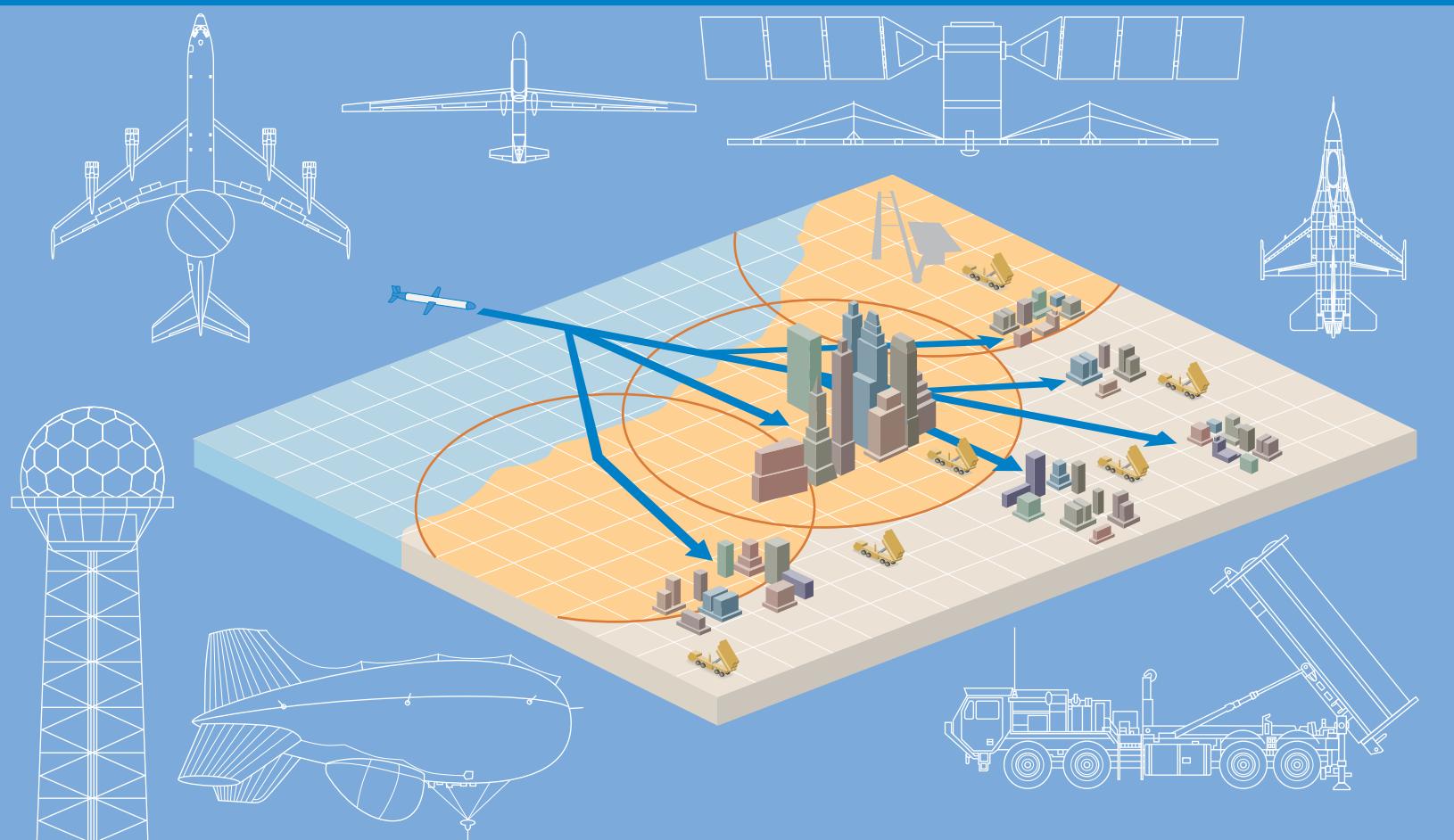




National Cruise Missile Defense: Issues and Alternatives



At a Glance

Since the 1980s, the United States has invested considerable resources to develop and field ballistic missile defenses to protect the U.S. homeland from attack by long-range ballistic missiles. In recent years, concerns have arisen that another type of weapon—land-attack cruise missiles (LACMs)—may also pose a threat to the U.S. homeland. Unfortunately, the systems that the U.S. military has deployed to protect the United States from ballistic missile warheads that fly high above the atmosphere are ill-suited to counter LACMs, which fly close to Earth’s surface.

This Congressional Budget Office report examines the potential for LACM attacks against the United States and the types of systems that might be fielded to provide a cruise missile defense with nationwide coverage. Such coverage would be analogous to that provided by national ballistic missile defenses.

CBO’s analysis yielded the following findings:

- **Cruise missiles could be used to attack the United States.** Adversaries attempting such attacks could range from nonstate groups (including terrorists) that might be able to acquire a small number of missiles to “peer powers” (nations with large, advanced militaries) capable of launching much more sizable attacks.
- **Cruise missiles could be defeated with available technology, but a wide-area defense of the contiguous United States would be costly.** Modified versions of systems that the military uses today could be purchased for homeland cruise missile defense. CBO estimates that the lowest-cost “architectures” it examined—integrated systems that comprise airborne or space-based radars, surface-to-air missiles, and fighter aircraft—would cost roughly \$75 billion to \$180 billion to acquire and operate for 20 years. Fielding additional regional or local defenses to protect Alaska, Hawaii, and U.S. territories would add to the cost.
- **Operational factors could hamper defenses.** Because many civilian aircraft fly in U.S. airspace, targets would have to be positively identified as threats before defenses could engage them. However, very little time is available for defenses to act against LACMs, so any delay in achieving positive identification would significantly challenge the effectiveness of defenses, and even advanced battle management systems might be hard-pressed to respond in time. Also, adversaries could launch many LACMs to overwhelm defenses in a specific location.
- **Adversaries would have attractive alternatives to using LACMs.** Because, in many circumstances, adversaries could attack the United States with systems that would be easier to successfully employ, less expensive, and potentially more damaging than LACMs—from truck bombs detonated by terrorists to ballistic missiles launched by Russia, China, and possibly North Korea—decisionmakers would need to consider whether the cost of a wide-area cruise missile defense was proportionate to the overall risk posed by LACMs.



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Dollar amounts are expressed in 2021 dollars. To remove the effects of inflation, the Congressional Budget Office adjusted costs with its projection of the gross domestic product price index from the Bureau of Economic Analysis.

Numbers in the text and tables may not add up to totals because of rounding.

Summary

In recent testimony to the Congress, commanders of the United States Northern Command—which is responsible for air defense of the U.S. homeland—have voiced a need to improve the ability to defeat advanced land-attack cruise missiles (LACMs). The U.S. Navy’s Tomahawk missiles are well-known examples of LACMs, weapons that fly like aircraft to their target. Defending against LACMs is difficult because they can fly low to avoid being detected by radar and can be programmed to take unanticipated routes to their target.

The Congressional Budget Office was asked to examine the threat that LACMs might pose to the United States homeland and to estimate the composition and cost of illustrative cruise missile defense (CMD) “architectures” that would be analogous to the nationwide defense provided by today’s ballistic-missile defense system.

CBO found that a homeland CMD would be feasible but expensive, with costs ranging from roughly \$75 billion to \$465 billion over 20 years to cover the contiguous United States. The lowest-cost architectures that CBO examined—integrated systems based on radars carried by high-altitude unmanned aircraft or on satellites—would cost roughly \$75 billion to \$180 billion. Additional regional or local defenses to protect Alaska, Hawaii, and U.S. territories would add to that cost.¹ Fielding a more expansive CMD architecture that also protected Canada, which has formally partnered with the United States to defend North American airspace since 1957, would add to that cost, but the costs of an expanded system would probably be shared by the two nations. Because adversaries wishing to attack the United States have many alternatives to LACMs, policymakers would need to decide whether such investments would be worth the cost.

1. Alaska and Hawaii are covered by current ballistic missile defenses. CBO limited its analysis to the 48 states and the District of Columbia in the contiguous United States because the characteristics of defenses designed to protect smaller areas—local or regional defenses—have been well studied in the context of defending U.S. military forces deployed abroad.

CBO’s Approach

To examine the scale and cost of cruise missile defenses for the U.S. homeland, CBO analyzed several illustrative architectures with different combinations of *sensors* (radars positioned around the perimeter of the contiguous United States) to detect, track, and identify inbound LACMs; *shooters* (fighter aircraft and surface-to-air missiles, or SAMs) to destroy those LACMs; and a *battle management system* to coordinate the defense. An architecture was deemed effective if the radar could detect a threat with enough time for fighter aircraft or a SAM battery to engage it before it reached the U.S. coast or border. Against a particular type of LACM, the number and locations of radars and shooter bases (SAM sites or airfields) would depend on the detection range of the radars, the speed and range of the shooters, and the response time of the battle management system.

CBO considered five radar platforms:

- Towers on the ground at a total height of at least 700 feet (including the elevation of local terrain),
- Tethered aerostats (blimps) at 10,000 feet,
- Commercial aircraft modified for airborne early-warning and control (AEW&C) at 30,000 feet,
- High-altitude, long-endurance unmanned aerial vehicles (HALE-UAVs) at 60,000 feet, and
- Satellites orbiting about 600 miles above Earth.

For shooters, CBO’s illustrative CMD architectures included:

- Long-range surface-to-air missiles (LR-SAMs), and
- Fighter aircraft on alert at airfields around the country.

CBO did not consider infrared sensors or new types of weapons such as lasers or other directed-energy weapons because those systems will probably have ranges that are too short for wide-area CMD.

Performance of the battle management system would be critical for CMD because of the short time available

Table S-1.

Cost and Composition of Illustrative Architectures for a Cruise Missile Defense of the Contiguous United States

	Cost (Billions of 2021 dollars)			Composition of Architectures		
	Initial Acquisition	Annual Operation and Support	20-Year Total	Number of Sensor Systems for Continuous Operation	Number of LR-SAM Sites	Number of Fighter Locations
Architecture 1: Detection and Tracking With Radar on HALE-UAVs	13 to 15	2.7 to 3.5	77 to 98	64	20 to 30	30 to 40
Architecture 2: Detection and Tracking With Radar on Modified Commercial Aircraft (AEW&C aircraft)	28 to 36	7.7 to 10.2	187 to 246	124	40 to 50	50 to 90
Architecture 3: Detection and Tracking With Radar on Aerostats	30 to 86	2.3 to 17.7	98 to 466	75	60 to 800	n.a.
Architecture 4: Detection and Tracking With Space-Based Radar	58 to 97	0.7 to 1.1	106 to 179	78	20	10 to 15

Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

Values in this table are based on a defensive perimeter around the 48 contiguous states that would be designed to protect against cruise missiles flying at a low altitude (300 feet) and at a subsonic speed (500 miles per hour).

The ranges of values for quantities and costs include the effect of response time—that is, the time that elapses between the detection of a cruise missile and the order to employ a shooter. Low values correspond to 5 minutes between detection and shooter employment. High values correspond to 15 minutes. The ranges of values for costs also include the uncertainty that surrounds the cost estimates for the architectures' component systems.

Twenty-year totals include additional acquisition costs that might be incurred if equipment wears out or is lost to accidents and needs to be replaced.

AEW&C = airborne early-warning and control; HALE-UAV = high-altitude, long-endurance unmanned aerial vehicle; LR-SAM = long-range surface-to-air missile; n.a. = not applicable.

to intercept low-altitude LACMs after they have been detected. In its analysis, CBO used reaction times—the time between a target's detection and the decision to launch an interceptor—of 5 minutes and 15 minutes as a proxy for the battle management system's performance.

What CBO Found

CBO found that the most significant factor determining the effectiveness of a CMD is the range of its radar sensors, which, in turn, is determined primarily by their altitude. Establishing an unbroken, continuously operating radar perimeter of the contiguous United States to provide warning about a low-altitude cruise missile (flying at 300 feet) would require one of the following: 23 orbits of HALE-UAVs (requiring 64 aircraft to keep one continuously aloft at each location), 31 orbits of AEW&C aircraft (requiring 124 aircraft), 50 tethered aerostat sites (requiring a total of 75 aerostat systems), 78 radar satellites, or 150 ground-based radar sites.

The estimated costs of roughly \$75 billion to \$465 billion over 20 years include \$13 billion to \$97 billion for initial acquisition and \$700 million to \$18 billion per year for operation and support (see Table S-1). Additional acquisition costs to replace systems that wear out or are lost to accidents over 20 years are also included.

Architecture 1 and Architecture 4, which would have radar at high altitudes on long-endurance platforms—HALE-UAVs and satellites, respectively—would provide the least costly solutions because their endurance and long detection ranges would reduce the required number of sensor locations, LR-SAM sites, and alert fighter bases. The HALE-UAV option (Architecture 1) would have a lower up-front acquisition cost than the satellite option and could probably be fielded sooner. The satellite option (Architecture 4) would be more technically challenging and have a much higher acquisition cost,



but lower operation and support costs would narrow the difference in costs after 20 years.

The satellite-based architecture could also provide sensor coverage for the entire country (not just its perimeter, and including Alaska, Hawaii, and U.S. territories) and possibly most of the world, making it useful for other military and nonmilitary applications. Satellites orbiting Earth might be more vulnerable to attack than HALE-UAVs operating close to the United States, however.

CBO also found that an architecture based on AEW&C aircraft (Architecture 2) could provide an area defense with LR-SAMs and fighters, but they would be very expensive because their limited endurance and altitude mean that a larger number of aircraft would be needed to continuously fly sensor orbits, and those aircraft would be costly to operate. An architecture based on aerostats (Architecture 3) could provide enough warning time to employ LR-SAMs against inbound targets (although hundreds of LR-SAM sites would be needed unless battle management response times were very short), but not enough warning time to employ fighters. Ground-based radars could not provide a feasible area defense because they could not detect low-altitude LACMs early enough for LR-SAMs or fighters to make their intercepts under most circumstances.

Limitations of the CMD Architectures That CBO Examined

The illustrative architectures that CBO examined would be subject to several important operational limitations.

- The defenses would have limited capacity—eight LR-SAMs and two fighters at a particular time and location. A raid consisting of many LACMs could overwhelm them. For example, a Yasen-class guided missile submarine in the Russian Navy can reportedly carry up to 32 LACMs (3M-14 Kalibr) in its eight vertical launchers.
- A CMD system operating in U.S. airspace would have to rapidly distinguish LACMs from thousands of commercial and general aviation aircraft. To avoid shooting down unintended targets, the system might require human “eyes on the target” before a weapon could be fired. That could limit the effectiveness of LR-SAMs, which often need to be fired shortly after LACMs are detected.
- It might be difficult for even advanced battle management systems to achieve the response times

CBO assumed in its calculations (5 to 15 minutes between detection and interceptor launch).

- Adversaries could circumvent area defenses by launching LACMs close to the coast or border (for example, from a ship just offshore or a truck near a border crossing), leaving insufficient time for defenses to respond.

Other Factors to Consider

In addition to operational constraints, policymakers would need to consider the merits of fielding a CMD system relative to the likelihood of a cruise missile attack and the potential damage such an attack could inflict. Adversaries would need to weigh the expense and effort of acquiring and using LACMs, the unique capabilities they offer—primarily the ability to attack defended targets from a distance—and the availability of other ways to attack the United States that would be easier to execute, less expensive, and more likely to succeed (see Table S-2).

Examples of threat considerations include the following:

- Terrorists could use truck bombs or other improvised attacks to cause much greater damage to undefended civilian targets than would be possible with the relatively small warheads on LACMs.
- Regional powers attempting to hinder U.S. military action would have little incentive to attack the United States homeland and risk retaliation.
- Peer powers could use other means to attack the U.S. homeland. Moreover, the U.S. nuclear deterrent would probably give a peer nation pause before choosing to attack the U.S. homeland with any type of missile, even ones that only carry conventional warheads.

Policymakers might opt to pursue smaller CMD architectures to handle threats to specific targets rather than provide a comprehensive nationwide defense. For example, a peer power might attempt a preemptive attack on U.S. nuclear deterrent forces with LACMs fired from just off the U.S. coast; such LACMs could not be detected by today’s (mostly ballistic) missile warning systems. A limited “warning only” system of CMD sensors coupled with point defenses could defeat such an attack. (For a description of several scaled-back CMD architectures that CBO examined, see Appendix A.)

Table S-2.**Considerations for Evaluating Cruise Missile Threats**

Adversary	Launcher	Scale of Attack	Objective	Example Targets	Alternative Means of Achieving Objective
Nonstate Group	Surface	One to a few LACMs	Political, terror	Civilian targets	Car or truck bombs, bombs in shipping containers, suicide bombers or gunmen, attacks on Americans abroad
Regional Power	Surface, submarine	One to a few LACMs	Political, deter U.S. actions in that region	Civilian targets, government or military facilities	Ballistic missiles, sabotage, attacks on U.S. forces abroad, cyber attacks
Peer Power in a Regional Conflict	Surface, submarine, aircraft	A few to many LACMs	Deter U.S. actions, support regional military operations	Government facilities, military bases, power infrastructure	Ballistic missiles, attacks in theater, attacks on U.S. forces abroad, attacks on U.S. allies, cyber attacks
Peer Power in a Global Conflict	Surface, submarine, aircraft	Many LACMs	Deter U.S. actions, support military operations in general war	Nuclear deterrent forces, national C3, leadership, ships in port, bomber bases	Ballistic missiles, attacks on U.S. allies, cyber attacks

Data source: Congressional Budget Office.

Nonstate groups are organizations not affiliated with a government. Examples include terrorists, paramilitaries, and armed resistance groups.

Peer powers are nations with large, advanced militaries. Russia and China are typically considered to be today's peer powers.

C3 = command, control, and communications facilities; LACM = land-attack cruise missile.



Chapter 1: A Brief History of Missile Threats to the U.S. Homeland and Efforts to Counter Them

Since the founding of the United States, geography has been an important factor in the nation's defense. The oceans to its east and west and its large, unthreatening neighbors to the north and south serve as substantial obstacles to military threats such as invasion by a foreign power. Not since the War of 1812 with Great Britain, the world's preeminent power at the time, has the United States mainland faced a serious prospect of invasion. Although adversaries with strong navies might have been able to cross the ocean and conduct raids against U.S. coastal cities—indeed, German and Japanese submarines operated off the U.S. coasts during World War II—they could be countered with coastal defenses such as land-based artillery and a Navy sized and equipped to operate in home waters.

Post–World War II Period: Bombers Pose the First Long-Range Threats

Circumstances changed with the Soviet Union's development of long-range aircraft and nuclear weapons following World War II. For the first time, devastating attacks against the contiguous United States became possible without an adversary's having to assemble a large invasion force in Canada or Mexico or an amphibious invasion force capable of operating across thousands of miles of ocean.¹ With a single airplane able to destroy an entire city, the geographic barrier to large-scale attacks against the United States was significantly reduced. Although intercontinental bombing missions were (and still are) very challenging, only a few bombers with nuclear weapons would need to reach their targets to inflict major damage. In 1949, the Soviet Union fielded the Tupolev Tu-4 Bull bomber (a copy of the American B-29 that was reverse-engineered from U.S. Army Air Corps aircraft that crashed or made emergency landings in the Soviet Union). In about 1955, the Soviet Union

fielded the Tu-95 Bear, later versions of which remain in service today.

The United States responded to the new threat with an extensive network of air defense radars on land and sea and in the air to detect attacking bombers, and many surface-to-air missile sites and fighter aircraft to destroy them before they could drop their nuclear bombs. The United States and Canada established the North American Air Defense Command (NORAD) in 1957 to provide coordinated air defense of both nations.² In a summary of its regular forces during the second half of 1960, NORAD listed more than 450 radar stations, more than 800 fighter aircraft, and 275 SAM sites in Canada and the United States that were operated by more than 160,000 personnel (see Figure 1-1). Of note in the summary is that the first ballistic missile early-warning radar station had entered service that year. The advent of long-range ballistic missiles would soon call into question the utility of NORAD's elaborate air defense systems.

1960s: Long-Range Ballistic Missiles Enter Service

As their name indicates, ballistic missiles are unpowered and unassisted by aerodynamic lift forces for most of their trajectory. Much as a golf ball is under power only when it is in contact with the club, a purely ballistic missile is powered for only a few seconds or minutes while its booster burns at the beginning of its flight.³ The

1. In this report, references to the contiguous United States include the lower 48 states in North America and the District of Columbia.

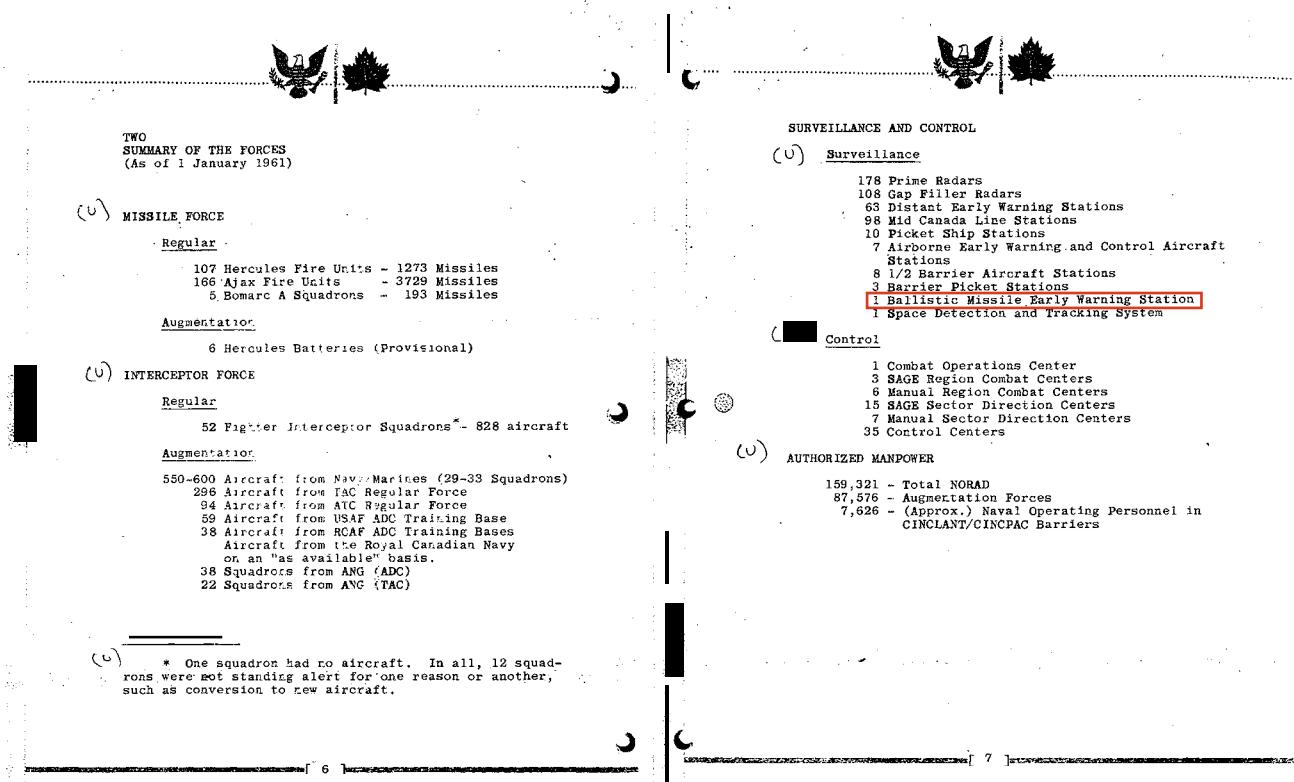
2. In 1981, NORAD was renamed the North American Aerospace Defense Command.

3. Ballistic missiles are named for their mostly ballistic trajectory; thrust provided by rocket motors propels them upward, and after the thrust ends they travel along a predictable, parabolic path to the target. Some ballistic missiles have delivery systems that provide additional maneuvering power later in the missile's trajectory. However, that power is usually intended to fine-tune the warhead's aim or complicate missile defenses rather than to substantially contribute to the missile's flight.



Figure 1-1.

North American Air Defense Command Forces, January 1961



Data source: North American Air Defense Command and Continental Air Defense Command Historical Summary, July to December 1960.

The historical information displayed here illustrates the magnitude of effort needed to defend an area as large as the United States and foreshadows how a change in technology can render a defensive architecture obsolete. In this case, the advent of intercontinental ballistic missiles is indicated by the first ballistic missile early-warning station that entered service on September 30, 1960, in Thule, Greenland.

German V-2 used toward the end of World War II was the first successful ballistic missile. Its maximum speed of 3,400 miles per hour at rocket burnout carried it to an altitude of nearly 300,000 feet and a range of about 200 miles. Significant advances in rocket and guidance technology would be needed to produce a missile capable of achieving the higher speeds and altitudes required to yield a ballistic trajectory capable of reaching the United States without having a launcher located close to the U.S. coast. For example, the U.S. Minuteman III intercontinental ballistic missile (ICBM) has a range greater than 6,000 miles, attains a velocity at burnout of 15,000 miles per hour, and reaches an altitude of about 700 miles.⁴

In late 1959, the Soviet Union's first land-based ICBM, the R-7A, entered service. The R-7A was based on the rocket that had launched the Sputnik satellite into orbit and had a range exceeding 7,000 miles. By the early 1970s, the Soviets had also deployed the R-29 submarine-launched ballistic missile (SLBM), early versions of which had a range of nearly 5,000 miles, which meant that submarines did not have to approach the U.S. coast and risk attack by antisubmarine warfare patrols.⁵

The advent of ICBMs and SLBMs all but eliminated the ability of antibomber defenses to deter nuclear attack. Although nuclear bombers remained a component of

4. See U.S. Air Force, "LGM-30G Minuteman III" (September 30, 2015), <https://go.usa.gov/xAYhv>.

5. The Soviets first deployed SLBMs at about the same time that their ICBMs entered service, but they initially had much shorter range. The first operational example was the R-13 SLBM carried by Hotel I class submarines. The R-13 had a range of less than 400 miles, and the submarine had to surface before launching.

both superpowers' nuclear forces, the strategy of deterrence through mutual assured destruction replaced elaborate air defenses as the primary means of protecting the United States from nuclear attack. By the mid-1970s, most of NORAD's surface-to-air missile sites had been deactivated, its fighter forces had been dramatically reduced, and its warning systems had shifted to ground radars and satellites with infrared sensors designed to track ballistic missiles and their warheads on high-altitude trajectories from the Soviet Union.

To help strengthen nuclear stability and to avoid an offense-defense arms race, the United States and the Soviet Union agreed on limits to antiballistic missile (ABM) forces with the 1972 ABM Treaty. In the mid-1970s, the United States fielded a limited ballistic missile defense system—the Safeguard system deployed to defend ICBM sites—that complied with the ABM Treaty, but because of technological limitations it was not considered to be very effective and was withdrawn after only a few months of service. Interest in ballistic missile defenses was revived during the Reagan Administration, but systems capable of defeating even a few ICBMs would not enter service until the Ground-Based Midcourse Defense (GMD) system became operational in 2004.

1980s: Long-Range Cruise Missiles Enter Service

In addition to ballistic missiles, both superpowers developed land-attack cruise missiles for their nuclear arsenals. Those missiles enabled ships not designed for large SLBMs to deliver nuclear warheads and also increased the effective range of bombers and enabled them to deliver nuclear warheads from beyond the reach of antiaircraft systems that might be defending important targets.⁶ Warhead options for cruise missiles eventually expanded to conventional explosives and other “special-purpose” packages.

According to the Department of Defense’s (DoD’s) definition, a LACM is “an armed unmanned aerial vehicle designed to attack a fixed or relocatable target” that “spends the majority of its mission in level flight, as

6. Bombers were considered to be a deterrent to a massive first strike by ICBMs because they could be launched upon the first indications of nuclear attack but recalled if the warning was in error. The launch of ICBMs has to be delayed until there is strong assurance that an attack is actually under way because they cannot be recalled.

it follows a preprogrammed path to the predetermined target.”⁷ Although performance parameters such as speed and altitude differ among today’s LACMs, almost every type fielded to date has been powered by jet engines during most or all of its flight. This has distinguished cruise missiles from ballistic missiles, which fly a mostly unpowered ballistic trajectory after an initial, relatively short, powered boost phase. Another important difference is that cruise missiles typically fly at low altitude—a few hundred feet or lower—to avoid detection by radar, whereas ICBMs’ trajectories take them above the atmosphere, where they can be detected from a few thousand miles away.

Although short-range LACMs were first used in World War II—the German V-1 had a range of about 160 miles—the development of long-range LACMs was initially limited to major powers because of technological hurdles. In particular, the inaccuracy of inertial guidance systems for attacking targets over long distances limited LACMs to nuclear warheads, the province of major powers. To hit targets deep in an adversary’s territory with the accuracy necessary for a conventional explosive warhead, land-attack cruise missiles required detailed terrain maps, advanced terrain matching systems, and a lengthy mission-planning process. Examples of early LACMs that used terrain matching include the AGM-86 Air-Launched Cruise Missile (which entered service with the U.S. Air Force in 1982), the BGM-109 tomahawk (U.S. Navy, 1983), and the Soviet Union’s Kh55/Kh555 family of missiles (1984). All of those missiles carried nuclear warheads.

Because advanced LACMs were initially confined to the major powers, the threat they posed to the United States and its territories fell under the umbrella of nuclear deterrence. However, the danger posed to deployed military forces by shorter-range LACMs with conventional warheads was not discounted, and systems such as the Army’s Patriot included capability against cruise missiles.

1990s to Today: Long-Range Missiles Proliferate

After the collapse of the Soviet Union, protection of the U.S. homeland from air or missile attack continued to depend primarily on nuclear deterrence, as practiced by the United States, Russia, and, increasingly, China

7. See Defense Intelligence Ballistic Missile Analysis Committee and National Air and Space Intelligence Center, *2020 Ballistic and Cruise Missile Threat* (July 2020), <https://go.usa.gov/xAtuJ>.

Table 1-1.**Selected Land-Attack Cruise Missiles Worldwide**

Country	Missile	Launch Mode	Warhead
China	YJ-63	Air	Conventional
	CJ-10	Ground	Conventional
	CJ-20	Air	Conventional
France	APACHE-AP	Air	Submunitions
	SCALP-EG	Air and ship	Penetrator
	Naval SCALP	Submarine and surface ship	Penetrator
Germany, Sweden, Spain, and South Korea	KEPD-350	Air	Penetrator
India and Russia	BrahMos 1	Air, ground, ship, and submarine	Conventional
	BrahMos 2	Air, ground, ship, and submarine	Conventional
Iran	Meshkat/Soumar	Air, ground, and ship	Conventional
Israel	Popeye Turbo	Air	Conventional
Pakistan	Ra'ad	Air	Conventional or nuclear
	Babur	Ground	Conventional or nuclear
Russia	AS-4	Air	Conventional or nuclear
	AS-15	Air	Nuclear
	SS-N-21	Submarine	Nuclear
	Kh-555	Air	Conventional
	Kh-101	Air	Conventional
	3M-14	Ground, ship, and submarine	Conventional, nuclear possible
	3M-55	Ground, ship, and submarine	Nuclear possible
Taiwan	Wan Chen	Air	Conventional
	HF-2E	Ground	Conventional
United Arab Emirates	Black Shaheen	Air	Penetrator
United Kingdom	Storm Shadow	Air	Penetrator

Data source: Defense Intelligence Ballistic Missile Analysis Committee and National Air and Space Intelligence Center, *2017 Ballistic and Cruise Missile Threat* (June 2017), <https://go.usa.gov/x7zWA>.

as its military capabilities grew. However, the proliferation of advanced weapons among other nations, as well as the general availability of technologies such as precise satellite navigation, raised concerns that long-range ballistic and cruise missiles would be acquired by nations or nonnation groups for which the principles of superpower deterrence might not apply. In the case of cruise missiles, the *2017 Ballistic and Cruise Missile Threat* report identified more than a dozen nations with LACMs (see Table 1-1) and projected that the proliferation of long-range missiles (both cruise and ballistic) would continue as more nations pursued space-launch capabilities (space-launchers can be modified for use as ICBMs) or tried to purchase missiles from current

producers.⁸ The more recent *2020 Ballistic and Cruise Missile Threat* report and the Missile Defense Review that was published in 2019 reaffirmed concerns about the threat that advanced cruise missiles may pose to the U.S. homeland.⁹

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8. See Defense Intelligence Ballistic Missile Analysis Committee and National Air and Space Intelligence Center, *2017 Ballistic and Cruise Missile Threat* (June 2017), <https://go.usa.gov/x7zWA>.
 9. See Defense Intelligence Ballistic Missile Analysis Committee and National Air and Space Intelligence Center, *2020 Ballistic and Cruise Missile Threat* (July 2020), <https://go.usa.gov/xAtuJ>; and Office of the Secretary of Defense, *Missile Defense Review* (2019), <https://go.usa.gov/x7MQB> (PDF, 27.3 MB).

Missile proliferation has led to a reevaluation of the need for defensive systems to protect the U.S. homeland from missile or air attack. The most recent policy, which is described in the 2019 Missile Defense Review, calls for sizing missile defenses to address rogue states that possess small numbers of offensive missiles but to continue relying on nuclear deterrence to address the larger quantities and greater sophistication of offensive missiles fielded by Russia and China.

Ballistic Missiles

To date, efforts to develop and field missile defenses for the U.S. homeland have focused primarily on systems to counter ICBMs that an adversary could use from its home territory to attack the United States. The most prominent example is North Korea, which has successfully developed and tested nuclear weapons and ballistic missiles with intercontinental range and threatened to use them against the United States. Similarly, Iran has programs to develop both nuclear weapons and long-range ballistic missiles. Substantial investments in land- and sea-based missiles, land-, sea-, and space-based sensors, and communications networks to enable the missiles and sensors to work together provide today's homeland defense against ICBMs.¹⁰

Cruise Missiles

Cruise missiles were initially of less concern because they typically have shorter ranges and smaller payloads than ballistic missiles. However, LACMs have improved in terms of accuracy, ease of mission planning, and ability to elude air defenses with the addition of stealth characteristics. To date, however, maximum ranges are thought to have remained less than about 2,500 miles, much shorter than the ranges of ICBMs.¹¹ Shorter range means an adversary might not be able to simply launch a missile from its home territory but would have to position a launcher closer to the United States (within 1,000 to 2,500 miles to attack a coastal city). Smaller payloads—about 1,000 pounds or less—mean that a conventional

explosive warhead would have limited destructive power, and development of a nuclear warhead would be more difficult because of the greater degree of miniaturization that would be required.

The terrorist attacks of September 11, 2001, reawakened concerns about air defense of the United States. Immediate efforts focused on preventing repeat attacks with aircraft, but the proliferation and improving capabilities of LACMs have not been ignored. Unfortunately, ballistic missile defenses are of little use against cruise missiles because of their very different flight profiles. A limited cruise missile defense (including several surface-to-air missile sites and fighters on alert at Andrews Air Force Base) was deployed as part of improvements to overall air defense in the National Capital Region, and efforts have been made to provide improved radars to fighter aircraft that are on alert around the country and tasked with defending U.S. airspace by intercepting unidentified aircraft or aircraft that stray from filed flight plans. The new radars improve the fighters' ability to detect and engage cruise missiles. Although the United States Northern Command (USNORTHCOM) has expressed its desire to further improve and expand defenses in the National Capital Region, concepts for an integrated, homeland cruise missile defense are only in the early stages of development.¹² USNORTHCOM is working with the Air Force, Canada's Department of National Defence, and the Missile Defense Agency (MDA) to study ways to improve the air defense of North America.¹³

Long-range radars operated by the Federal Aviation Administration (FAA) and the Air Force provide significant radar coverage of the continental United States today, with more than 100 ground-based radar stations around the country (see Figure 1-2, top panel). Although those radars provide extensive, overlapping coverage at the high altitudes typically flown by commercial aircraft, the curvature of Earth limits the horizon of radar for targets at low altitudes (such as most cruise missiles), which

10. Until recently, Standard missiles have not been thought to have sufficient range and speed to defeat ICBMs. However, tests are planned to evaluate whether the latest versions of the SM-3 would in fact be able to intercept them. See Congressional Budget Office, *Costs of Implementing Recommendations of the 2019 Missile Defense Review* (January 2021), www.cbo.gov/publication/56949.

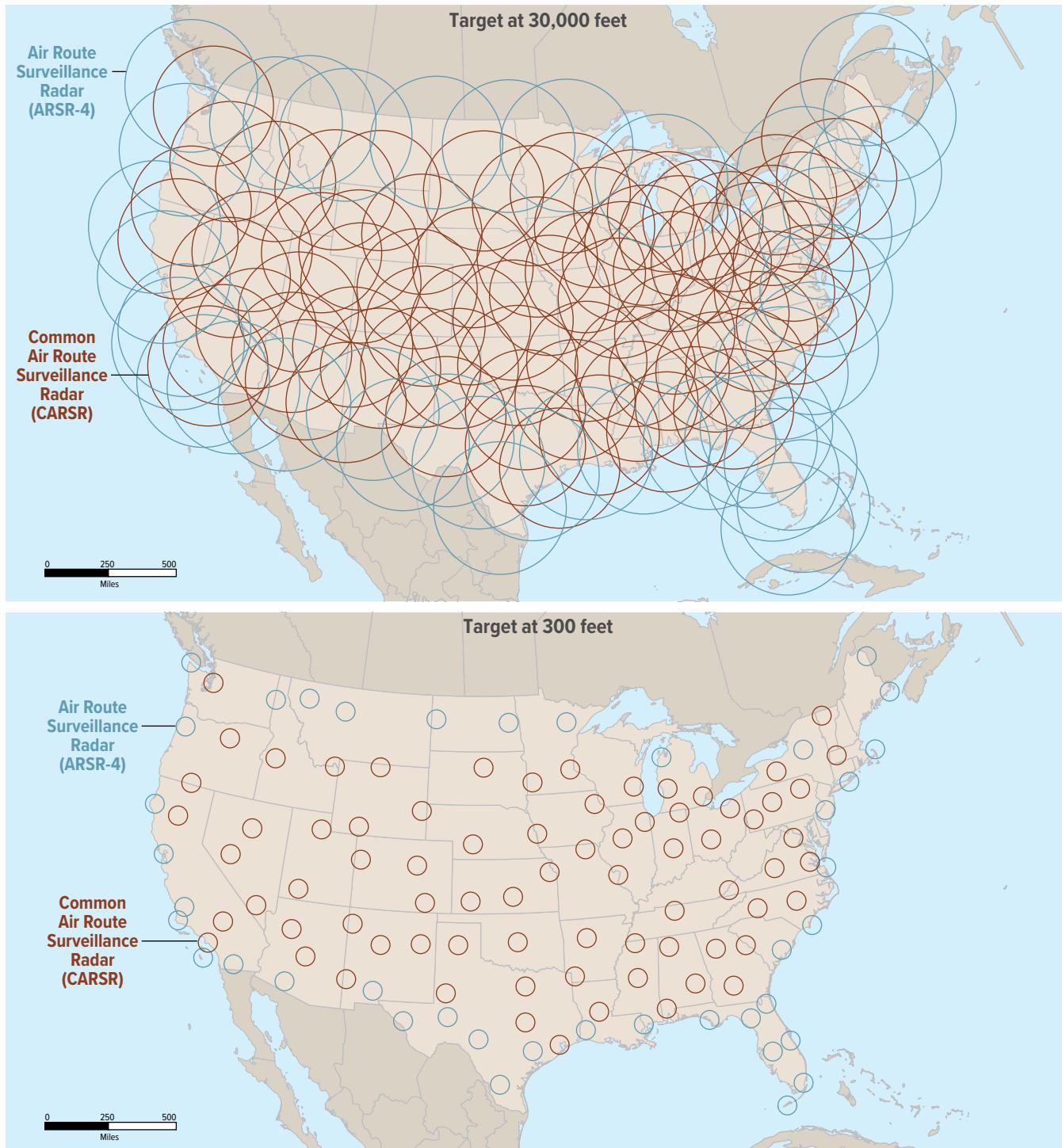
11. There have been unconfirmed reports that Russia is developing a cruise missile with a range exceeding 2,800 miles for use by the Russian Navy.

12. See the statement of General Terrence J. O'Shaughnessy, USAF, Commander of the U.S. Northern Command and North American Aerospace Defense Command, before the Senate Armed Services Committee (February 13, 2020), <https://go.usa.gov/x7z9a> (PDF, 143 KB).

13. See Jason Sherman, "MDA Sets Up Homeland Cruise Missile Defense Shop; U.S., Canada Considering Ways to Reduce Blind Spots," *Inside Defense* (October 5, 2020), <https://tinyurl.com/y5kurgca>.

Figure 1-2.

Estimated Coverage of Ground-Based Air Route Surveillance Radars for Targets at Two Altitudes



Data source: Congressional Budget Office.

The effects of terrain obstructions are not included.

results in significantly reduced coverage (see Figure 1-2, bottom panel). Those radars and their possible successors would almost certainly be a part of a nationwide cruise missile defense. DoD, the FAA, and the Department of Homeland Security are partners in exploring alternatives for new Spectrum Efficient National Surveillance Radars, which are planned for fielding starting in the mid-2020s.

On the Horizon: Hypersonic Missiles

A new type of missile called a hypersonic glide vehicle (HGV) is blurring the distinction between cruise and ballistic missiles. Like ballistic missiles, HGVs are initially accelerated (boosted) to hypersonic speed—defined as five times the speed of sound, or faster—by a rocket but then, like cruise missiles, use aerodynamic lift (but without power) to glide long distances. Hypersonic

cruise missiles that would be powered for all or most of their flight, like traditional cruise missiles, are also being developed.

Weapons such as HGVs are largely intended to evade current ballistic missile defenses, but their high-altitude flight—necessary to avoid frictional heating that is created at high speeds in the thicker air at low altitudes—and their very high speed make them poor targets for cruise missile defenses that are designed to defeat low-altitude targets flying at much lower speeds. Consequently, CBO does not examine defenses to defeat hypersonic threats in this report. To protect the homeland from potential hypersonic missiles, it might be necessary to develop yet another defensive architecture.



Chapter 2: The Likelihood of Cruise Missile Attacks Against the U.S. Homeland

The existence of land-attack cruise missiles that could be used to attack the U.S. homeland is undisputed. However, it is also important to consider the likelihood of such an attack when contemplating the fielding of cruise missile defenses. That likelihood depends on the following:

- Whether potential adversaries possessed or would be able to obtain LACMs and, if so, whether they would be able to employ them against the U.S. homeland; and
- Whether potential adversaries would choose LACMs (either solely or in concert with other weapons) for such attacks.

Decisionmakers would need to evaluate those issues when assessing whether or how much to invest in homeland cruise missile defenses.

Today, there is a varied roster of adversaries to consider when evaluating the potential for cruise missile attacks on the U.S. homeland. Those threats range from non-state entities, such as terrorist groups, to countries with advanced militaries (peer powers).¹ In assessing potential threats, CBO considered three categories of adversary—terrorists or other nonstate actors, nation-states with regional power, and peer powers—and evaluated each in terms of the criteria listed above. Although all three have or could obtain LACMs, it is much less clear that they all could use those missiles against the U.S. homeland or that they would not opt for other means if they were to attempt an attack. Potential attackers would have to weigh the expense and effort of acquiring and using LACMs against the unique capabilities LACMs

offer—primarily the ability to attack defended targets from a distance.²

Terrorists or Other Nonstate Actors

The terrorist attacks of September 11, 2001, were essentially cruise missile attacks, with hijacked commercial airliners used as missiles and the terrorists themselves used as guidance systems. The possibility that nonstate actors could acquire actual LACMs to repeat those attacks cannot be ruled out. However, because today's cruise missiles lack intercontinental range, the geographic location of the United States could make it difficult for terrorists or other nonstate actors to position launchers close enough to conduct an attack. Other, less complicated, means of attacking the United States are available, calling into doubt whether nonstate actors would opt for LACMs.

Ability to Acquire and Employ LACMs

At first glance, it seems unlikely that terrorists or other nonstate entities would be able to acquire and use military equipment as sophisticated as cruise missiles. But it has already happened. In 2006, Hezbollah attacked an Israeli warship with an antiship cruise missile (ASCM) thought to have been supplied by Iran. More recently, U.S. Navy ships were unsuccessfully attacked with cruise missiles fired by rebel forces in Yemen.

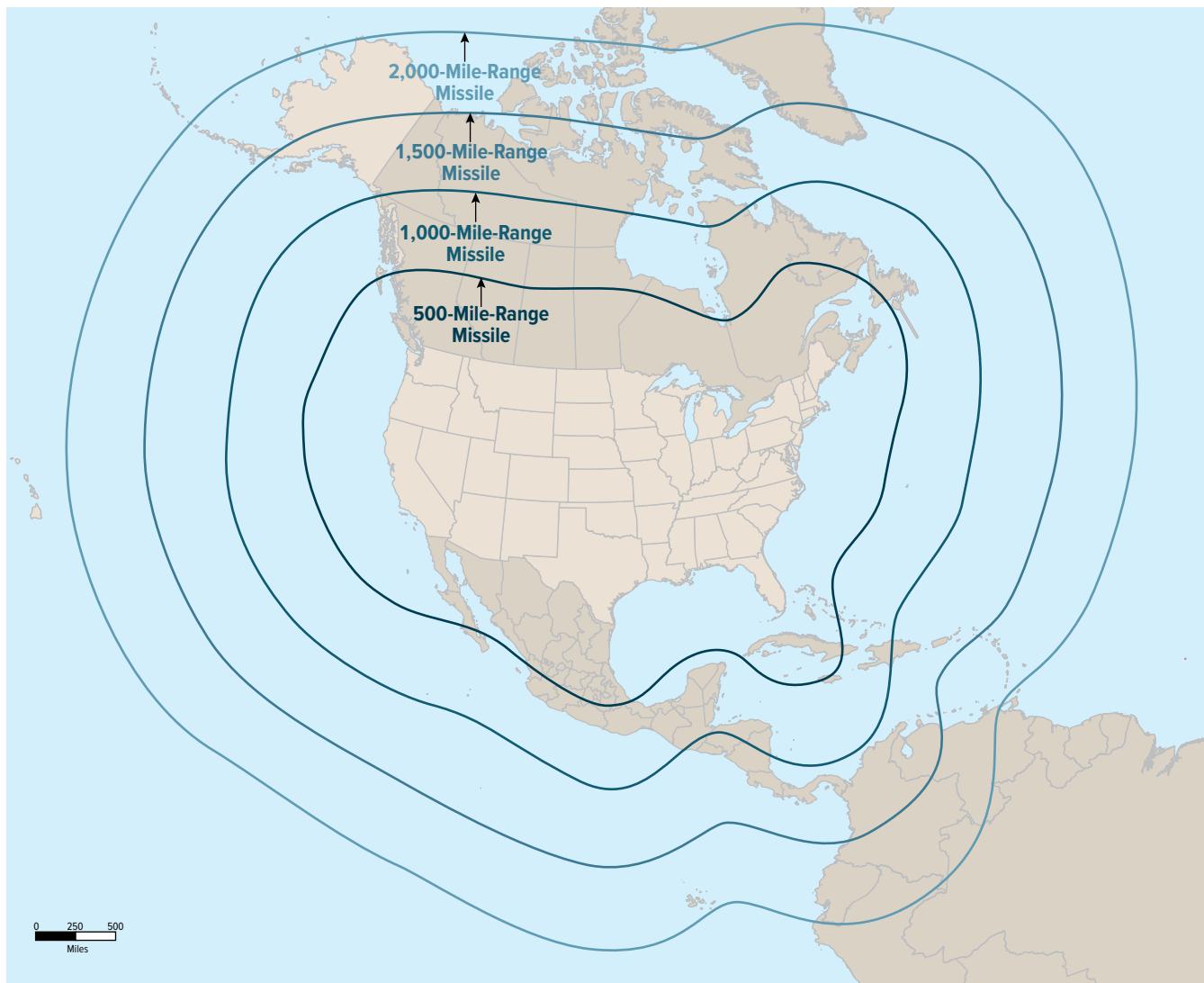
The weapons in those examples were ASCMs, which have proliferated more widely around the world than LACMs. Nearly every country with a navy possesses ASCMs. A much smaller number currently have LACMs in their inventories. Although smaller numbers of LACMs worldwide suggest a lower likelihood of their falling into nonstate hands, the National Air and Space Intelligence Center (NASIC) projects more proliferation

1. For example, see Center for Strategic and International Studies, CSIS Missile Defense Project, "Missiles of the World" (accessed January 25, 2021), <https://missilethreat.csis.org/missile/>.

2. For a more detailed examination of those potential attackers, their motives, and other ways they might choose to attack the United States, see RAND, *Evaluating Novel Threats to the Homeland: Unmanned Aerial Vehicles and Cruise Missiles* (2008), www.rand.org/pubs/monographs/MG626.html.

Figure 2-1.

Areas Where Cruise Missile Launchers Would Need to Be Located to Attack the Contiguous United States



Data source: Congressional Budget Office.

in the future.³ For example, there have been reports that Iran has obtained Russian-designed Kh-55 missiles with an estimated range of up to 1,500 miles and that it has manufactured a domestic version. Because Iran is thought to have provided the ASCMs used in the Hezbollah and Yemen attacks, it may also provide LACMs to nonstate groups. Indeed, LACMs—which some sources indicated were also supplied by Iran to

Yemeni rebels (but possibly fired by Iran, as well)—successfully attacked oil facilities in Saudi Arabia in September 2019. Because faster missiles tend to be larger, more complex, and more expensive, subsonic LACMs are more likely to be obtained by nonstate actors than are supersonic or hypersonic ones.

The Middle Eastern attacks described above were launched from territory controlled by those launching them. Attacking the U.S. homeland with today's LACMs would require the ability to position a launcher within

3. See Defense Intelligence Ballistic Missile Analysis Committee and National Air and Space Intelligence Center, *2020 Ballistic and Cruise Missile Threat* (July 2020), <https://go.usa.gov/xAtuJ>.

about 1,500 to 2,000 miles of the United States. Because of the location of the United States, that would mean launching from or across the ocean or from limited land locations close to the United States (see Figure 2-1).

To use ground-based LACMs, a nonstate organization would need to position a launcher in North America, northern South America, the Caribbean, Greenland, or Russia, which would almost certainly require the cooperation of another nation's government. A terrorist group might be able to take advantage of a weak or failing government in the Western Hemisphere to infiltrate a ground launcher without the knowledge of local officials. However, such an attempt would be complicated by the very close attention that the U.S. military and intelligence agencies would pay to a failing government in this hemisphere.

Placing a LACM launcher on a ship and firing from off the U.S. coast would be another possibility. Nonstate actors are unlikely to have submarines or ocean-going naval vessels but might place a launcher on a freighter or other large commercial ship. The CLUB-K "missiles-in-a-container" that Russia is offering for sale would appear to be designed for just such a tactic. Attack via commercial ship would not be without complications. The missile container would need to elude security-screening procedures at the port of embarkation, provisions would need to be made for hiding the missile operators aboard the ship, and the attacker would need to ensure that the missile container would be in the top layer of a shipload that might include several thousand other containers. A nonstate actor with sufficient resources could obtain or charter an entire ship to avoid those difficulties, although in that case the adversary might instead attempt to load the entire ship with explosives to detonate if they thought their ship could enter a U.S. port without being intercepted by the Coast Guard or Navy. Keeping track of ships approaching the U.S. coast is one of the missions assigned to United States Northern Command, the combatant command with primary responsibility for homeland defense.

Delivery of LACMs by aircraft would be even more difficult for a nonstate entity. It would require long-range military aircraft capable of launching cruise missiles along with airborne refueling support to reach the United States. Only the world's most advanced militaries possess that capability.

The number of LACMs that a nonstate actor could acquire and launch against the U.S. homeland would most likely be very small, limiting potential damage even if an attack was possible. Damage would be severe if a nuclear warhead (or warheads) was used for the attack, but a terrorist or other nonstate organization in possession of a nuclear weapon would probably try a more reliable means of reaching its target. For example, hiding a nuclear weapon in a shipping container and setting it to detonate at a U.S. port would probably be easier than hiding a nuclear-tipped cruise missile, its launcher, and personnel in a shipping container bound for the United States.

Alternative Means of Achieving Objectives

Past experience suggests that the objective of an attack on the U.S. homeland by a nonstate actor would probably be to inflict a large number of casualties and instill fear in the population as a means of influencing U.S. policy or gaining local prestige. Any society, and open societies in particular, have a plethora of essentially undefended locations that could be attacked to satisfy that objective. A primary reason to use cruise missiles is their ability to penetrate defenses—for example, to attack aircraft at a defended military base. If undefended (or lightly defended) targets met an attacker's objectives, other means of inflicting casualties and damage would be easier to execute and less prone to failure than LACMs. It is cheaper and easier to attack a shopping mall with several tons of explosives in a truck or a few people with automatic rifles than with a half-ton warhead on a cruise missile that might not reach its target.

Nation-States With Regional Military Power

Regional powers would be more likely than nonstate entities to obtain LACMs and the expertise to employ them. (Iran is known to possess LACMs, for example.) However, it would still be a challenge for regional powers to attack the U.S. homeland with LACMs because their militaries typically lack the power-projection capability needed to operate far from their territory. Additionally, as with nonstate entities, the objectives that a regional power might hope to accomplish with an attack on the U.S. homeland could be accomplished by other means.

Ability to Acquire and Deliver LACMs

Regional powers would probably be able to add LACMs to their arsenals if they chose to do so. The 2017 report on missile threats prepared by the Defense Intelligence

Ballistic Missile Analysis Committee and NASIC listed several regional powers that have already obtained LACMs, and the 2020 report observes that proliferation is continuing. As with nonstate actors, subsonic LACMs might be the most common, but supersonic missiles have also entered the inventories of regional powers. An example is the supersonic BrahMos missile jointly developed by India and Russia. Although primarily an antiship missile, the BrahMos has a land-attack capability, but its limited range—BrahMos Aerospace claims about 200 miles—would require launchers to be located relatively close to the United States. Iran is also thought to be producing a long-range LACM named the Soumar, which is based on Russian-built Kh-55 missiles it had previously acquired. The range of the Soumar, which may have been one of the weapons used in the attacks on Saudi Arabia in September 2019, is not known for certain, but it has been estimated to be between 800 and 1,500 miles.⁴

A regional power's attempt to attack the U.S. homeland with a LACM would be subject to many of the difficulties faced by nonstate actors because the armed forces of most regional powers are not equipped or trained to operate far from their home territory (that is, to project power). Although delivery of LACMs by long-range bombers would be unlikely, regional powers could use submarines such as the widely exported Kilo-class diesel-electric boat—which can carry four Kalibr LACMs—to come within range of the U.S. coast. Many navies do not train for such long-range missions but could certainly begin doing so. Missile launchers could also be hidden on commercial ships. A state actor could do this more easily than terrorists if it controlled a port from which ships carrying missiles could embark.

Regional powers would probably be capable of delivering only a few LACMs against the U.S. homeland. That would limit the damage that could be inflicted with conventional warheads. Nuclear warheads would be a greater concern. However, regional powers with aspirations to attack the United States with nuclear missiles would probably opt for ballistic ones (as has North Korea) because they can be fired from the safety of home territory.

4. See Center for Strategic and International Studies, CSIS Missile Defense Project, “Soumar” (accessed January 25, 2021), <https://missilethreat.csis.org/missile/soumar/>.

Alternative Means of Achieving Objectives

A regional power might use attacks or the threat of attacks on the U.S. homeland with conventionally armed LACMs as a means of influencing U.S. foreign policy. Although it is unlikely that such attacks would be able to inflict significant damage on U.S. military forces, the threat of such attacks could be a means to deter or shape U.S. actions. However, a regional power would be vulnerable to an overwhelming U.S. military response in a way that stateless terrorist groups might not. Conventional military deterrence should, therefore, have the strong effect of dissuading a regional power from such an attack. Shorter-range attacks (or the threat of attacks) against U.S. forces deployed to their region, or civilian targets of U.S. allies in their region, would be an easier way for a regional power to hinder U.S. military operations or influence U.S. policy but with less risk of provoking an overwhelming U.S. response.

Peer or Near-Peer Nations

Nations with peer or near-peer military capabilities—currently, Russia and China—have demonstrated the ability to produce cruise missiles and would probably be able to deliver them against targets in the U.S. homeland. Many of the LACMs produced by Russia and China can be armed with conventional or nuclear warheads. Conventional attacks on the U.S. homeland could have the goal of deterring U.S. military action in other parts of the world or directly affecting an overseas conflict by destroying military facilities that support U.S. forces abroad (for example, satellite control stations or port facilities used to deploy forces). Cruise missiles could also be used along with ballistic missiles as part of a limited or general nuclear war.

Ability to Acquire and Deliver LACMs

Russia and China both produce LACMs with a wide variety of performance characteristics. Both possess inventories of subsonic and supersonic missiles (see Table 1-1 on page 8). Russian LACMs can be launched from ground vehicles, surface ships, submarines, and aircraft. Of those platforms, submarines and long-range bombers would be capable of launching long-range cruise missiles against targets in the United States. Russia is relatively close to the United States in the north, and the Russian military trains to conduct long-range naval and air missions. The longer-range LACMs in Russia's inventory could strike targets in Alaska from Russian territory. China's ability to attack the U.S. homeland with LACMs is more limited because

of the longer distances to be covered and because China has less experience with military operations far from its region. However, China could improve its ability to conduct military operations far from home should it choose to do so.

If Russia or China opted to attack with LACMs, they could do so in much larger numbers than regional powers or nonstate actors. For example, a single Yasen-class guided missile submarine in the Russian Navy reportedly can carry up to 32 Kalibr (3M-14) land-attack missiles. Consequently, an attack from Russia or China could overwhelm defenses that might be sufficient against an adversary with fewer missiles.

Alternative Means of Achieving Objectives

Russia and China already possess arsenals of intercontinental ballistic missiles and long-range submarine-launched ballistic missiles that could be used for a widespread nuclear attack on the U.S. homeland. Although cruise missiles with nuclear warheads could also take part in such an attack, they would probably be superfluous in a full nuclear exchange.

Despite the availability of ICBMs, cruise missiles could be an attractive alternative for a peer or near-peer nation in some circumstances. In the case of nuclear war, stealthy, low-flying cruise missiles could be used as a first wave to attack critical targets, such as command and control and leadership facilities, with little or no warning. Long-range ballistic missiles, by contrast, can typically be detected up to 30 minutes before reaching the United States, which allows time for national leaders to be moved to secure locations and for some strategic systems, such as bombers or airborne command posts, to be scrambled and therefore avoid being destroyed on the ground. (Ballistic missiles fired from submarines on lower-altitude flight paths known as depressed trajectories could also be used to reduce warning times.)

Cruise missile attacks on the United States could also take place during conflicts that have not crossed the threshold of nuclear war. For example, LACMs carrying conventional warheads could be used to attack U.S. naval bases or ports, preventing the United States from sending military forces or supplies to a regional conflict elsewhere in the world. Although long-range ballistic missiles armed with conventional warheads could also be used for such attacks, their use would risk nuclear war because the United States would have no way of

distinguishing ICBMs with conventional warheads from ones with nuclear warheads until they hit their targets. Conventionally armed cruise missiles might not be detected until they hit their targets, at which time it would be obvious that the attack was not a nuclear one. If they are detected, however, they would raise the same risk of nuclear war. Similarly, under an “escalate to de-escalate” strategy that is thought to be a part of Russian military doctrine, one or a few nuclear-tipped LACMs could be launched against the U.S. homeland (the escalation) in an attempt to halt U.S. conventional operations elsewhere (the subsequent de-escalation).

Weighing Threats in Making Decisions About Fielding a Nationwide Cruise Missile Defense

CBO was asked to examine the composition and cost of potential nationwide cruise missile defense architectures. In evaluating the merits of fielding a nationwide CMD system, the costs of development, deployment, and operation should be considered relative to the likely threat posed by cruise missiles.

Two general characteristics that are useful for describing the overarching objective of a missile defense architecture are its *extent* (the area it is tasked to defend and from what directions) and its *capacity* (the number of shot opportunities per cruise missile and the number of cruise missiles the system can engage at a given place and time without being overwhelmed). For example, the current Ground-Based Midcourse Defense system is designed to defend the entire United States from ballistic missiles with trajectories that approach from generally north-easterly directions (its extent), and for limited raid sizes (its capacity). The extent and capacity can be tailored to the threats a defender desires to defeat.

The choice of extent and capacity would be different for systems designed for different threats (see Table 2-1). A terrorist organization in possession of cruise missiles would have the flexibility to attack anywhere its missiles could reach because the objective would be to instill fear, not destroy a particular target. A regional nation attempting to deter or shape U.S. actions with the threat of cruise missile attacks might also opt to attack civilian targets in the United States despite the risk of grave consequences. Although attacking some targets would be more spectacular than others, hitting any target in the United States with a cruise missile would probably be counted as a great success.

Table 2-1.

Considerations for Aligning LACM Threats With Defensive Strategies

Adversary	Scale of Attack	Example Targets	Defense Strategy Options
Nonstate Group	One to a few LACMs, NBC warhead possible	Civilian targets	Deterrence (no active defenses); area defense of U.S. perimeter
Regional Power	One to several LACMs, NBC warhead(s) possible	Civilian targets, government or military bases	Deterrence (no active defenses); area defense of U.S. perimeter
Peer Power in a Regional Conflict	A few to tens of LACMs, NBC warheads possible	Government facilities, military bases, power infrastructure	Deterrence (no active defenses); local defense of critical targets; area defense of U.S. perimeter
Peer Power in a Global Conflict	Many LACMs, nuclear warheads likely, biological or chemical warheads possible	Strategic deterrent forces, national C3, leadership, ships in port, bomber bases	Deterrence (no active defenses); local defense of critical targets; area defense of U.S. perimeter; warning-only system of sensors around U.S. perimeter

Data source: Congressional Budget Office.

C3 = command, control, and communications facilities; LACM = land-attack cruise missile; NBC = nuclear, biological, chemical.

The extent of a CMD system to counter that threat would need to be very large, possibly encompassing the perimeter of the contiguous United States with additional coverage for Alaska, Hawaii, and U.S. territories. However, terrorists would be unlikely to have more than a few missiles, so the capacity of the defense could be low. A judgment must be made about whether building a wide-area, albeit low-capacity, CMD system to counter terrorists would be worth the cost given the other, less complicated ways terrorists might strike. Regional powers might be able to conduct larger attacks, but they could be more easily deterred by the threat of a conventional military response from the United States. (The U.S. military operations in Afghanistan after the terrorist

attacks of September 11, 2001, are an example of such a response, although the Afghani military did not conduct those attacks.)

Similarly, decisionmakers would need to make assessments about building defenses to counter LACMs launched by Russia or China. Those nations' potential ability to launch large numbers of LACMs could overwhelm all but high-capacity defenses. But providing high capacity over large areas would be very costly. Consequently, decisionmakers might opt to defend key targets against Russian or Chinese cruise missiles—in addition to relying on nuclear deterrence—rather than field a nationwide CMD.



Chapter 3: Technical Characteristics of Cruise Missiles and the Components of Cruise Missile Defenses

The architecture of cruise missile defenses capable of protecting the U.S. homeland would consist of sensors to detect land-attack cruise missiles and interceptors to destroy them. The number of sensors and interceptors that would be needed, and where they should be located, would depend on four factors:

- The characteristics of the missiles the system was tasked with defeating,
- The performance of the components (sensors, interceptors, and battle management systems) that comprise the defense,
- What the system was expected to handle (for example, the area to be defended, or the number of missiles that could be simultaneously engaged), and
- Whether the system was expected to be operational at all times or just during a crisis.

The implications of the first two factors, which focus on the performance of individual pieces of equipment, are discussed in this chapter. The third and fourth factors are considered in the next chapter's discussion of defensive objectives and illustrative defensive architectures.

Characteristics of LACMs and Their Implications for Cruise Missile Defenses

The specific characteristics of modern cruise missiles vary widely. Among them are range, speed, altitude, stealth features, and type of warhead, all of which can have strong implications for the design parameters of a cruise missile defense. Another characteristic of LACMs is the type of vehicle used to launch them. The type of launcher would probably have little or no effect on the required capabilities of defensive sensors and interceptors but could affect other aspects of how a defender might address the LACM threat. For example, some launchers might be easier to detect and destroy before

their LACMs were fired, and the type of launcher could affect the ability of an adversary to simultaneously attack from several directions or to launch from close to U.S. borders.

Range

The ranges of LACMs vary from about 200 miles to over 2,000 miles (see Table 3-1). Longer-range missiles would probably be of greater concern with respect to attacks against the U.S. homeland because a longer range would allow an adversary to keep its launchers farther from U.S. soil, which would decrease the chance that the launchers would be detected before the adversary could initiate an attack. A longer range would also enable an attacker to hit targets deeper inside the U.S. mainland. The threat posed by long-range missiles has been cited as a reason for expanding cruise missile defenses for the U.S. homeland. For instance, in February 2019, the Commander of United States Northern Command noted that Russia's "new generation of air- and sea-launched cruise missiles feature significantly greater standoff ranges and accuracy than their predecessors, allowing them to strike North America from well outside NORAD radar coverage."¹

Shorter-range LACMs could still pose a threat, however, because much of the U.S. population and many important government and military facilities are located near the coasts. A short-range missile launched from a ship could not reach nuclear command-and-control facilities in the Midwestern United States but might be able to attack a naval base or coastal city. Short-range missiles can be effective against those targets if their launchers are able to approach without being detected, as might

1. See the statement of General Terrence J. O'Shaughnessy, USAF, Commander of the U.S. Northern Command and North American Aerospace Defense Command, before the Senate Armed Services Committee, *USNORTHCOM and NORAD Posture Statement* (February 26, 2019), <https://go.usa.gov/x7z9a> (PDF, 143 KB).

Table 3-1.

Reported Performance Characteristics of Selected Land-Attack Cruise Missiles

Country	Missile	Range (Miles)	Speed (Miles per hour)	Altitude (Feet)	Warhead	Entered Service
China	HN-2	800 to 1,300	400 to 600	70	900-lb. HE or nuclear	2002
	HN-3	1,300 to 1,900	700	30 to 70	900-lb. HE or nuclear	2007
Russia	Rk-55	1,500	500	600	1,000-lb. HE or nuclear	1984
	Kh-555	2,200	600	130 to 400	900-lb. HE	2004
	3M-14 Kalibr	900 to 1,200	600	70 to 300	1,100-lb. HE or nuclear	Before 2015
India and Russia	BrahMos	180	1,500	30	700-lb. HE	2008
Iran	Soumar	Less than 1,500	400 to 600	130 to 400	900-lb. HE	2012
United States	Tomahawk	700 to 1,500	570	50 to 100	1,000-lb. HE or nuclear	1984

Data sources: *Jane's Weapons: Strategic*, 2020–2021; *Jane's Weapons: Naval*, 2020–2021. See www.cbo.gov/publication/56950#data.

HE = high-explosive; lb. = pound.

be the case for surprise attacks with submarine-launched LACMs or LACMs concealed on commercial ships. Defeating short-range LACMs could be challenging because area defenses might not be able to respond in the very short time that elapsed between when the missile was launched and when it would reach its target.

Speed

Most LACMs in service today fly at subsonic speeds—typically between Mach 0.5 and Mach 0.8, or 400 to 600 miles per hour at sea level—under the power of a small turbojet or turbofan engine.² Some, however, can fly at supersonic speeds—typically Mach 2 to 3, or 1,500 to 2,300 miles per hour—under the power of a ramjet engine, but those missiles usually have shorter ranges than subsonic missiles.

All else being equal, increasing a LACM's speed decreases the amount of time the defense has to react after it detects an incoming attack. Higher speed has disadvantages, however. Faster missiles tend to be larger and more expensive for a given payload, and they usually need to fly higher, where air resistance is lower, to achieve adequate ranges. (The disadvantage of higher altitudes

is discussed below.) Heating of a missile's surface from friction caused by faster movement through the air also increases the possibility of detection by infrared sensors, which detect heat.

Altitude

Cruise missiles can be designed to fly at altitudes as low as a few feet to as high as tens of thousands of feet. It is easier to achieve long range at higher altitudes because the jet engines powering the missile operate more efficiently and there is less drag in the thinner air. However, a missile flying close to the surface is harder to detect and intercept because it can be obscured behind the curvature of Earth, and it can be difficult for defensive radar to distinguish a low-flying missile from radar reflections off of Earth's surface (known as ground clutter).

For many missiles, different altitudes might be chosen for different parts of an attack route. For example, a LACM might be directed to initially fly at a higher altitude for improved range but then drop close to the surface near the target to increase the chances of eluding defenses. Faster missiles would probably be limited to high altitudes because atmospheric drag at high speeds is prohibitive at low altitudes. (Some supersonic cruise missiles can dash for short distances at low altitudes, however.) Flying at higher altitudes avoids dense air but increases the distance at which LACMs can be detected by most air defense sensors, at least partially reducing the advantage of speed.

2. The speed of sound in air at sea level is about 760 miles per hour (mph). Engineers use the term "Mach" to relate speed to the speed of sound, or Mach 1. Therefore, Mach 0.5 is half the speed of sound (380 mph), and Mach 2 is twice the speed of sound (1,520 mph). Subsonic speeds are those below Mach 1; supersonic speeds are Mach 1 and higher.



Stealth Features

Another means of making a cruise missile more difficult to detect is the incorporation of stealth (also called low-observable, or LO) features in its design. Cruise missiles can be coated with radar-absorbing materials, and their airframes can be shaped to reduce the amount of radar energy that is reflected back to the defense's radar receivers. Both of those measures decrease the range at which radar can distinguish a cruise missile from the background signal.

Countering stealth features requires some combination of increased radar power, decreased distance between adjacent radars in a defensive perimeter, and increased sophistication of signal processing, all of which increase a defender's costs. However, stealth features typically impose costs on the attacker as well. In addition to the monetary cost that comes with a more sophisticated missile design, stealth features can result in shorter ranges for a given size of missile because radar-absorbent materials add weight, and stealthy shapes may not be aerodynamically efficient.

Type of Warhead

Cruise missiles can be armed with a variety of warheads matched to the type of damage they are intended to inflict. For example, versions of the Navy's Tomahawk have included nuclear warheads (the now-retired TLAM-N, with a W80 nuclear warhead), conventional submunition warheads (the TLAM-D, with 166 BLU-97/B bomblets), and unitary conventional warheads (several variants with a single 1,000-pound chemical explosive warhead).³ Unitary conventional warheads are the most common both for the Tomahawk and among other LACMs worldwide.

Although the type of payload carried by a LACM will not typically affect a particular missile defense sensor's ability to detect and track it or a particular defensive weapon's ability to destroy it, the overall design of a cruise missile defense system can be affected if both conventional and nuclear threats must be considered. For example, nuclear warheads can be designed with so-called salvage fuses that detonate if the missile

3. A submunition warhead contains several or many smaller explosive devices (sometimes called bomblets) packaged as one unit. They are usually used to attack so-called area targets such as trucks dispersed in a field where many small explosions might be preferable to a single large one. A unitary warhead is a single explosive device.

carrying them is hit by an interceptor. To counter such a feature, it might be necessary to field defenses that can intercept LACMs well outside U.S. territory (which would decrease the time available to detect, track, and destroy them) or to develop weapons capable of not just shooting down the missile but also reliably destroying the warhead itself. That increased difficulty would add to the complexity and cost of a defense system. The threat of nuclear payloads would probably also increase the effectiveness that would be required of CMD systems because allowing even one missile to hit its target would be considered inadequate.

Type of Launcher

Cruise missiles can be launched from many different platforms, including trucks, ships, submarines, and aircraft. However, the larger the missile, the more limited the launcher options. In general, achieving longer ranges, higher speeds, and heavier warheads leads to larger, heavier missiles because those characteristics require more fuel, larger and more powerful engines, and larger airframes to accommodate them.

Although the type of launcher would have little effect on the performance required of individual defensive systems tasked with defeating LACMs after they were in the air, it could have profound implications for the defense as a whole. In particular, launchers that were easy to conceal could make it easier for an adversary to launch an attack from a location that was unfavorable to the defense. For example, less time would be available for the defense to respond to a LACM launched from a submarine close to the U.S. coast than one launched from a surface ship far out to sea. Having less time to respond to a launch might require the United States to field faster interceptors at more closely spaced locations, both of which would add to the cost and complexity of the defense. Concealed launchers could also reduce the ability of the United States to destroy LACMs before they were fired (a so-called left-of-launch defense).

Performance Characteristics of the Components of Cruise Missile Defenses

Cruise missile defenses, and air defenses in general, consist of three primary components:

- *Sensors*, which are systems such as radar and infrared detectors that detect, track, and identify threat missiles;

- *Shooters*, which are systems such as surface-to-air missiles or fighter aircraft that intercept and destroy or otherwise defeat threat missiles; and
- *Battle management systems*, which coordinate the actions of the sensors and shooters.

Sensors, shooters, and the underlying battle management systems that integrate them into a coordinated defense are the building blocks that can be combined into different air defense architectures depending on the defender's objectives—for example, a *point defense* for a single facility or cluster of facilities or an *area defense* for a geographic region.

A particular challenge for homeland CMD would be determining whether a target is an actual threat. Cruise missiles can fly at speeds and altitudes similar to civilian aircraft, making target identification an important step in a defensive engagement in an environment with many civilian aircraft.

Sensors for Detection and Tracking

The sensor systems that make up a cruise missile defense would need to be able to detect and track threats soon enough and accurately enough to employ shooters against them. The critical performance characteristic for the sensor components of a cruise missile defense is *effective range*, the distance at which the sensor can both detect a flying object and classify it as a potential threat. Having a longer effective sensor range decreases the number of sensors needed to observe a given area and increases the time available to employ interceptors before an incoming cruise missile can reach its target. The range of an individual sensor is primarily dependent on the performance of the device (its power, resolution, signal processing) and its height above the ground, which determines its horizon (the line-of-sight limit attributable to the curvature of Earth).

The target's characteristics also affect a sensor's range. For active sensors—such as radar—that transmit a signal and detect its reflection from the target, detection range could be reduced if the target incorporated radar-absorbent surface coatings or special shaping to reduce the signal that is reflected back to the radar's antenna. For passive systems—such as infrared sensors that detect heat emitted from an object—detection range could be reduced by mixing hot exhaust with cooler air before the exhaust exits the engine of the cruise missile.

Type of Sensor. The choice of sensor would depend on the performance and physical signature characteristics of threat missiles. The most common sensors capable of detection at long ranges are radars and, if the target is very hot or in the upper atmosphere, passive infrared detectors. Other sensors such as optical cameras or laser radar (commonly referred to as LIDAR) might be employed in special circumstances, but their relatively short detection ranges in the atmosphere would make them less suitable for the large area that must be covered in defense of the entire United States against low-altitude threats.

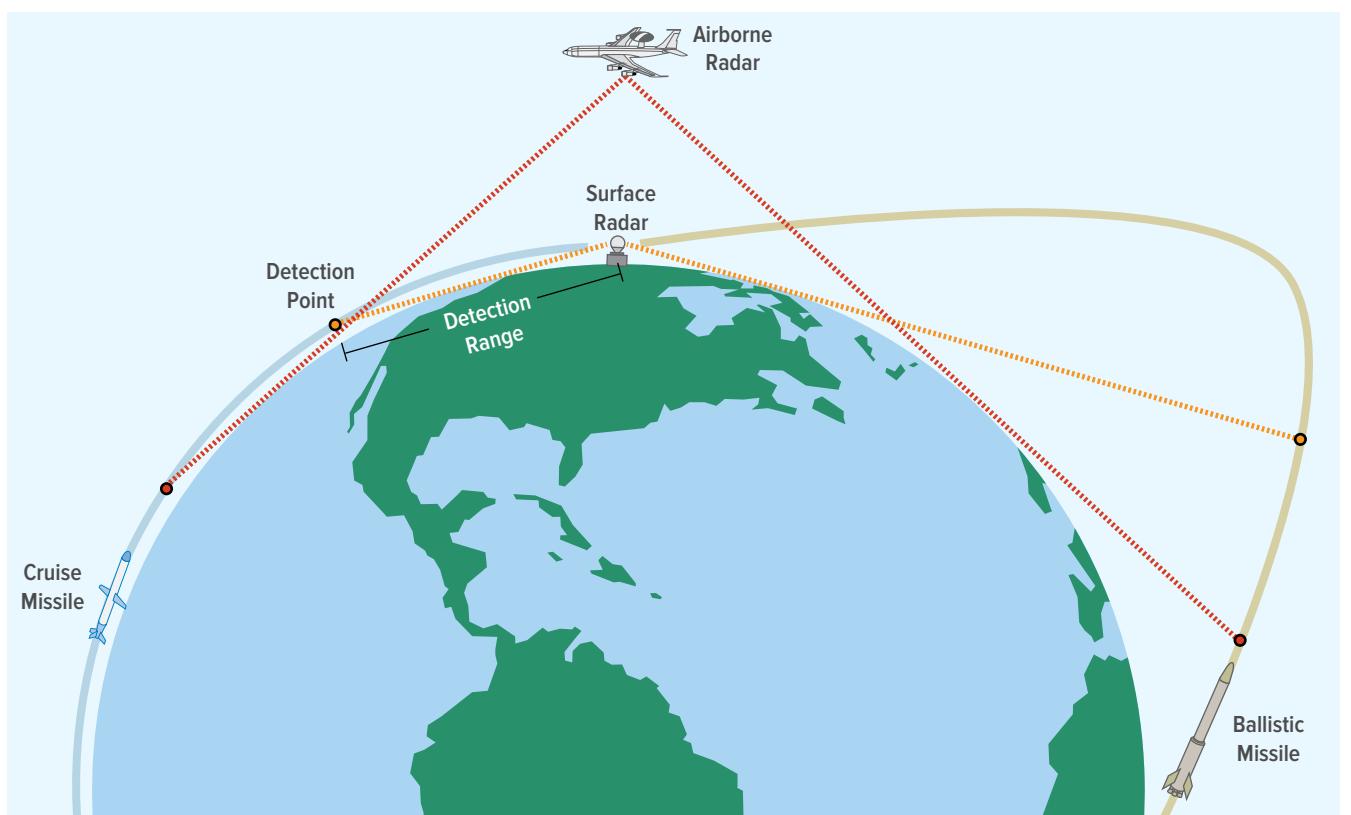
Radar would be the primary type of sensor used to detect and track cruise missiles over long distances. Subsonic LACMs would be difficult to detect with infrared sensors because they have small thermal signatures—the rockets that boost them into the air before their jet engines start are small and burn for only a few seconds, and air-launched cruise missiles might not need a booster—and atmospheric drag at their low speed does not result in much heating of the missile's surface. Supersonic cruise missiles are easier to detect with infrared sensors because they have hotter engines and greater frictional heating of their surfaces, but detection ranges are still limited. Radar is also less affected by atmospheric conditions, such as the presence of clouds or haze, which limit the detection range of sensors that rely on infrared and shorter-wavelength radiation, especially against targets flying low in the atmosphere. (An interceptor might be able to use short-range laser or passive imaging sensors for improved guidance as it approached its target, however.) The low altitude flight of cruise missiles relative to ballistic missiles also would make it difficult for satellite-borne infrared ballistic missile defense sensors to detect them.⁴

The primary characteristics that determine effective radar range are *antenna performance* (transmission power and reception sensitivity), *signal processing capability* (to distinguish the target from background noise), and the *height of the antenna* above local terrain. An antenna's performance and signal processing determine whether a measurable radar return from a target can be achieved at a given range, and an antenna's height above the ground

4. Infrared sensors are very useful against long-range ballistic missiles because those missiles have boosters that burn very hot for several minutes and their cold warheads follow trajectories that extend above the atmosphere where it is possible to detect them against the even colder background of space.

Figure 3-1.

Radar Horizon Versus Altitude of Sensor



Radar horizon limits are attributable to the curvature of Earth. The distance to a radar's horizon increases with the height or altitude of its antenna and the altitude of its target.

Data source: Congressional Budget Office.

Actual horizon limits are much shorter than they appear in this figure because the figure is not to scale.

determines the radar horizon limit (the upper bound of detection range) that results from the curvature of Earth. The capabilities of modern radars with active electronically scanned array (AESA) antennae are such that radar horizon would probably be the limiting factor in effective range for cruise missile defenses, although stealthy LACMs flying at very low altitudes might be challenging for even the most modern radar systems to detect and track.

Sensor Platform. Another primary aspect of a sensor architecture for cruise missile defense is the type of platform upon which sensors are located.

Two characteristics of sensor platforms are particularly important:

- The *height of the platform* determines the horizon limit of the sensor (see Figure 3-1); and
- The *endurance of a platform*—the length of time it can continuously operate before returning to base or being shut down for maintenance—determines how many platforms are needed to maintain continuous coverage of a given area.

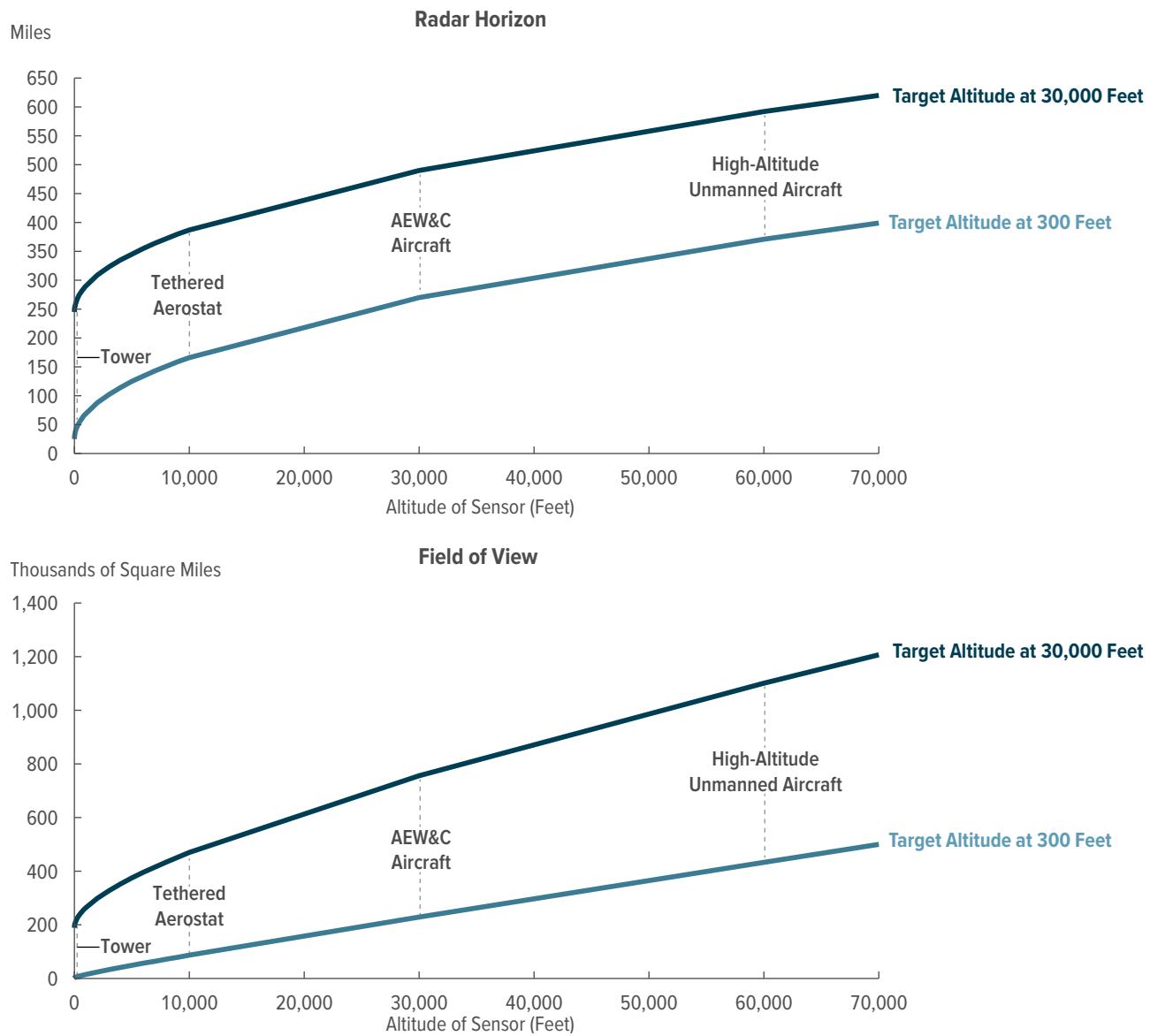
If the sensor is located on a satellite in Earth's orbit, the details of orbital dynamics are also important.

The Height of Sensor Platforms. The horizon-limited range of a sensor depends on its height above the ground, the altitude of the target, and the presence of terrain features such as hills, mountains, trees, or buildings. If terrain features are not considered (that is, Earth's surface is assumed to be smooth), the horizon-limited



Figure 3-2.

Radar Horizon and Field of View for Generic Ground and Airborne Sensor Platforms



Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

AEW&C = airborne early-warning and control.

range of a radar on the surface would be about 25 miles for a target flying at 300 feet. In that example, if the radar had a 360-degree field of view, it could observe at most about 2,000 square miles. (The contiguous United States has an area of more than 3 million square miles.) The observable area would be smaller if terrain features blocked the view in some directions, which is very common in practical applications. The horizon-limited range and potential area observed would increase as the altitude

of the target and the altitude of the radar increased (see Figure 3-2). The problem of terrain obstructions would decrease, as well.

A short detection range would allow little time to shoot down attacking missiles—only 3 minutes would be available to a defender to detect, identify, and respond in the example above if the missile was traveling at 500 miles per hour (or 0.65 Mach) and 300 feet in altitude and the

radar was on the surface and in the same location as the cruise missile's target (or was the target). Elevating the sensor to 700 feet (by placing it on a hilltop or tower, perhaps) would more than double its horizon against that target, to about 60 miles, and increase the time available for a response to 7 minutes.

Many sensors located at or near the surface would be needed if the defense was required to cover a large area. Therefore, providing coverage of large areas such as the U.S. mainland would probably require airborne sensors to overcome the short horizon at and near the surface. A surveillance aircraft such as the Air Force's E-3 airborne warning and control system (AWACS) flying at 30,000 feet would have a sensor horizon of 270 miles, cover about 230,000 square miles, and provide a 32-minute warning time for a cruise missile flying at Mach 0.65 and 300 feet toward a target under the aircraft's orbit. A high-altitude unmanned aircraft such as the Air Force's RQ-4B Global Hawk would have a sensor horizon of 370 miles, cover about 430,000 square miles, and provide a 44-minute reaction time. A satellite in low Earth orbit would have an even longer horizon—about a 2,300-mile range and a field of view of nearly 17 million square miles for a satellite altitude of 500 miles.⁵ Over that large distance, however, sensor performance (the radar's power and sensitivity and its ability to rapidly scan large areas), not the horizon, would probably be the limiting factor.

The Endurance of Sensor Platforms. In addition to a sensor platform's height or altitude affecting the number of sensor locations that would be needed to defend a given area, more than one sensor and platform would need to be purchased for each location if the platform's endurance did not permit it to operate almost without interruption. The examples above include three types of platform: ground structures, aircraft, and satellites. Because ground structures have essentially unlimited endurance, only one sensor would be needed for each location. Ground-based sensors might be inoperable for repairs or routine maintenance, but those downtimes would be relatively short and could be scheduled at unpredictable times to make it difficult for an adversary to exploit the resulting gap in coverage. A portable sensor could also be used to provide temporary coverage during periods of repair.

5. Low-Earth-orbit altitudes are roughly defined to be more than 100 miles but less than 1,200 miles above Earth's surface.

A single aircraft, on the other hand, could be on-station for only a limited period of time. Much time would be spent refueling and maintaining the aircraft. In addition, the aircraft would spend time flying between its operating location (its orbit) and its airbase. Consequently, more than one aircraft would be needed to keep each sensor location in continuous operation. The exact number of aircraft needed for each sensor location would depend on the length of time the aircraft could remain aloft, its speed and the distance from its base, the time to refuel and service it for each mission, and its overall reliability. As an example, three to four long-endurance unmanned aircraft are typically needed to provide continuous operation of one orbit far from their base; two to three can be adequate if the orbit is closer to base. For a manned aircraft, the endurance of its crew may also limit the length of a mission.

The Effect of Satellite Orbits. Satellites pose a different issue. At the lower orbital altitudes that are better suited for detecting and tracking cruise missiles, both the satellite's orbital motion and Earth's rotation prevent a satellite from being positioned over a single point on Earth's surface.⁶ Thus, although satellites could operate virtually continuously, for much of the time they would not be in the proper location to detect a cruise missile attack on the United States. (When not over the United States, the satellites' radars would probably be turned off periodically to conserve battery power.) As a result, a constellation of many satellites would be needed to ensure that the entire country is always within the view of enough sensors.

The precise number needed would depend on the orbital altitude and the sensitivity and performance characteristics of the sensor. A constellation of satellites with infrared sensors (such as the ones under consideration for ballistic and hypersonic missile defenses) would probably have limited capability against LACMs, but a constellation of radar satellites might be effective. Compared with infrared sensors, however, radars are much more difficult and expensive to place on satellites.

Although many satellites would be needed to ensure that the United States was in view at all times, those satellites

6. Satellites in very high orbits—about 22,000 miles—above Earth's equator can remain located above a single point on the equator. However, those geostationary orbits are so high that it is challenging for sensors to detect objects such as cruise missiles that operate between the surface and the top of the atmosphere.

could provide valuable surveillance of other parts of the globe during the course of their orbits. Indeed, the capabilities of a satellite constellation designed to detect and track airborne targets might be similar to the “custody layer” constellation that has been proposed by the Space Development Agency (SDA) to track surface targets. If the SDA fielded a custody layer that was also able to detect and track LACMs accurately enough to guide interceptors until their homing seekers could acquire the targets, and if that information could be accurately and rapidly transmitted to the missile defense interceptors, the incremental cost to field a homeland CMD using radar satellites would be substantially reduced.

Shooters

Systems capable of shooting down cruise missiles include antiaircraft guns with a range of less than a mile, surface-to-air missiles with a range of well over 100 miles, and fighter aircraft that can fly several hundred miles. Short-range weapons are better suited for defending single locations or small areas; long ranges are needed to defend large areas with a reasonable number of shooters. A defensive architecture designed to defend the entire United States or its coasts would require long-range shooters, although short-range weapons could be used as an extra layer of defense for critical targets. Among weapons available today, SAMs and fighter aircraft would provide the greatest ability to defend large areas. Other shooters, such as antiaircraft cannon, lasers, and hypervelocity guns, might be suitable for smaller areas or individual targets.

Between SAMs and fighters, the former would have the advantages of being able to be launched quickly (after sensors have located and established tracking of the target cruise missile) and fly to the target at a very high speed. Fighters would have the advantage of much longer range if they had sufficient time to take off and fly to their target. Because cruise missiles can be hard to distinguish from commercial or private aircraft on radar and other long-range sensors, another advantage of fighters is the potential to have a pilot visually identify the target as a missile threat before attempting to shoot it down. The January 8, 2020, downing of an airliner in Iran by a SAM system illustrates the importance of positive identification.⁷

7. See Matthew S. Schwartz, “Iranian Report Details Chain of Mistakes in Shooting Down Ukrainian Passenger Plane,” *NPR Daily Newsletter* (July 12, 2020), <https://tinyurl.com/y5jnr3kn>.

Surface-to-Air Missiles. The U.S. military currently operates several types of SAM, from the shoulder-fired Stinger (a maximum range of about 5 miles) to the ship-launched Standard Missile-6 (SM-6), which has a range of about 200 miles (according to unclassified sources). For a CMD system, the Department of Defense could opt to use an existing type of missile (possibly with modifications) or develop a new missile designed specifically for the CMD mission.

Several characteristics are important for SAMs tasked with wide-area air and missile defense. *Long range* is a key characteristic to provide defense of a large area with a reasonable number of launcher locations. Similarly, *high speed* allows a SAM to reach a target in less time, which increases the distance it can cover (up to a missile’s maximum range) in the limited time available to engage a target. To be effective against lower-altitude targets, long-range SAMs would need to be able to receive guidance updates from external sources (that is, from sources other than sensors co-located with the missile’s launcher, which would probably be horizon-limited) during the portion of flight before the SAM is close enough for its onboard sensor, or seeker, to lock on to its target.

The ability to engage targets at a variety of altitudes can also be important. For example, a Terminal High-Altitude Area Defense (THAAD) or Standard SM-3 missile, both of which are designed to counter ballistic missiles at very high altitude, could not be used against a LACM flying at 300 feet. A SAM’s seeker must also be able to detect and lock on to its target. Radar seekers must be able to distinguish a low-altitude target from signals reflected from the surface, and infrared seekers must be able to detect relatively cool targets.

Three SAMs in today’s inventory have the potential to contribute to wide-area homeland CMD:

- The Navy’s SM-6 has a long range and is designed to defeat aircraft and cruise missiles. Although primarily developed to defend ships at sea, it has demonstrated the ability to defeat low-altitude cruise missiles over land.
- The Army’s Patriot SAM system can be used against cruise missiles (in addition to its ability to defeat short- and medium-range ballistic missiles). Although effective for defending limited areas, a very large number of Patriot launch sites would be needed for the broader homeland defense mission because of its limited range—about 100 miles.

- The Army's THAAD has longer range than the Patriot but is designed only for intercepts in the upper atmosphere (or higher) and is generally not considered to be capable against cruise missiles. It might be possible to develop modified versions of those missiles that would be better tailored for homeland CMD—for example, with longer ranges or, in the case of THAAD, capability against cruise missiles in the lower atmosphere.

Alternatively, an entirely new missile could be developed.

The Army and Navy also operate shorter range systems that could be used to defend selected locations either alone or in addition to a wide-area defense system. Those include the National Advanced Surface-to-Air Missile System, which is a ground-launched version of the AIM-120 air-to-air missile, and the Rolling Airframe Missile, which was initially based on the Sidewinder air-to-air missile and is found on many Navy ships. However, those missiles have ranges that are too short to make them suitable for a wide-area defense of the United States.

Fighter Interceptors. The military maintains fighters on alert at several U.S. locations to intercept unidentified aircraft, aircraft that have deviated from their scheduled flight plans, and aircraft that are approaching or have entered restricted airspace. Aircraft on alert are fueled and armed, and pilots are on hand and ready to fly intercept missions if called upon. Even when on alert, however, it takes time for pilots to get to their aircraft, start engines, taxi, and take off. Typical times between the order to go and the aircraft's leaving the ground are at least 5 to 10 minutes. (The time could be reduced if, for example, pilots waited in their aircraft near the end of the runway, but it is difficult to maintain that posture for extended periods of time.)

Once airborne, a fighter would be guided to its cruise missile target with information from tracking sensors. Upon reaching the vicinity of the target, a fighter would use its own sensors (probably radar, but possibly an infrared search-and-track system) to acquire the target and launch air-to-air missiles to shoot it down. The air-to-air missiles in use today—medium-range AIM-120s with radar seekers and shorter-range AIM-9s with infrared seekers—could be used against cruise missiles. The Air Force and Navy are developing a new air-to-air missile—the AIM-260—that will have longer range than

the AIM-120, potentially increasing the reach of fighter defenses as long as visual identification is not required.

Most of the fighters in today's inventory (including Navy and Marine Corps aircraft) could be tasked with cruise missile defense. However, the Air Force and Air National Guard are charged with homeland air defense missions today and would probably be tasked with cruise missile defense, as well. Further, fighters equipped with active electronically scanned array radars would be much more effective than those with older radars because AESA radars are better able to detect and track small targets flying at low altitude. The Air Force's F-22A and F-35A aircraft are equipped with AESA radars, and the Air Force has replaced older radars on its F-15Cs with new AESA radars. According to 2021 budget documents, Air Force plans include adding AESA radar to 402 of the 935 F-16Cs currently in service. Indeed, upgrading F-16s with AESA radar for homeland defense has been a priority for the United States Northern Command. As of October 2020, F-16s in four Air National Guard squadrons had been equipped with the new radar.

Other Shooters. Several types of shooter other than SAMs and fighters could be used to defeat cruise missiles. The Navy's Phalanx Close-In Weapon System, for example, is a 20-mm Gatling gun controlled by a radar that can engage targets at a range of about a mile or less. The Army has fielded a truck-based version of the system for defense against artillery and mortar rounds. There have also been proposals for improved cannon that shoot very high-velocity projectiles—so-called hypervelocity guns—to defeat fast-moving targets. Efforts are also under way to develop directed-energy weapons such as lasers or microwaves with enough power to defeat missiles or artillery projectiles in flight, and prototype systems are being tested. As with cannon, initial versions of these weapons would probably be short range, limiting their use to defense of a single target or small area (also known as point defense).

Battle Management Systems

A battle management system (BMS) integrates the activities of sensors, shooters, and the people responsible for employing them into a coordinated defense. In the case of cruise missile defense, BMS functions—overall command and control, battle management, and communications—must be accomplished very rapidly. A BMS consists of the communications links between the components of the defense as well as the computers and algorithms that synthesize information from those

systems into a tactical picture upon which commanders can base their defensive actions. Those functions must be accomplished quickly enough so that sufficient time remains for shooters to be employed. In the case of cruise missile defense, the time available to detect, decide, and engage can be as short as a few minutes. To maximize the time available to employ shooters, the desired responses for different situations must be planned in advance, and the sensors and BMS must provide commanders sufficient information to make prompt decisions. In recognition of this challenge, the Air Force's first field test of technologies and operational concepts for its Advanced Battle Management System, a future network with which the service plans to coordinate and control its operations, was focused on defeating a cruise missile threat to the U.S. homeland.

A particular challenge for the BMS of a cruise missile defense is assessing whether objects detected by the system's sensors are actually threats, because many types of cruise missiles fly at speeds and altitudes similar to civilian aircraft (or could be intentionally programmed to do so). According to the Federal Aviation Administration, there are nearly 30,000 scheduled commercial flights per day in the United States. Moreover, more than 200,000 general aviation aircraft are registered in the United States.⁸ American and Canadian fighters have averaged about 100 intercepts of unidentified aircraft each year, most involving small general aviation aircraft inadvertently entering restricted airspace.⁹ Every target detected by the defender's sensors must be positively identified as a threat before it can be shot down.¹⁰

Representative Defensive Systems and LACM Threats That CBO Used to Analyze CMD Architectures

The sections above describe a variety of LACM threats as well as several types of defensive sensors and shooters in service today that could be purchased for use as components of a defense against those threats. (Air defenses in today's force are already in great demand.) CBO based its

8. See Aircraft Owners and Pilots Association, *State of General Aviation, 2019*, <http://tinyurl.com/vpobvhda> (PDF, 793 KB).

9. See Drew Brooks, "Sentinels of the Sky," *National Guard Association of the United States Magazine* (April 3, 2019), <https://tinyurl.com/3i9d30ob>.

10. Ballistic missile defenses do not have that complication because there are no benign objects that would be following an ICBM-like trajectory. The dilemma for ballistic missile defenses is not whether to engage targets but, rather, which targets to engage if multiple missiles or decoy warheads are present.

analysis of illustrative CMD architectures on calculations pitting generic sensors and shooters against two types of generic cruise missile. Those sensors and shooters are based loosely on existing systems.

Alternatively, new systems could be developed specifically for the CMD mission. CBO noted areas where more exotic technologies might remedy defensive shortfalls, but uncertainties about what capabilities might be achieved with those technologies, how long it might take to field them, and what they might cost made a quantitative analysis of such systems impractical.

Generic LACMs

To measure the capabilities of notional cruise missile defenses, CBO assessed their ability to defeat two generic classes of LACMs possessing performance characteristics suitable for attacking the U.S. homeland. Speed and altitude distinguish the two classes:

- Subsonic, low-altitude missiles, and
- Supersonic, medium-altitude missiles.

Those two classes are representative of LACMs currently known to be in service or under development.¹¹

Subsonic, Low-Altitude LACMs. This class of missile can be difficult to detect and intercept because it flies close to Earth's surface and has a long range. It is powered by a small, efficient turbojet or turbofan engine. Well-known examples include the U.S. Navy's Tomahawk and the Russian 3M-14 Kalibr missiles. Although all cruise missiles are sophisticated weapons, subsonic LACMs present fewer technological challenges to the builder than faster missiles and also tend to be smaller than faster missiles with comparable ranges and payloads. For those reasons, subsonic LACMs are the most common type of LACM in service today. Several nations are known or thought to produce this class of missile, and some have made them available for export.

The generic subsonic missile modeled by CBO has a cruise speed of about 500 miles per hour (or roughly Mach 0.7) and flies at an altitude of 300 feet. It is roughly based on performance characteristics reported

11. Some cruise missiles are known to combine characteristics of these generic types. For example, some cruise missiles that are subsonic for most of their flight can accelerate to supersonic speeds to evade terminal defenses. CBO did not analyze such missiles other than to note that they could reduce the expected performance of defensive systems against them.

for the Russian 3M-14 Kalibr. It could be launched from a wide variety of platforms, including trucks, ships, attack submarines, and fighter-sized (or larger) aircraft. The Russian Club-K missile system (an export version of the Kalibr), for example, has been packaged in a launcher that resembles a 40-foot shipping container that could be lashed to the deck of merchant ships or towed by commercial trucks.

Supersonic, Medium-Altitude LACMs. Supersonic LACMs, which are typically powered by a ramjet engine, are less common than their subsonic cousins because they are larger, more complex, and more expensive for a given range and payload. The benefits of high speed can outweigh those disadvantages in some situations, including providing the ability to more rapidly reach mobile targets before they can be moved or hidden or to penetrate heavy air defenses that could shoot down slower missiles. (Most supersonic cruise missiles today are antiship missiles designed to penetrate the heavy air defenses arrayed around naval forces.) Although the disadvantages of supersonic LACMs would make them less likely choices for attacking targets in the U.S. homeland than subsonic LACMs, changes in circumstances or technology could make using them more attractive in the future. For example, advances in supersonic propulsion might result in smaller supersonic LACMs that would be easier to conceal and transport.

The generic supersonic missile modeled by CBO has a cruise speed of 2,300 miles per hour (Mach 3) and flies at an altitude of 30,000 feet. An example of this class of missile is the Russian Kh-32, which is launched from Tu-22 Backfire bombers. The Kh-32 is primarily an anti-ship missile, however, with a range intended only to keep the bombers that launch it outside a ship's air defenses. Longer range would probably be desired for a LACM designed to attack targets in the mainland United States. A supersonic LACM with a range suitable for attacking the U.S. homeland would be quite large, which could limit the types of launchers from which it could be fired to large military ground vehicles, bomber-sized aircraft, large surface combatant ships, and submarines with large launcher cells.

Generic Components of Cruise Missile Defenses

The illustrative architectures for cruise missile defense of the U.S. homeland that CBO analyzed comprise two categories of components:

- Sensor platforms for initial detection and subsequent tracking of threats, and

- Shooters that would be tasked to destroy those threats.

CBO's quantitative analysis considered five generic types of sensor platform and two generic types of shooter. Combination systems—sensor platforms that also carry weapons for destroying cruise missiles—would also be possible. The systems considered would augment existing ground-based radars and aircraft currently on alert.

CBO did not undertake a detailed analysis of battle management systems for CMD. Current ballistic missile defenses are coordinated by systems that provide command and control, battle management, and communications, and the services are developing new battle management systems—for example, the Air Force's Advanced Battle Management System. A CMD system would probably be integrated with systems such as those.

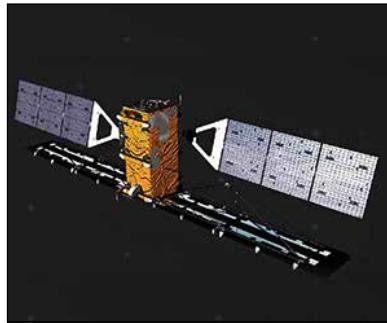
Generic Sensor Platforms. All of the sensor platforms analyzed by CBO would be equipped with radar that has a long range and is relatively insensitive to atmospheric conditions (compared with infrared sensors). The critical performance characteristics for CBO's calculations were platform altitude, which determines area covered, and platform endurance, which determines the number of platforms needed to continuously operate each sensor orbit.

The five platforms considered by CBO were as follows: ground bases located on local high terrain (such as a hilltop) or on towers if there was no high terrain at the coast or border (CBO assumed an elevation of 700 feet above sea level or the surrounding terrain for its calculations); tethered aerostats at 10,000 feet; airborne early-warning and control aircraft based on a commercial airframe flying at 30,000 feet; high-altitude, long-endurance unmanned aerial vehicles flying at 60,000 feet; and a constellation of satellites in a low Earth orbit at an altitude of 575 miles (see Figure 3-3). Many of the ground- or tower-based radars could be ones that are currently operated by the FAA and the Air Force. CBO based its estimate of the area observed by each sensor on the assumption that radar horizon would be the limiting factor and that Earth is smooth.

For all but the satellites, CBO based its estimates for its illustrative sensor platforms on actual systems that have been developed. The generic ground-based and tethered aerostat platforms were based on two Army systems: the trailer-mounted Sentinel radar (if more were needed to

Figure 3-3.

Characteristics of the Generic Sensors in the CMD Architectures That CBO Examined

	Radar on Ground (High local terrain or tower)	Radar on Tethered Aerostat	Radar on Modified Commercial Aircraft
Height:	700 feet	10,000 feet	30,000 feet
Horizon:	60 miles	165 miles	270 miles
Endurance:	Nearly continuous	About 30 days	11 hours
Contemporary			
Example:	U.S. Army Sentinel	U.S. Army JLENS	Royal Australian Air Force E-7
			
	Courtesy of the U.S. Army	Courtesy of the U.S. Army	© Andrew Harker/Shutterstock.com
	Radar on High-Altitude, Long-Endurance UAV	Radar on Satellite in Low Earth Orbit	
Height:	60,000 feet	575 miles	
Horizon:	370 miles	2,500 miles	
Endurance:	30 hours	Nearly continuous	
Contemporary			
Example:	U.S. Navy MQ-4C Triton	Canadian RADARSAT-2	
			
	Courtesy of the U.S. Navy	© Canadian Space Agency	

Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

CMD = cruise missile defense; JLENS = Joint Land-Attack Cruise Missile Defense Elevated Netted Sensor; LACM = land-attack cruise missile; UAV = unmanned aerial vehicle.

fill gaps in current ground-based radar coverage) and the Joint Land-Attack Cruise Missile Defense Elevated Netted Sensor (JLENS) aerostat that was canceled in 2017. CBO based its performance estimates for the AEW&C platform derived from commercial aircraft and the HALE-UAV on the Navy's P-8A Poseidon patrol aircraft and MQ-4C Triton surveillance aircraft, respectively. CBO did not consider Air Force E-3 AWACS

performance because a future fleet of manned AEW&C aircraft would more likely be based on a modern twin-engine jet (the P-8A is a derivative of the Boeing 737) rather than the older, less efficient E-3, which is based on the four-engine Boeing 707. CBO based its illustrative satellite architecture on a constellation of radar satellites in low Earth orbit.

Figure 3-4.

Characteristics of the Generic Shooters in the CMD Architectures That CBO Examined

Long-Range Surface-to-Air Missile (LR-SAM)

- Speed:** 2,700 mph (Mach 3.5)
Range: 200 miles (remote targeting)
Launch Time: 1 minute
Contemporary
Example: U.S. Navy SM-6



Courtesy of the U.S. Navy

Fighter Aircraft

- 700 mph (sustained); 1,000 mph (dash)
 700 miles (sustained); 250 miles (dash)
 5 minutes

U.S. Air Force F-16C



Courtesy of the U.S. Air Force

Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

CMD = cruise missile defense; mph = miles per hour.

In addition to different sensor ranges, differences in mission endurance—from essentially unlimited endurance for ground-based sensors to about 36 hours for a HALE-UAV—would result in the need for different numbers of systems to provide continuous coverage of a given airborne sensor orbit. The need for more than one system per orbit would increase both the acquisition and operation costs of a defensive architecture.

Generic Shooters. CBO considered two generic systems as shooter components for its notional homeland CMD system: a long-range surface-to-air-missile and fighter aircraft (see Figure 3-4). The LR-SAM would be similar to the SM-6 version of the Navy’s Standard missile and have a range of about 200 miles. CBO assumed that the LR-SAM batteries would only include missiles, their launchers, and communications links to the CMD command and control system but not their own radar. The LR-SAMs would be launched when directed by the BMS

and guided to the vicinity of the target by the CMD sensor platforms, at which time onboard seekers would acquire the target and complete the engagement. Today’s SM-6 missiles are typically guided by their ship’s radar. The Navy, however, has successfully experimented with engagements that are initiated by distant sensors. This “off-board” cueing and guidance enables the missiles to take full advantage of how far they can fly.

The generic fighters tasked with the CMD mission would be equipped with active electronically scanned array radars to provide the best chance to quickly locate and attack their targets. The effective range of the generic fighters would usually be dependent on the time available for the fighter to reach its target, not the distance the fighter could fly before needing to refuel. Fighters’ flight paths would be straight to the correct intercept point (an assumption favorable to the defense) at about 700 miles per hour.



Chapter 4: Capability and Cost of Illustrative Architectures for a National Cruise Missile Defense

The sensors, long-range surface-to-air missiles, fighter aircraft, and battle management systems that make up the building blocks of cruise missile defense can be combined into a wide variety of architectures of different extents (for example, from point defenses of individual targets to an area defense of the entire United States) and capacities (for example, single or multiple layers of shooters able to handle raid sizes from a few to many cruise missiles). The United States currently operates point or limited-area air and cruise missile defenses for military forces deployed abroad (including Army surface-to-air missile systems for defending ground forces and naval systems for defending individual ships or surface task forces) as well as a limited air and cruise missile defense system in the National Capital Region.

Today, air defense for the contiguous United States is provided by a network of ground-based radars, and a small number of fighters on air defense alert at several air bases around the country that are available to counter suspected airborne threats. The fighters are intended primarily to intercept unidentified aircraft, aircraft that have strayed from planned flight paths, and aircraft that are not properly communicating with air traffic control. Some are also tasked with intercepting foreign military aircraft approaching the United States—in particular, Russian patrols that routinely fly along the periphery of U.S. airspace. However, the small number of those fighters and the lack of a system of sensors to detect low-flying targets over long ranges limit their effectiveness against cruise missiles.

Constructing a point defense architecture is relatively straightforward if effective sensors and shooters can be arrayed around the location being defended because the cruise missile will eventually have to come to them (see Figure 4-1, top panel). The challenge for planners of area defense architectures is identifying locations for sensors and shooters without advance knowledge of an

attacking cruise missile's planned target or flight path (see Figure 4-1, bottom panel).

In its analysis, CBO examined several illustrative architectures for providing an area defense for the contiguous United States. The notional cruise missile defenses that CBO examined were wide in extent (covering the entire perimeter of the 48 contiguous states) but of limited capacity (eight surface-to-air missiles and two fighter aircraft at a particular time and location). To examine what might be required to field such cruise missile defenses, CBO estimated the effectiveness and cost of illustrative defensive architectures that consist of different combinations of generic component systems and that are designed to defeat the generic subsonic cruise missile described in Chapter 3. (CBO also assessed how those architectures would perform against faster land-attack cruise missiles.) The performance characteristics of the defensive components and cruise missiles are representative of current systems or systems that could be fielded in the near future. CBO did not examine defenses for Alaska, Hawaii, and U.S. territories other than to recognize that providing such defenses would require additional systems at additional cost. Systems for those locations would probably be structured more like point defenses with more-nuanced characteristics than could be considered in this analysis.

To focus on potential costs to the United States, CBO did not include Canada in its illustrative cruise missile defense architectures. If policymakers opted to pursue a nationwide cruise missile defense, it is quite possible that such a defense would also include Canada as part of the North American Aerospace Defense Command. An expansion of CBO's illustrative architectures several hundred miles northward could cover the vast majority of Canada's population with a marginal increase in costs. The two NORAD nations would need to reach an agreement about how to share the costs and missions of such a binational system.

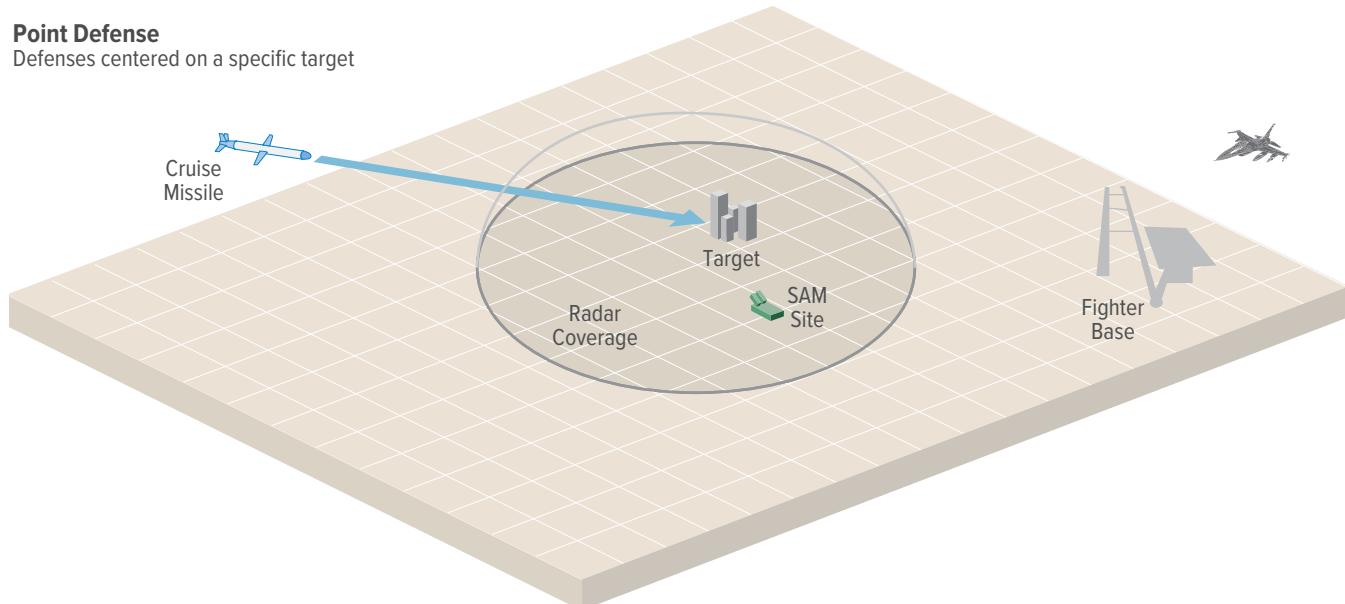


Figure 4-1.

Challenges of Positioning Components of Area Air Defenses

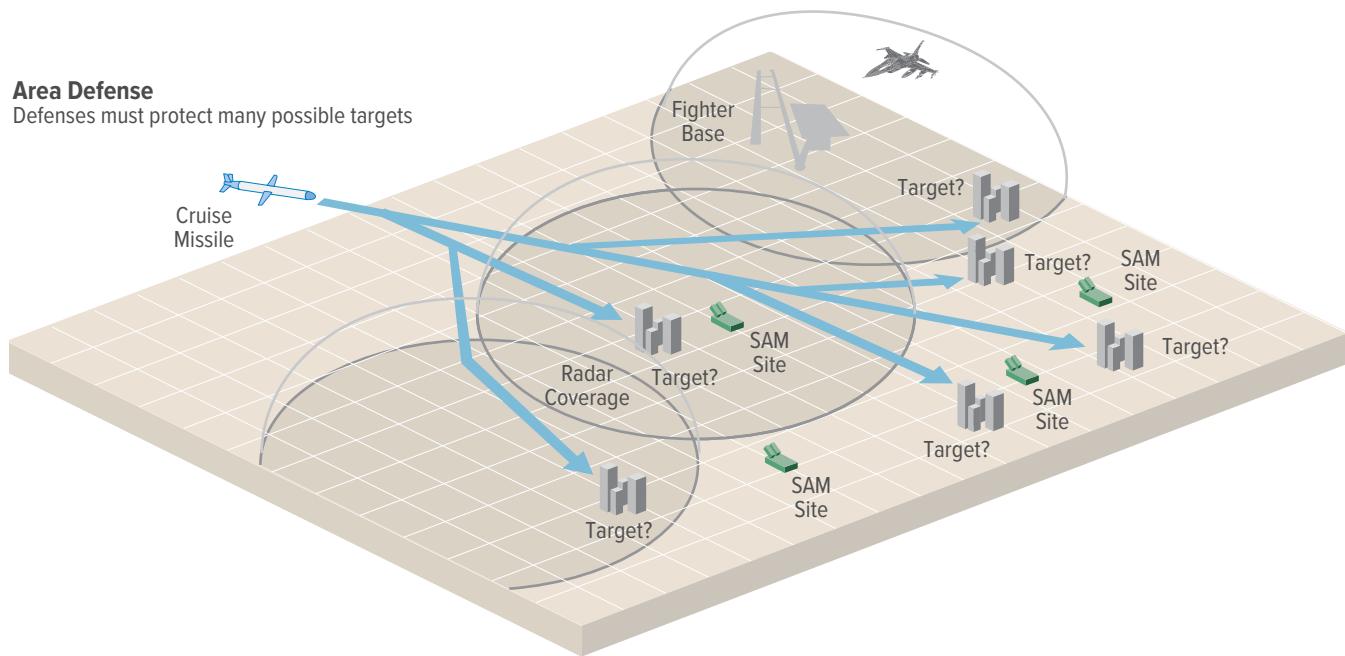
Point Defense

Defenses centered on a specific target



Area Defense

Defenses must protect many possible targets



Data source: Congressional Budget Office.

SAM = surface-to-air missile.

How CBO Constructed Illustrative CMD Architectures

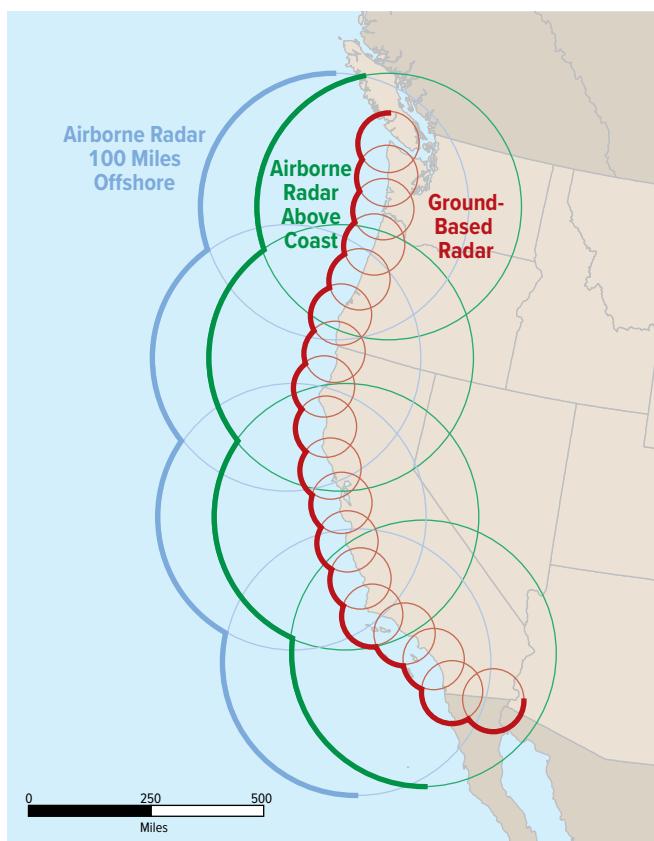
The specific structure of a CMD architecture depends on the level of defense it is expected to provide and the performance characteristics of its component sensors and shooters. Each of the illustrative architectures that CBO examined includes the following components:

- A chain of sensors around the 48 contiguous states that would be capable of detecting cruise missiles approaching U.S. territory from any direction,
- SAM sites and bases with alert fighters to provide a full SAM layer *and* a full fighter layer capable of intercepting cruise missiles approaching U.S. territory from any direction, and



Figure 4-2.

Comparison of Short-Range and Long-Range Radars in Defensive Perimeters Against Low-Altitude Targets



Earlier detection provides more time for shooters to respond.

Data source: Congressional Budget Office.

Detection ranges are for targets flying at an altitude of 300 feet, ground radars at a height of 700 feet (including the elevation of local terrain), and airborne radars at an altitude of 30,000 feet.

- Sufficient numbers of sensor and shooter locations so that, with coordination provided by a responsive battle management system, cruise missiles could be intercepted before they entered U.S. territory.

The locations and numbers of sensors and shooters would depend on their performance characteristics. For example, sensors with longer range would be fewer in number and more widely spaced than sensors with shorter range. And not all combinations would be equally effective. In addition to requiring fewer sites or orbits, radars at higher altitudes look out farther from the coast or border (see Figure 4-2). That provides earlier detection, which gives

more time to employ shooters, potentially reducing the number of shooter sites required. Similarly, faster response times (shorter times to decide to launch an interceptor and faster speed once it is in the air) and longer range would typically reduce the number of shooters needed for a particular architecture.

CBO focused on the outer perimeter of the 48 contiguous states to prevent cruise missiles from reaching the many military bases and cities along the coast. Air traffic control radars operated by the Federal Aviation Administration would include many inland locations that could assist with tracking land-attack cruise missiles bound for inland targets. Such an in-depth defense would be the ideal for countering LACMs: If the outer perimeter was breached, systems behind it could offer additional opportunities to defeat the threat. The short horizon of ground-based radar would limit coverage, however, and only fighters could be used to counter LACMs after they were inland. Although CBO did not consider inland coverage in addition to an outer perimeter, the aircraft- and satellite-borne radars in CBO's illustrative architectures could provide inland sensor coverage—the former on an ad hoc basis and the latter as a matter of course (see below). Additional SAM sites or fighter locations would be needed to defeat any cruise missiles that got through the perimeter on the way to inland targets.

Precise calculations of the performance of air defense systems are extremely complicated. They can involve electromagnetic interactions among transmitters, targets, and receivers, details about terrain and atmospheric conditions, the command and control structure and speed of communications, and tactics employed by the adversary. CBO used simplified calculations and examined illustrative CMD architectures to show the scale of defenses that would be needed. In particular:

- For sensors, detection ranges were based on the radar horizon between the sensor and the target. Elevated sensors and higher-altitude targets would lead to longer detection ranges. Radar systems were assumed to have sufficient power and resolution to detect targets out to their horizon. To prevent an adversary from using a missile flight path equidistant between two radars (where the depth of the sensor coverage would be shallowest), adjacent radars were assumed to be positioned with enough overlap to provide a depth of coverage no less than 80 percent of the individual radars' detection range.
- For shooters, maximum SAM range was based on the maximum distance they can fly and the assumption

that there would be perfect guidance to the intercept point. Fighter ranges were based on perfect guidance to the intercept point at an optimum speed (because flying at higher speeds, particularly supersonic speeds, reduces range).

- For battle management, CBO examined two response times: either 5 minutes or 15 minutes between detection of a LACM and the decision to launch a SAM or scramble fighters. (CBO assumed that battle management for CMD would be performed by systems already in place for ballistic missile defense and air defense.)

Under those performance assumptions, which would generally be favorable to the defender, CBO estimated the numbers of sensors and shooters that would be needed to establish a defensive perimeter around the U.S. homeland. In addition to being based on favorable assumptions about the performance of component systems, the illustrative architectures would have other limitations, and actions taken to address them could result in higher costs. (See the section titled “Limitations of the Primary Architectures” later in this chapter.)

Primary CMD Architectures That CBO Examined and Their Costs

To examine the many different architectures that could be assembled from combinations of sensors, shooters, and battle management systems, CBO organized its analysis into five primary architectures based on the type of sensor platform. To examine the effect of fielding defenses of different extents and capacities, CBO also examined a few variants of those primary architectures.

In this section of the report, CBO first examines the primary architectures it based on airborne sensors—Architecture 1 (with HALE-UAVs), Architecture 2 (with AEW&C aircraft), and Architecture 3 (with aerostats)—in order of increasing cost. A satellite architecture—Architecture 4—would have lower costs than those based on AEW&C aircraft and aerostats but is discussed after the airborne architectures because the technical considerations for satellites differ from those of airborne platforms. A ground-based architecture—Architecture 5—is discussed only briefly because it could not detect LACMs early enough for shooters to intercept them before they reached the coast or border.

The first four architectures employ two common shooters: LR-SAMs and fighters (except in the case of aerostats,

which provide insufficient warning for fighters). The architectures are designed to counter the more common low-altitude, subsonic LACM launched at long range (at least 500 miles from the coast or border) and to provide coverage along the entire perimeter of the contiguous United States.

CBO also considered variants of the primary architectures to examine the effects of scaling back defenses to cover only the East, West, and Gulf coasts, positioning sensor orbits offshore (to increase warning time), increasing capacity by doubling the number of LR-SAM sites, and providing sensors only to warn of an attack. (The variants are presented in Appendix A.)

For the first four architectures, CBO provides estimates of three types of costs, all in 2021 dollars:

- Initial acquisition costs,
- Annual operation and support costs, and
- A 20-year total, consisting of initial acquisition costs, 20 years of annual operation and support costs, and additional acquisition costs that would be incurred if equipment needed to be replaced.

For each type of cost, CBO provides a range of values that reflect different response times for the battle management system and the uncertainty surrounding CBO’s estimates of the costs for the architectures’ component systems. The low end corresponds to a version of the architecture that would provide 5 minutes between detection and shooter employment, and the high end corresponds to a response time of 15 minutes. Because longer response times would result in the need for more LR-SAM sites and locations with fighters on alert, the 5-minute response time is reflected in the lower cost estimate and the 15-minute response time is reflected in the higher cost estimate for the architectures’ component systems. (For a more detailed description of how CBO estimated the costs of its illustrative CMD architectures, see Appendix B.)

Architecture 1: Radar on High-Altitude, Long-Endurance Unmanned Aerial Vehicles

The perimeter of the 48 contiguous states, without considering the intricate details of the coastline, is about 9,300 miles. CBO estimated that 23 HALE-UAV orbits would be needed to cover that perimeter (see Table 4-1). Several aircraft would be needed to fill each orbit to account for transit to and from base and time spent in maintenance. The average number of aircraft needed per

Table 4-1.

Composition and Cost of Illustrative Architectures for a Cruise Missile Defense of the Contiguous United States

	Detection and Tracking Sensors		Shooters		Cost (Billions of 2021 dollars)		
	Number of Locations or Orbits	Number of Systems for Continuous Operation	Number of LR-SAM Sites	Number of Fighter Locations	Initial Acquisition	Annual Operation and Support	20-Year Total
Architecture 1: Detection and Tracking With Radar on HALE-UAVs	23	64	20 to 30	30 to 40	13 to 15	2.7 to 3.5	77 to 98
Architecture 2: Detection and Tracking With Radar on Modified Commercial Aircraft (AEW&C aircraft)	31	124	40 to 50	50 to 90	28 to 36	7.7 to 10.2	187 to 246
Architecture 3: Detection and Tracking With Radar on Aerostats	50	75	60 to 800	n.a.	30 to 86	2.3 to 17.7	98 to 466
Architecture 4: Detection and Tracking With Space-Based Radar	78	78	20	10 to 15	58 to 97	0.7 to 1.1	106 to 179

Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

Values in this table are based on a defensive perimeter around the 48 contiguous states that would be designed to protect against cruise missiles flying at a low altitude (300 feet) and at a subsonic speed (500 miles per hour).

The ranges of values for quantities and costs include the effect of response time—that is, the time that elapses between the detection of a cruise missile and the order to employ a shooter. Low values correspond to 5 minutes between detection and shooter employment. High values correspond to 15 minutes. The ranges of values for costs also include the uncertainty that surrounds the cost estimates for the architectures' component systems.

Twenty-year totals include additional acquisition costs that may be incurred if equipment wears out or is lost to accidents and needs to be replaced.

AEW&C = airborne early-warning and control; HALE-UAV = high-altitude, long-endurance unmanned aerial vehicle; LR-SAM = long-range surface-to-air missile; n.a. = not applicable.

orbit for continuous operations would be fairly low for the HALE-UAV because of its long endurance; CBO estimated that a total of 64 aircraft would be needed (including aircraft in various stages of maintenance) to provide continuous coverage—an average of 2.8 aircraft per orbit. (If an attack was detected, it might be possible to use sensor aircraft that are ready to fly but not on-station to provide additional perimeter coverage or inland coverage.)

With its roughly 370-mile detection range at 60,000 feet, the HALE-UAV would provide up to 44 minutes of warning before a generic subsonic LACM would reach the coast. For the SAM defensive layer, meeting that timeline would require 20 LR-SAM sites for a 5-minute reaction time by the battle management system, or 30 sites for a 15-minute reaction time. Fighters on alert at 30 to 40 locations around the country would be needed to provide a fighter layer. The relatively compact LR-SAM sites could be located on federal lands around the perimeter of the country. Alert fighters could be provided from

the home bases of Air Force, Navy, and Marine Corps squadrons. Although many bases currently hosting fighter squadrons are located near the southern border or coasts, there are few fighter bases along the U.S. northern border (see Figure 4-3). It may be necessary, therefore, to establish detachments of alert aircraft at additional airfields.¹

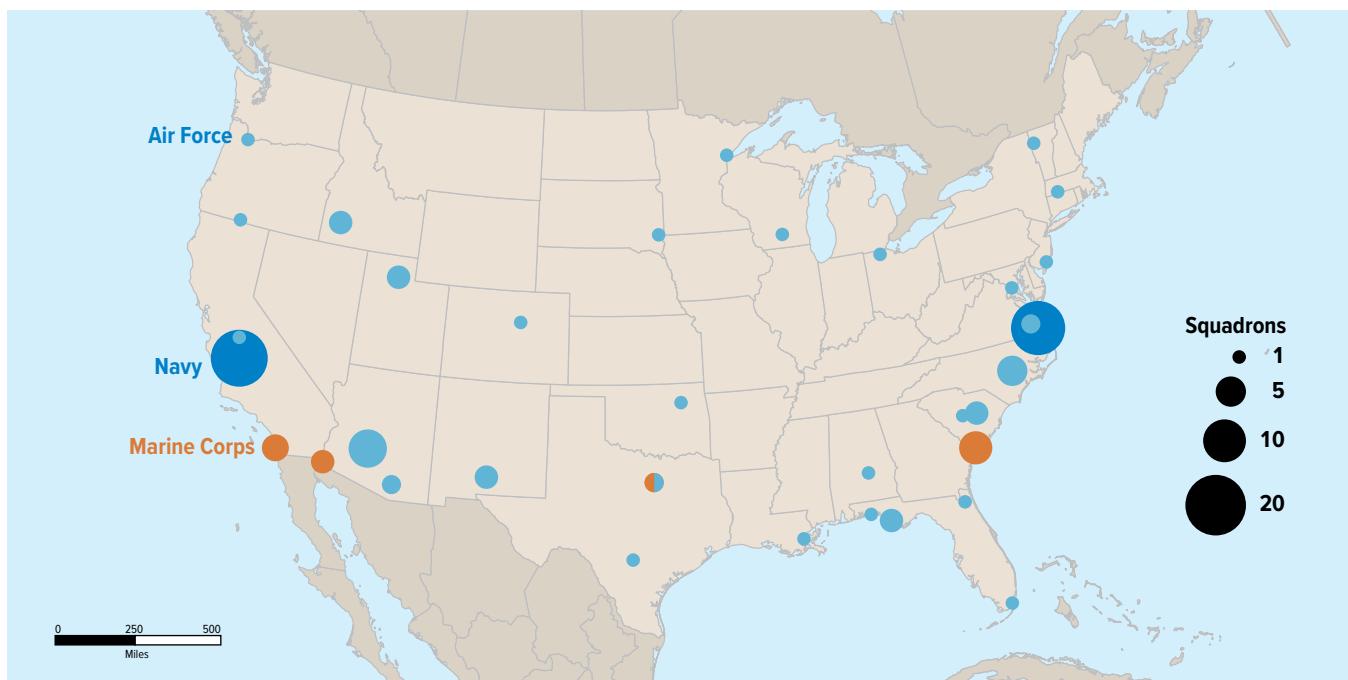
CBO estimated that the cost to maintain alert aircraft would be similar to the costs of the alert aircraft locations currently operated by the Air National Guard (see Appendix B). Costs could be higher if it was necessary to purchase new fighter aircraft and dedicate them to the mission.

The sensors and shooters under Architecture 1 would cost \$13 billion to \$15 billion (in 2021 dollars) to acquire and \$2.7 billion to \$3.5 billion per year to operate, CBO

1. If CBO's illustrative CMD architectures were expanded to include Canada, Royal Canadian Air Force units could also contribute to fighter coverage to the north.

Figure 4-3.

Locations of Military Bases Hosting Squadrons Equipped With Fighter Aircraft



Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

estimates. Total costs to acquire the systems and operate them for 20 years would be \$77 billion to \$98 billion. That amount includes funding to replace equipment when it wears out or is lost to mishaps. Because it is unlikely that a HALE-UAV aircraft could last 20 years at the high usage rate envisioned for the CMD mission, CBO's 20-year costs include a full replacement of the fleet.

Architecture 2: Radar on Modified Commercial Aircraft

CBO estimated that 31 orbits of airborne early-warning and control aircraft at 30,000 feet would be needed to cover the perimeter of the contiguous United States. The average number of aircraft per orbit is higher than for the HALE-UAV because of the shorter endurance of the AEW&C aircraft. CBO estimated that 124 aircraft would be needed to fill each of those orbits continuously, an average of 4 aircraft per orbit.

With its roughly 270-mile detection range at 30,000 feet, the AEW&C aircraft would provide about 30 minutes of warning before a generic subsonic LACM could reach the coast. For the SAM defensive layer, meeting that timeline would require 40 LR-SAM sites for a 5-minute

battle-management-system reaction time or 50 sites for a 15-minute reaction time. Fighters on alert at 50 to 90 locations around the country would be needed to provide a fighter layer. The larger number of fighter locations needed under Architecture 2 could not be provided from locations where fighters are currently based; alert aircraft would have to be positioned at additional bases to provide full fighter coverage under Architecture 2.

The sensors and shooters under Architecture 2 would cost \$28 billion to \$36 billion (in 2021 dollars) to acquire and \$7.7 billion to \$10.2 billion per year to operate, CBO estimates. Total costs to acquire the systems and operate them for 20 years would be \$187 billion to \$246 billion. That amount includes funding to replace a small number of aircraft that might be lost to mishaps, but not a full replacement of the fleet as with Architecture 1. The life of a commercial aircraft is usually limited by the number of pressure cycles—the number of times it is taken to cruising altitude—that it can endure before metal fatigue makes its fuselage unsafe. Although aircraft like the Boeing 737, upon which an AEW&C aircraft for CMD might be based, have long range, the airline industry also uses them for short flights. As a result, they are designed

to last many cycles (about 75,000 for the 737). Because missions would be long and the accrual of cycles therefore slow for aircraft acting as platforms for CMD sensors, the AEW&C aircraft under Architecture 2 would probably last well beyond 20 years.

Architecture 3: Radar on Aerostats

CBO estimated that 50 aerostat locations would be needed to cover the perimeter of the contiguous United States. The number of aerostat orbits is higher than AEW&C orbits under Architecture 2 because the system's lower altitude limits it to a shorter detection range, but the number of systems per orbit is much lower because aerostats are expected to remain aloft for up to 30 days. CBO estimated that one system undergoing maintenance for every two sites would be needed, which would result in a total of 75 aerostats (an average of 1.5 aerostats per site).

With its roughly 165-mile detection range at 10,000 feet, the aerostats would provide at most 18 minutes of warning before a generic subsonic LACM would reach the coast. That short warning time would be insufficient to provide a defensive layer of fighter aircraft, which could render Architecture 3 ineffective if rules of engagement required visual identification of targets. Supporting a SAM defensive layer would be challenging, as well: Meeting that timeline would require 60 LR-SAM sites for a 5-minute BMS reaction time or 800 sites for a 15-minute reaction time. In the latter case, the LR-SAM sites would virtually be acting like a string of point defenses spaced about 12 miles apart around the entire country. With such a short distance between sites, shorter-range (and therefore less expensive) SAMs could be purchased instead of LR-SAMs if it was determined that a reaction time of about 15 minutes was the best that could be achieved. However, costs would still be much higher than the costs for the other architectures because of the large number of sites that would be needed.

The aerostats and LR-SAMs under Architecture 3 would cost \$30 billion to \$86 billion (in 2021 dollars) to acquire and \$2.3 billion to \$17.7 billion per year to operate. Total costs to acquire the systems and operate them for 20 years would be \$98 billion to \$466 billion, including one full replacement of aerostats over that period. The large spread in estimated costs would result because of the large difference in the number of LR-SAM sites for

the two BMS response times.² The inability to support a fighter layer and the extremely high cost under all but very optimistic assumptions about BMS reaction times suggest that Architecture 3 would not be practical for the defense of wide areas. Aerostats are better suited to support point defenses or the defense of small areas because the ability to concentrate shooters in a smaller area reduces the need for long warning times.

Architecture 4: Radar on Satellites

The illustrative satellite architecture examined by CBO is based on a low-Earth-orbit constellation proposed for the global tracking of airborne targets.³ The constellation would consist of 78 satellites in orbits at an altitude of 575 miles and inclined 89 degrees from the equator. The orbital configuration could provide coverage around the globe.

With its global coverage, the constellation of radar satellites would be able to detect LACMs almost at the time they were launched. As a result, the warning time would depend on how far from the border an adversary chose to launch its LACMs, not on the range of a specific radar. For example, the satellite constellation under Architecture 4 could provide a 60-minute warning against the generic subsonic LACM launched 500 miles from the coast or border. A HALE-UAV, on the other hand, could only provide a 44-minute warning because the LACM would have flown about 130 miles before coming within the HALE-UAV's radar horizon. With such long warning times, the number of LR-SAMs needed in Architecture 4 would be determined by their range, not the BMS response time as in the other architectures. The SAM layer under Architecture 4 would require 20 LR-SAM sites for both a 5-minute BMS reaction time and a 15-minute reaction time, CBO estimates. Fighters on alert at 10 to 15 locations around the country would be needed to provide a fighter layer.

Acquisition costs to field Architecture 4 would be \$58 billion to \$97 billion (in 2021 dollars) for the 78 radar

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2. Costs for the slower BMS response time would be about \$15 billion less if a shorter-range missile (in this example, a ground-launched version of the AIM-120 air-to-air missile) was purchased instead of LR-SAMs and other equipment at the SAM sites was unchanged. The resulting cost—\$451 billion over 20 years—would still be much higher than the costs for the other architectures that CBO examined.
 3. See M.V. Tollefson and B.K. Preiss, "Space Based Radar Constellation Optimization," vol. 3, *1998 IEEE Aerospace Conference Proceedings* (IEEE, 1998), pp. 379–388.

satellites and 20 LR-SAM sites, and \$700 million to \$1.1 billion per year to operate them (and the fighters). Total costs to acquire those systems and operate them for 20 years would be \$106 billion to \$179 billion, including one full replacement of the satellite constellation over that period because satellites in low Earth orbit typically last no more than 10 years. Because the number of shooters would be the same for both BMS response times, the range in costs for Architecture 4 results primarily from uncertainty surrounding the cost to develop and field an entirely new space system. The low end of the 20-year costs is comparable to the high end of costs for Architecture 1. The satellite-based architecture would require substantially more funding for acquisition (particularly during initial fielding) but substantially less funding for operation and support.

Because the satellites in Architecture 4 could provide coverage around the globe, they would have many more uses than simply detecting aircraft or LACMs around the border of the contiguous United States. In addition to providing coverage of the interior regions of the United States, Hawaii, Alaska, and the U.S. territories, they could potentially monitor air traffic over the rest of the world. However, power limitations on board the satellites under Architecture 4 might preclude operations over all parts of the globe. As a result, although the satellites would have access all around Earth, operators might have to prioritize particular regions for observation, depending on needs at the time. (Satellites could be designed to operate nearly continuously but at a higher cost.)

Despite this limitation, the capability could be a valuable supplement to (or replacement for) other military systems such as today's AWACS aircraft. Indeed, the capabilities of CBO's notional satellite constellation might have similarities to the custody layer constellation that has been proposed by the Space Development Agency to support worldwide military operations. Satellites orbiting Earth might be more vulnerable to attack by technologically advanced adversaries than HALE-UAVs operating close to the United States, however.

Architecture 5: Ground-Based Radar

CBO estimated that 150 ground-based radars operating at an average of 700 feet above their surroundings (either on local high terrain or towers) would be needed to detect low-altitude LACMs approaching the United States. About 50 radar stations are currently situated at or near the perimeter of the country, so roughly 100 additional

ground-based radars would be needed. However, because ground-based radar could not provide enough warning to employ shooters under CBO's assumptions about BMS response times, CBO did not examine this architecture. Against low-altitude LACMs, ground-based radars are most effective when positioned at or very close to the LACM's target and when the rules of engagement allow for nearly immediate employment of SAMs.

Limitations of the Primary Architectures

Although CBO's illustrative Architectures 1 through 4 would provide CMD coverage of the contiguous United States, they would have limitations. First, some of CBO's calculations of system performance are based on best-case assumptions. For example, radar detection ranges might be less than the distance to the horizon if the architectures' radars had difficulty distinguishing low-altitude or stealthy LACMs from ground clutter (radar reflections from the surface). Second, imperfect tracking information would decrease the effective reach of SAMs and fighters because they would not fly the shortest route to their target. The range of results for each architecture should account somewhat for such uncertainties. Finally, other factors, including limited shooter capacity, the need for positive identification of targets, and measures that adversaries could take that would decrease the effectiveness of the system—such as programming LACMs to fly indirect routes, launching LACMs close to the border or coast, or using faster LACMs—are worthy of consideration by policymakers weighing the merits of fielding a national CMD system. Addressing those limitations would increase costs.

Limited Capacity of Shooters

The primary architectures examined by CBO include eight LR-SAM missiles per site and one or two fighter aircraft on alert at each fighter location. Each LR-SAM site could potentially engage eight LACMs, but commanders might opt to dedicate at least two LR-SAMs per target to increase the chances of a successful intercept. At two shots per LACM, the systems used under CBO's architectures would have the capacity to engage the four LACMs from a single Club-K launcher disguised as a shipping container. Adversaries other than nonstate groups would probably have access to more missiles and might be able to overwhelm CBO's notional defenses. Of course, capacity could be increased by placing more LR-SAMs at each site. For large raids, the defense's limiting factor might be the ability of the battle management system to direct SAMs and fighters against multiple targets.

Fighters also would have limited capacity. Although fighters can carry several air-to-air missiles, the short times they would have to respond to a LACM attack would probably limit each fighter to one LACM unless the inbound threats were flying close together (a circumstance an adversary could easily avoid).

The Need to Positively Identify Targets

As described in Chapter 3, the need to confirm that a target is indeed a LACM and not a stray aircraft is a serious challenge for cruise missile defenses, particularly during peacetime. (The January 8, 2020, downing of a Ukrainian airliner by Iranian air defenses illustrates the need for positive identification.) Requirements for positive identification could slow response times or even preclude the use of SAMs, which would significantly reduce the capacity of CBO's illustrative CMD architectures. To mitigate this limitation, it might be possible to equip SAMs with imaging seekers that could automatically assess whether a target is a LACM or an aircraft, enabling the SAM to veer off and self-destruct if it was the latter. That capability would come at increased cost and still might not be reliable enough for policymakers to permit its use under any but wartime conditions.

In some circumstances, the behavior of the target might be sufficient to classify it as a threat. For example, it would be highly unusual for a business jet to be flying 500 miles per hour at 300 feet above the surface. Rules of engagement could be established to permit the use of SAMs without positive identification under such conditions. Such an approach might still be deemed too risky, particularly near large coastal airports where aircraft capable of high speeds operate close to the ground. (The Ukrainian airliner that was shot down by Iran in 2020 was departing the airport in Tehran.) An adversary might even try to confuse the defense by using an altitude and route similar to those of commercial air traffic and equipping its LACMs with transponders carried by commercial aircraft to further disrupt defensive action.

Indirect Routes for Threat LACMs

The engagement calculations underlying CBO's analysis reflect the assumption that threat LACMs would not change direction after SAMs were launched or fighters were scrambled to intercept them. If LACMs were programmed to change direction as they approached U.S. territory, SAMs launched against them might not have enough range to complete an intercept, and there might not be enough time to launch additional SAMs from a

different site. As a result, effective SAM coverage could be reduced. Fighter intercepts would also be affected, although fighters would potentially have the ability to counter LACM course changes by accelerating to a higher speed.

LACM Launches Close to the Coast or Border

The engagement calculations underlying CBO's analysis reflect the assumption that threat LACMs would be launched at least 500 miles from the coast or border, ensuring that the CMD sensors (except for satellites) could take advantage of their full detection ranges. If an adversary opted to launch its LACMs closer in, however, warning times could be shorter and the ability to employ shooters reduced or eliminated (see Figure 4-4). For example, if the generic subsonic LACM that CBO examined (which flies at 300 feet altitude and 500 miles per hour) was launched from 300 miles, the warning time offered by radar on a HALE-UAV platform (Architecture 1) would be reduced by 12 minutes (or about 20 percent) and the warning time offered by radar on a satellite (Architecture 4) would be reduced by 24 minutes (or about 40 percent). The defense would lose the ability to employ shooters as launches got closer to the coast or border and flight times shortened to the point where they were similar to BMS response times. Of course, positioning LACM launchers (probably trucks or ships) closer to the border or coast would increase the chance of their being detected and seized or destroyed before their cruise missiles could be launched.

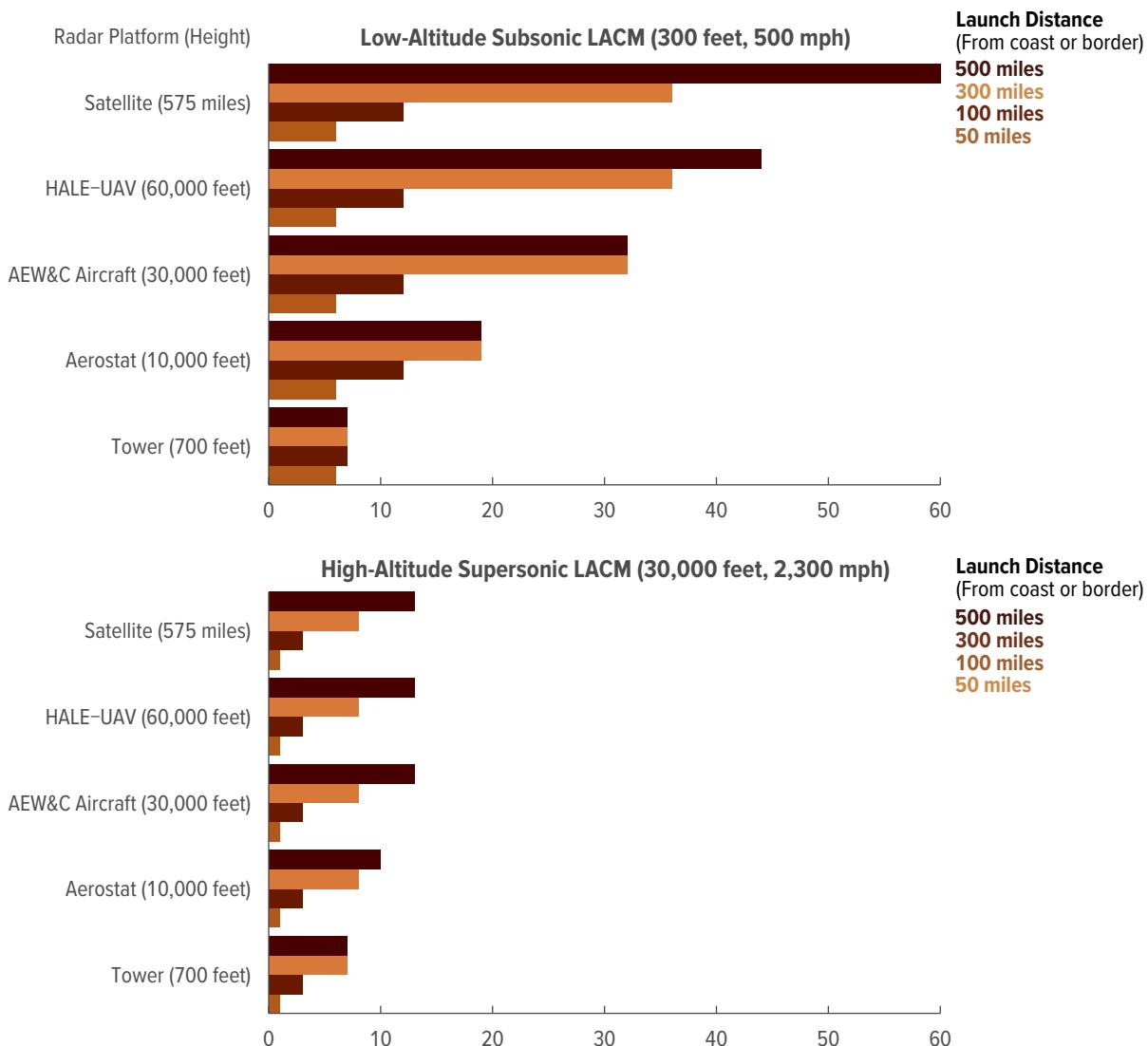
Supersonic LACMs

All else being equal, the higher speed of long-range, supersonic LACMs tends to reduce warning times for CMD systems relative to slower missiles. That reduction can be offset to some degree by the need for those missiles to avoid air resistance by flying at much higher altitudes, which increases the range at which they can be detected. Under most of the conditions relevant to CMD, however, the effect of higher speed is greater than the effect of higher altitude, so supersonic missiles would decrease warning time substantially. For example, a comparison of the two panels of Figure 4-4 shows that the warning time possible with radars on HALE-UAVs (Architecture 1) for LACMs launched at least 500 miles from the coast or border would be 44 minutes against the generic subsonic LACM that CBO examined (which travels at 500 miles per hour) but only 13 minutes against the generic supersonic LACM (which travels at 2,300 miles per hour).

Figure 4-4.

Warning Time Versus Distance From Which LACMs Are Launched

Warning Time in Minutes

Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

AEW&C = airborne early-warning and control; HALE-UAV = high-altitude, long-endurance unmanned aerial vehicle; LACM = land-attack cruise missile; mph = miles per hour.

China and Russia are developing even faster missiles—ones that fly at Mach 5 or faster. Such hypersonic missiles could not be defeated by the illustrative architectures examined in this study. The Missile Defense Agency has been tasked with developing defenses against this type of missile. The satellites under Architecture 4 might provide warning, but faster and more agile SAMs and more SAM sites would be needed. (DoD has indicated, however, that

the SM-6—the missile upon which the notional LR-SAM is based—might have some capability against hypersonic missiles.) Improved air-to-air missiles for use by the fighter aircraft would probably be needed as well, but unless a hypersonic missile was launched and detected very far from the U.S. border or coasts, fighters could not reach them in time.

Appendix A: Variants of CBO's Illustrative CMD Architectures

The Congressional Budget Office constructed four primary defensive architectures to illustrate the implications of fielding a cruise missile defense (CMD) system capable of protecting the contiguous United States. Each of those architectures includes the following components:

- A chain of radars around the 48 contiguous states that would be capable of detecting cruise missiles approaching U.S. territory from any direction,
- Surface-to-air missile (SAM) sites and bases with alert fighters that would provide a full SAM layer *and* a full fighter layer capable of intercepting cruise missiles approaching U.S. territory from any direction, and
- Sufficient numbers of sensors, SAM sites, and fighter locations so that cruise missiles could be intercepted before they entered U.S. territory.

The four architectures are distinguished by the type of platform that would carry their radar sensors:

Architecture 1 would use high-altitude, long-endurance unmanned aerial vehicles (HALE-UAVs); Architecture 2 would rely on manned airborne early-warning and control (AEW&C) aircraft based on a commercial jetliner; Architecture 3 would use tethered aerostats; and Architecture 4 would use satellites in low-earth orbit.¹ (For additional information about the four primary architectures, see Table 4-1 on page 37.)

In general, defenses can be characterized by their *extent* (the area defended) and their *capacity* (the number of threats that could be countered). The primary CMD architectures that CBO examined were wide in extent (covering the perimeter of the 48 contiguous states) but of limited capacity (eight SAMS and two fighters at a particular time and location). However, policymakers could opt to pursue different architectures tailored to different assumptions about threats or in an effort to reduce costs. CBO examined several such possibilities.

1. Low-Earth-orbit altitudes are roughly defined to be more than 100 miles but less than 1,200 miles above Earth's surface.

Variant A: Defense of Ocean Borders Only

Policymakers might determine that attacks by land-attack cruise missiles (LACMs) through Canada or Mexico would be too unlikely to warrant defending the entire perimeter of the contiguous United States. In that case, defending the East, West, and Gulf coasts (with extensions to the north and south to detect attempts to route LACMs around the ends of coastal sensor fences) would be a lower-cost option than defending the full perimeter. CBO estimated that Atlantic and Pacific sensor lines would total roughly 6,000 miles, about two-thirds of the roughly 9,300-mile perimeter defended in CBO's primary architectures. Quantities of equipment and costs would be correspondingly smaller for all of the architectures (see Table A-1 and see Table A-2). The decrease would be smallest for Architecture 4 because the same number of satellites would be needed in orbit; only the number of LR-SAM sites and fighter bases would decrease.

Variant B: Forward-Positioned Orbits for Airborne Sensors

Positioning airborne orbits out from the coasts and borders (assuming Canada and Mexico would permit operations in their airspace) could increase warning times by enabling earlier detection of LACMs launched from a long range. The greater perimeter length would increase the number of sensor orbits and, possibly, the number of aircraft per orbit because transit time between the orbit and the aircraft bases would be longer. However, the increased warning time could reduce the number of shooters needed, possibly resulting in a lower-cost architecture. CBO examined variations of Architecture 1 and Architecture 2 that would have sensor orbits located 100 miles out from the coasts and borders instead of right over the coasts and borders as in the primary architectures.

For both architectures, estimated 20-year costs are lower than those for the primary architectures—assuming a



Table A-1.

Composition and Cost of Variants of CBO's Illustrative Architectures for a Homeland Cruise Missile Defense

	Detection and Tracking Sensors		Shooters		Cost (Billions of 2021 dollars)		
	Number of Locations or Orbit	Number of Systems for Continuous Operation	Number of LR-SAM Sites	Number of Fighter Locations	Initial Acquisition	Annual Operation and Support	20-Year Total
Variant A: Defense of Ocean Borders Only							
Architecture 1A: Detection and Tracking With Radar on HALE-UAVs	13	36	15 to 20	20 to 25	9 to 10	1.5 to 2.0	45 to 57
Architecture 2A: Detection and Tracking With Radar on Modified Commercial Aircraft (AEW&C aircraft)	19	76	25 to 35	30 to 60	18 to 23	4.7 to 6.4	115 to 155
Architecture 3A: Detection and Tracking With Radar on Aerostats	30	45	40 to 500	n.a.	19 to 54	1.4 to 11.0	61 to 290
Architecture 4A: Detection and Tracking With Space-Based Radar	78	78	15	7 to 10	58 to 97	0.6 to 0.9	103 to 175
Variant B: Forward-Positioned Orbits for Airborne Sensors							
Architecture 1B: Detection and Tracking With Radar on HALE-UAVs	24	66	20	10 to 15	13 to 15	2.7 to 3.2	78 to 92
Architecture 2B: Detection and Tracking With AEW&C Aircraft	33	132	20	20 to 25	28 to 35	7.6 to 9.5	185 to 232
Variant C: More LR-SAMs							
Architecture 1C: Detection and Tracking with Radar on HALE-UAVs	23	64	20 to 30	30 to 40	14 to 17	2.8 to 3.7	80 to 103
Architecture 2C: Detection and Tracking With AEW&C Aircraft	31	124	40 to 50	50 to 90	30 to 38	7.9 to 10.5	192 to 254
Architecture 3C: Detection and Tracking With Radar on Aerostats	50	75	60 to 800	n.a.	32 to 121	2.5 to 21.7	105 to 581
Architecture 4C: Detection and Tracking With Space-Based Radar	78	78	20	10 to 15	59 to 98	0.8 to 1.2	109 to 182
Variant D: Warning Only							
Architecture 1D: Detection and Tracking With Radar on HALE-UAVs	23	64	0	0	11 to 13	2.2 to 2.7	66 to 80
Architecture 2D: Detection and Tracking With Aircraft	31	124	0	0	25 to 32	6.8 to 8.5	166 to 208
Architecture 3D: Detection and Tracking With Radar on Aerostats	50	75	0	0	26 to 29	1.4 to 1.7	76 to 90
Architecture 4D: Detection and Tracking With Space-Based Radar	78	78	0	0	57 to 95	0.4 to 0.6	98 to 168

Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

Values in this table are based on a defensive perimeter around the 48 contiguous states that would be designed to protect against cruise missiles flying at a low altitude (300 feet) and at a subsonic speed (500 miles per hour).

The ranges of values for quantities and costs include the effect of response time—that is, the time that elapses between the detection of a cruise missile and the order to employ a shooter. Low values correspond to 5 minutes between detection and shooter employment. High values correspond to 15 minutes. The ranges of values for costs also include the uncertainty that surrounds the cost estimates for the architectures' component systems.

Twenty-year totals include additional acquisition costs that might be incurred if equipment wears out or is lost to accidents and needs to be replaced.

AEW&C = airborne early-warning and control; HALE-UAV = high-altitude, long-endurance unmanned aerial vehicle; LR-SAM = long-range surface-to-air missile.

Table A-2.

Change in the Cost of Variants of CBO's Illustrative Architectures for a Homeland Cruise Missile Defense Relative to the Primary Architectures

Billions of 2021 Dollars

	Lower Cost Estimate (Reflecting faster BMS response time)			Higher Cost Estimate (Reflecting slower BMS response time)		
	Initial Acquisition	Annual Operation and Support	20-Year Total	Initial Acquisition	Annual Operation and Support	20-Year Total
Variant A: Defense of Ocean Borders Only						
Architecture 1A: Detection and Tracking With Radar on HALE-UAVs	-4	-1.2	-32	-5	-1.5	-41
Architecture 2A: Detection and Tracking With Radar on Modified Commercial Aircraft (AEW&C aircraft)	-10	-3.0	-72	-12	-3.8	-91
Architecture 3A: Detection and Tracking With Radar on Aerostats	-10	-0.9	-37	-32	-6.7	-176
Architecture 4A: Detection and Tracking With Space-Based Radar	*	-0.1	-2	*	-0.2	-4
Variant B: Forward-Positioned Orbits for Airborne Sensors						
Architecture 1B: Detection and Tracking With Radar on HALE-UAVs	*	**	1	*	-0.3	-6
Architecture 2B: Detection and Tracking With AEW&C Aircraft	*	-0.1	-2	*	-0.7	-14
Variant C: More LR-SAMs						
Architecture 1C: Detection and Tracking With Radar on HALE-UAVs	*	0.1	3	1	0.2	5
Architecture 2C: Detection and Tracking With AEW&C Aircraft	2	0.2	6	2	0.3	8
Architecture 3C: Detection and Tracking With Radar on Aerostats	3	0.2	7	35	4.0	115
Architecture 4C: Detection and Tracking With Space-Based Radar	*	0.1	3	*	0.1	3
Variant D: Warning Only						
Architecture 1D: Detection and Tracking With Radar on HALE-UAVs	-1	-0.5	-11	-2	-0.8	-18
Architecture 2D: Detection and Tracking With Aircraft	-3	-0.9	-21	-4	-1.7	-38
Architecture 3D: Detection and Tracking With Radar on Aerostats	-4	-0.9	-22	-56	-16.0	-376
Architecture 4D: Detection and Tracking With Space-Based Radar	-1	-0.3	-7	-1	-0.5	-11

Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

Twenty-year totals include additional acquisition costs that might be incurred if equipment wears out or is lost to accidents and needs to be replaced.

AEW&C = airborne early-warning and control; BMS = battle management system; HALE-UAV = high-altitude, long-endurance unmanned aerial vehicle; LR-SAM = long-range surface-to-air missile; * = change of less than \$1 billion; ** = change of less than \$0.1 billion.

slower battle management system (BMS) response time. (Those are the high end of the cost ranges shown.) In those cases, the cost of additional sensor orbits is more than offset by reductions in the number of long-range surface-to-air missile (LR-SAM) sites and fighter aircraft locations. That is also the case for Architecture 2B with the faster BMS response times (that is, the lower cost amounts), although the reduction is smaller. For Architecture 1B, however, the number of LR-SAMs could not be reduced by moving sensor orbits out from the coasts and borders because coverage would be limited not by warning time but by the range of the LR-SAM. As a result, the estimated 20-year costs of Architecture 1B are slightly larger than those for the primary architecture.

If Canada opted to participate in the fielding of cruise missile defenses as part of the North American Aerospace Defense Command, CBO's illustrative CMD architectures could be expanded northward, which might require a small number of additional sensor orbits and SAM sites, and the Royal Canadian Air Force could contribute to fighter coverage. The number of satellites would not be affected. CBO did not examine such an expanded architecture, however.

Variant C: More LR-SAMs

If raids consisting of more than a small number of LACMs were a concern, the capacity of CMD architectures could be increased by increasing the number of LR-SAMs at each site. CBO found that doubling the number of LR-SAMs at each site (from 8 to 16) would increase the 20-year cost of Architecture 1 by about \$3 billion to \$5 billion and Architecture 2 by about \$6 billion to \$8 billion. The increase would be much larger for the slower-response-time version of Architecture 3 because that architecture includes many more LR-SAM sites. Conversely, the increase for

Architecture 4 would be smaller because fewer LR-SAM sites would need additional missiles.

Variant D: Warning Only

Policymakers might opt to pursue less extensive CMD architectures to handle specific threats rather than providing a comprehensive nationwide defense. One possibility could be a “warning only” system of CMD sensors to hedge against a sudden attack against critical leadership and strategic communications and weapon sites that make up the U.S. nuclear deterrent. Satellites with infrared sensors are expected to give U.S. nuclear deterrent forces about 30 minutes to respond to an intercontinental ballistic missile attack from Russia or China. Leaders could be moved to secure locations, bombers could be launched from their bases, and other military forces could be prepared to respond. A precursor attack by low-flying LACMs fired from just off the U.S. coast might be able to destroy those assets with little or no warning.

A system of CMD sensors—possibly coupled with point defenses for critical targets such as the defenses currently deployed in the National Capital Region—could be fielded to warn of such an attack. CBO found that warning-only CMD systems based on HALE-UAV, AEW&C aircraft, or satellite-borne sensors would cost \$7 billion to \$38 billion less than CBO's primary architectures over 20 years. A warning-only system based on aerostat-borne sensors (Architecture 3D) would provide much greater savings than the slower-response-time version of CBO's primary aerostat-based architecture (Architecture 3) because the primary architecture would include a very large number of SAM sites. Aerostats would provide much shorter warning times than the higher-altitude sensors, however, and would probably not be suitable for a warning-only defense.



Appendix B: How CBO Developed Its Cost Estimates

For this report, the Congressional Budget Office used several methods to estimate the acquisition costs and operation and support (O&S) costs for the component systems of its illustrative cruise missile defense (CMD) architectures. Those component systems include sensors (and the platforms that carry them) to detect cruise missiles and shooters to destroy them.

Costs for Airborne Sensor Orbits: Architectures 1 Through 3

The costs for the three airborne sensor platforms examined in CBO's illustrative architectures are based on Selected Acquisition Reports (SARs) and budget justification materials prepared by the Department of Defense (DoD) for similar systems. Two of those platforms—the high-altitude, long-endurance unmanned aerial vehicle (HALE-UAV) and the airborne early-warning and control (AEW&C) derivative of a commercial aircraft—were based on systems that are in service today. The tethered aerostat was based on a system for which prototypes have been manufactured and tested. CBO used actual or estimated O&S costs of those systems for its notional platforms. To adapt those systems to the CMD mission, CBO's estimates of initial acquisition costs included \$3 billion for research, development, test, and evaluation (RDT&E).

Architecture 1

Acquisition costs for the HALE-UAV in Architecture 1 are based on the Navy's MQ-4C Triton unmanned surveillance aircraft. The MQ-4C is a modified version of the Air Force's RQ-4B Global Hawk. The Navy had purchased 14 MQ-4Cs through 2020 and expects to acquire 51 more by the mid-2030s.

It is difficult to estimate how the cost of a HALE-UAV with systems designed for tracking airborne targets might differ from today's MQ-4C and RQ-4B, which are primarily intended to track targets on the surface. To reflect that uncertainty, CBO's estimate for the notional HALE-UAV incorporates a range of costs. The low end of the

range is the approximate cost of the current MQ-4C. For the high end of the cost range, CBO added an estimate of the difference in cost between the standard MQ-4C's mission systems and the more expensive mission systems found on the E-2D Hawkeye (a carrier-based AEW&C aircraft).

About half of the 20-year acquisition costs for HALE-UAVs under Architecture 1 would be for the initial set of aircraft (including funding for RDT&E) and the other half would replace aircraft that wear out or are lost in accidents (see Table B-1). CBO also based its estimate of annual O&S costs for the HALE-UAV orbits on estimates reported in the Triton SAR with adjustments for the operational pace of the CMD mission.

Architecture 2

CBO based its cost estimates for a notional AEW&C derivative of a commercial aircraft in Architecture 2 on the Navy's P-8A Poseidon (a land-based maritime patrol aircraft that is a modified Boeing 737). The Navy completed purchases of 120 P-8As in 2020, and final delivery is expected in October 2023. As with the HALE-UAV, CBO based its low estimate of acquisition costs for the notional AEW&C aircraft on the current cost of the P-8A and its high estimate on the cost of the P-8A's airframe plus the cost of the radar system on the E-2D.

Replacement acquisition costs are low relative to initial acquisition costs because the aircraft should last 20 years, and the high reliability of the 737 should result in few losses stemming from accidents. O&S costs were based on estimates in the SAR for the P-8A, adjusted for the higher rate of use needed to maintain continuous CMD orbits. The higher O&S costs include factors such as the need for additional aircrew to meet monthly flight limitations, additional fuel, and more frequent maintenance.

Architecture 3

The notional aerostat sensor in Architecture 3 is based on the Army's Joint Land-Attack Cruise Missile Defense



Table B-1.

Average Acquisition and Operation and Support Costs per Orbit of Sensor Aircraft That CBO Considered

Number of Aircraft or Millions of 2021 Dollars

	Radar on HALE-UAV	Radar on Modified Commercial Aircraft (AEW&C Aircraft)	Radar on Aerostat	Notes
Average Number of Aircraft to Maintain 24-7 Orbit	2.8	4	1.5	Average includes aircraft that are not available at any given time for reasons such as periodic maintenance
Acquisition Cost of Initial Aircraft Set	490 to 570	820 to 1,040	510 to 590	Includes research, development, test, and evaluation costs and procurement costs
Acquisition Cost of Replacement Aircraft	450 to 550	140 to 190	450 to 530	Replacements for aircraft that wear out or are lost to attrition during 20 years of operation
Annual Operation and Support Cost	100 to 120	220 to 270	30 to 50	Includes military personnel, operation and maintenance, sustaining support, and system improvements

Data source: Congressional Budget Office. See www.cbo.gov/publication/56950#data.

AEW&C = airborne early-warning and control; HALE-UAV = high-altitude, long-endurance unmanned aerial vehicle.

Elevated Netted Sensor System (JLENS). Although that system was canceled, DoD prepared SARs that CBO used to estimate aerostat costs. Because the JLENS never entered production, considerable uncertainty surrounds its acquisition and O&S costs. CBO used average unit costs from the JLENS SAR for the high end of its cost estimates and a lower cost reflecting a much larger production run (75 systems instead of 14), which typically results in lower average unit costs.

Costs for Satellite Sensors: Architecture 4

To estimate the costs of Architecture 4, CBO used the same approach it used for estimating the costs of satellite constellations in *Alternatives for Military Space Radar*, which was published in January 2007.¹ CBO adapted the acquisition and O&S cost-estimating methods from that report, which focused on constellations for imaging and tracking ground targets, to a larger constellation designed to detect and track airborne targets. CBO used an updated parametric cost model to estimate satellite development and production costs and adjusted launch costs to reflect reductions in space-launch costs that have occurred since 2007.

Architecture 4 includes costs for RDT&E—\$12 billion to \$20 billion—that are substantially higher than those

of the other architectures, which are based on modified versions of existing systems. Procurement costs for the initial 78 satellites would be \$45 billion to \$76 billion, including costs to produce the satellites and launch them into space. Because satellites in low Earth orbit typically have a 10-year service life, CBO's estimate includes \$34 billion to \$61 billion to purchase and launch 78 replacement satellites.² Another 78 satellites might be needed shortly beyond the 20-year period considered in CBO's analysis. Because satellites mainly require monitoring after they are in orbit but not maintenance or fuel, O&S costs under Architecture 4 would be much lower than the O&S costs of the aircraft-based sensor platforms that require extensive maintenance.

Costs for CMD Shooters

CBO based the cost estimate of its notional long-range surface-to-air missile (LR-SAM) site on several sources. Costs for the eight LR-SAMs at each site were based on the Navy's SM-6 missile. CBO based the costs of the two launchers and supporting communications vehicles on data about Terminal High-Altitude Area Defense equipment provided by the Missile Defense Agency. CBO estimated the average cost of an LR-SAM site to be about \$70 million. That total would include \$29 million for eight missiles and their canisters, and \$17 million for two launcher vehicles. The other \$24 million

1. See Congressional Budget Office, *Alternatives for Military Space Radar* (January 2007), www.cbo.gov/publication/18252.

2. Low-Earth-orbit altitudes are roughly defined to be more than 100 miles but less than 1,200 miles above Earth's surface.

would be for vehicles with communications equipment, acquisition of land (if necessary), and construction at the site (for instance, for pads for the launchers, structures for the missile crews, security fencing, and access roads). CBO's estimate of costs for O&S—\$15 million to \$20 million annually per site—was based on Army National Guard costs in support of air defense in the National Capital Region.

CBO based its estimate of fighter costs on the Air Force's fiscal year 2021 budget request to operate today's

Aerospace Control Alert (ACA) locations. Specifically, the Air Force requested \$134 million for the 15 ACA sites operated by the Air National Guard (a 16th site is not operated by the Guard), or about \$9 million per site. CBO's cost estimates for its illustrative CMD architectures include \$10 million for each site above the 14 already in operation in the 48 contiguous states. (The two additional sites are located in Alaska and Hawaii.) CBO's higher estimated cost reflects the need for more aircraft to operate from airfields away from their home base.



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About This Document

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CBO continually seeks feedback to make its work as useful as possible. Please send any comments to communications@cbo.gov.



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