SURVIVABILITY IN THE DIGITAL AGE:

The Imperative for Stealth

By Maj Gen Mark Barrett, USAF (Ret.)
with Col Mace Carpenter, USAF (Ret.)

MITCHELL INSTITUTE for Aerospace Studies

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Executive Summary

Stealth, or aircraft signature reduction, is a potent and viable military capability in modern combat, and will remain so well into the future. It is not, however, an all or nothing capability, as some critiques have suggested. Investments in stealth technology significantly improve the ability of US aircraft to penetrate enemy air defenses and create significant costs for adversaries who attempt to defend against this technology.

In certain environments, stealth may have the ability to penetrate with little support. However, stealth is most effective when employed in concert with other aircraft, tactics, and capabilities. Adding stealth to a multi-capability force package creates a lethal synergy that is difficult to defend against. By reducing the enemy's ability to detect attackers, this complicates air defense efforts and reduces time for adversaries to react effectively.

The United States demonstrated the warfighting impact of stealth aircraft technology in Operation Desert Storm—the 1991 Gulf War—via F-117 Nighthawk stealth fighter operations. Freed from having to "package" large groups of aircraft to break through defenses, commanders utilized stealthy aircraft to strike strategic targets before air defenses were neutralized or destroyed. Stealth aircraft were also used to neutralize or destroy adversary air defenses, so conventional aircraft could penetrate high threat areas. Less than a decade later, both the F-117 stealth fighter and B-2 stealth bomber demonstrated similar capabilities in 1999's Operation Allied Force, over Serbia. Again, the use of stealth enabled friendly forces to strike deep immediately, reduced risk and losses of non-stealthy assets, surprised the enemy, and significantly improved economy of force by allowing aircraft that would have been tasked for support operations to strike other targets. The operational advantages offered by stealth aircraft like the F-117 and B-2 resulted in stealth's widespread adoption in many subsequent US aircraft designs and programs— such as the F-22, F-35, RQ-170, and X-47—and now the next generation bomber, the B-21. By 2022, approximately one-fourth of the US combat air forces will be stealthy—and the proportion should grow with each passing year as F-35s and B-21s enter service while non-stealthy aircraft retire. After years of observing US military operations, other nations too are convinced of the advantages of stealth design, and are moving to close the capability gap. Russia and China have adopted stealth in a range of new aircraft designs that are currently in development, and are slated to enter production in the next decade.

Stealth aircraft have now been in development and service for over 40 years. As with any military capability, the potential offered by technologies to counter stealth advantages are being developed, and also being debated. As a result, several questions must now be addressed. Do the advances in computational power and radar systems seen in the digital age undermine stealth aircraft survivability? Will stealth remain viable in future decades in the face of these technologies, or will its effectiveness wane? Should the United States continue to invest in stealth systems to improve them or mitigate technology that attempts to counter them, or shift its approach? Debate over these issues will increase in the coming years as spending on systems such as the F-35 and B-21 increases. In the service of trying to answer some of these questions, this study aims to provide an unclassified assessment of the long-term viability of stealth in the coming decades, and why it is vital to successful modern air warfare.

Introduction: Stealth and the Offense-Defense Contest

It is important to articulate, up front, what we mean when using the term "stealth" in the context of discussions about modern airpower. The word "stealth" simply means an object, in this case an aircraft, that is difficult to detect. Stealth does not make an aircraft completely "invisible" by any means, but can make it extremely difficult for it to be detected, tracked, and destroyed. Stealth also significantly reduces the range at which aircraft can be detected, and this in turn increases survivability. Stealth combined with speed creates additional challenges for enemy air defenders. Even if defenders can detect the presence of aircraft, the time they have to track, fire, and guide surface-to-air missiles (SAMs) is minimal. Sometimes engagement windows are so short, even detected stealth aircraft are nearly impossible to engage.

The survivability of a stealth aircraft is primarily the result of stealth design (the set of technologies that make the aircraft hard to detect) and tactics (the means by which operators employ stealth aircraft to maximize survivability and effectiveness). Modern stealth or "low observable" (LO) technologies allow aircraft to minimize their measurable signatures to prevent detection, tracking, and ultimately engagement. The most advanced LO aircraft designs enable manipulation of the entire electromagnetic spectrum (EMS) in order to reduce radio frequency (RF), infrared (IR), electro-optical (EO), visual, and acoustic sensor capabilities. The goal of LO design is to reduce the aircraft's signatures in each of these areas to as low a level as possible.

As demonstrated by combat operations dating back to World War I, visual detection of aircraft proved a poor means of providing defense against aircraft. Combat experience and detailed studies show that visually searching the vast expanse of sky for an unknown object remains a difficult task.

As demonstrated by combat operations dating back to World War I, visual detection of aircraft proved a poor means of providing defense against aircraft. Combat experience and detailed studies show that visually searching the vast expanse of sky for an unknown object remains a difficult task. Under ideal conditions, a small fighter can be detected at roughly three miles. Night, clouds, and adverse weather further reduce the ranges and chances of detection. Such small detection ranges make it virtually impossible to detect and track an aircraft to bring defenses to bear against the intruder.

The development of radar before World War II permanently changed the air combat attacker-defender duel. During the day or night, and in all types of weather, the new detection technology could determine the presence, location, altitude, and direction of attacking aircraft. Passing this information to interceptors and ground defenses enabled defenders to allocate and direct forces to effectively engage attacking aircraft.

Radar's long-range, all-weather capability has made it the cornerstone of modern air defense since its introduction—radar provides orders of magnitude improvements in detection ranges compared to visual means.

Therefore, avoiding detection by radar is key for an attacker, and reducing a defender's radar range by reducing the attacking aircraft's radar cross section (RCS) is one way to accomplish that. This is the distinguishing characteristic of stealth aircraft.

Table 1 shows how reducing RCS impacts modern fighter-borne and early warning radars. As seen in the table, at very small radar cross sections, the detection range of radars is reduced to levels similar to visual detection—and with similar impact upon the task of an air defense network. Stealth technology presents air defenses with the same challenge they had over seven decades ago, before the advent of radar.

RCS (m^2)	RCS (dB)	Fighter AESA Radar Range (mi)	Early Warning Radar Range (mi)
1	0	100	300
.1	-10	56	168
.01	-20	32	95
.001	-30	18	53
.0001	-40	10	30
.00001	-50	6	17
.000001	-60	3	9

Table 1: How detection range is reduced by smaller radar cross section.

Over the long run, the US will engage opponents who field increasing numbers of powerful digital multi-band radars. Because ground-based systems are bigger and able to deploy larger arrays, their theoretical ranges and capabilities will be greater than those carried by fighters and airborne early warning aircraft. The ground-based systems, if they can successfully detect and locate an aircraft, can alert SAM batteries and vector fighters to the threat location – perhaps without ever losing track. This will pose new challenges for US stealth aircraft, but there are several factors to keep in mind in this offense-defense struggle:

- Reduction in RCS continues to offer huge operational advantages by shrinking the ranges at which the aircraft can be detected. The laws of physics are hard to break. If newer radars can detect stealth aircraft at longer ranges, their ability to detect non-stealthy aircraft is also increased.
- Current operational stealth aircraft feature highly tuned systems that detect adversary radars and use knowledge of the aircraft's RCS to optimize routing in order to minimize the potential for detection and engagement. Stealth is a combination of reduced RCS and operational tactics that result in signature reduction.
- Multi-band or broadband stealth is growing in importance as more multi-band radars are fielded. Such radars are still in their infancy, but will grow in numbers over the coming decades. This will put an emphasis on larger, tailless designs such as the B-2, B-21, and X-47. Modern aircraft optimized for reduced RCS against high frequency radars such as those carried by fighters will still

enjoy a huge operational advantage but may become more detectable by low frequency radars. Mission planning for fighters with vertical tails will also become increasingly complex as side-aspect detection and engagement is better enabled by advanced sensors and high performance SAM systems, such as the SA-21.

- Just as radars have benefited from the advances of the digital age, so have stealth aircraft design capabilities. Nearly 50 years of working with stealth aircraft has given the US a significant advantage in the development of the next generation of stealth platforms. The United States is now developing its fourth generation of stealth aircraft—and to date, the US is the only military power to successfully field an operational stealth aircraft.[1] The computational capabilities available to design the F-117 and B-2 are dwarfed by the power now available to design teams. Simulations of interactions between designs and various threat radars are now far more accurate and realistic, allowing additional refinement of stealth design solutions before any hardware is actually built or tested. This capability should drive significant cost and schedule efficiencies in the development of the B-21, resulting in reductions in RCS beyond those achieved on other platforms.
- Stealth aircraft will be operating in coordination with non-stealthy aircraft. The latter feature larger radar cross sections, which are bound to draw attention from defenses. This is one of the reasons why stealth pilots have been known to refer to legacy aircraft (tongue in cheek) as "aluminum chaff." In the high-speed arena of air warfare, defenders will be highly stressed trying to locate stealth aircraft amid groups of non-stealth platforms.
- Since the advent of radar, development of electronic warfare capabilities has expanded significantly. Stealth, combined with electronic jamming and spoofing, can significantly increase the stealth capability of a force package—sometimes by an order of magnitude. On older generation aircraft, adversaries have been fielding digital radio frequency memory (DRFM) pods, which provide false targets to opposing radars. The small RCS of stealth aircraft combined with advanced processing and digital control make it much easier to use low-power spoofing with on-board AESA electronic attack RF systems to execute "digital cloaking" and disappear from adversary displays. This capability, combined with general wide area jamming, will further complicate an adversary's defense problem.

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The continued offense-defense battle between modern radars and stealth aircraft will continue for decades to come. Digital age improvements to radars are counterbalanced by the impact of that same digital technology on stealth aircraft design. Unlike other stealth aircraft (such as the F-22 and F-35) that have to balance stealth and aerodynamic performance requirements, the B-21 (like the B-2) will provide what is known as "all aspect, broadband stealth." The emerging anti-access/area denial (A2/AD) threat is requiring this approach, and modern computing is enabling it.

This study also explores the potential of other capabilities under development as potential counters to stealth—infrared, acoustic, and wake detection technology. Of these three areas, analysis indicates infrared has the most potential. That said, current infrared detection capabilities offer ranges greater than visual detection, but not as great as radar. Similar to visual detection, infrared sensing is also degraded by adverse atmospheric conditions (rain and cloud cover, for example), and current infrared sensor hardware is expensive, and difficult to maintain. All of these factors limit the overall utility of infrared sensors and have resulted in limited proliferation to date. Modern stealth aircraft like the B-2 currently utilize design features and employ techniques to minimize their infrared signature. Should infrared systems overcome current deficiencies and proliferate in the future, means of cloaking and actively managing an aircraft's infrared signature are available and could be leveraged to minimize this threat.

Emerging modern threats are pushing the importance of stealth technology to the forefront of counter A2/AD strategies. The analysis in this study illustrates the value of stealth in magnifying adversary problems in attempting to detect, track, and engage an LO aircraft. Not only is stealth viable in the future threat environment, it is also becoming a requirement for many of today's missions. The capability to significantly reduce the range and effectiveness of modern radar and other threat sensors is now a basic requirement for aircraft survival as contested air space becomes more common. Additionally, stealth simulations and planning are becoming critical for future successful joint force operations. These provide pilots and mission planners a detailed awareness of how their platform is perceived and viewed by an adversary, and other forces. This understanding is critical to managing risk, as it enables accurate predictions, insights, and awareness of the aircraft's vulnerabilities to specific threats.

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Detection capabilities of modern radars, meanwhile, are improving at a rate roughly parallel to "Moore's Law" (which stipulates computer processing power doubles about once every two years), elevating the risk to modern US aircraft. Despite this, LO characteristics of US aircraft still possess a significant advantage over air-to-air missile threats in the engagement phase, and a lesser but still notable advantage against SAMs, even with modern fire control elements.

Though the capability of modern electronic warfare radars, fire control systems, and other technologies has improved in order to attempt to detect stealth aircraft at greater ranges (and reduce the element of surprise), these improvements only slightly decrease survivability in the air-to-air realm. Early detection allows an adversary to launch fighters, but their ability to detect and engage remains relatively limited against stealth aircraft. The surface to air threat for detection and engagement is decidedly higher with early detection, but detection does not guarantee engagement. Missiles must be able to strike in the end game, and while detection has improved, stealth still provides a tangible advantage in combat.

In the air attacker-defender contest, however, one thing has not changed. The process of shooting down an aircraft remains a difficult combat task. Successfully breaking the "kill chain" at just one point can result in mission success for the attacker. The US Air Force uses the terminology "find, fix, track, target, engage, assess" (F2T2EA) to describe the kill chain. Generations of airmen have been trained in executing this process against targets, and breaking adversary chains targeting US and allied forces. Survivability during World War I and II hinged on speed and aircraft maneuverability to evade other aircraft in dogfights, where guns served as the aircraft's primary weapons. Following WWII, high altitude, supersonic aircraft like the SR-71 were developed to avoid threats. Moving into the 1960s and 70s, as radar technologies and air-to-air missiles became more reliable and lethal, the US turned to stealth to avoid detection altogether. Today, digital age technologies have significantly improved capabilities on both sides making control of the electromagnetic spectrum (EMS) more critical than ever. Stealth is central to controlling the EMS. Not only is stealth viable today and into the foreseeable future, it is also more necessary than ever before.

Attrition and Survival: A History of Airpower and Stealth

Airpower forces are historically very sensitive to attrition. Airpower is an equipment-intensive form of military power—without aircraft, a state does not possess airpower. Seemingly very low rates of attrition over time can rapidly reduce aircraft numbers, a vulnerability the US Air Force must increasingly confront today, as it has fewer aircraft in its inventory than at any time in its history. Accordingly, when faced with attrition, airpower commanders have reacted quickly with changes in operational concepts and tactics that often sacrifice mission effectiveness. At the outset of World War II, high attrition forced the Royal Air Force to switch from daylight bombing to night bombing (a shift that greatly reduced effectiveness). After the disastrous Schweinfurt raid over Germany, the US Eighth Air Force shifted to targets lying closer to the British Isles in order to reduce exposure to defenses.[2] To deal with deeper targets, the US Army Air Corps developed and fielded long-range fighter escorts to accompany bomber formations and reduce attrition. Similarly, the Royal Air Force deployed a range of electronic jamming assets to reduce the losses inflicted by German radar-equipped night fighters.

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The need to manage attrition from World War II onward required dedicating significant numbers of support aircraft—electronic jamming platforms, defense suppression aircraft, and fighter escort—to enable strike aircraft to hit targets and ensure their survival. In the Vietnam War, commanders had to marshal large packages of aircraft to enable their forces to punch through defenses and hit targets. Often, the number of support aircraft outnumbered the strike aircraft, in effect reducing the number of strike aircraft that could actually attack targets.[3]

Concern over the vulnerability of aircraft to modern air defenses was heightened by the experience of the Israeli Air Force in the Yom Kippur War of 1973, where the IAF lost 60 combat aircraft (out of a total inventory of 340 jets) in four days when encountering then-modern Soviet air defense systems.[4] The United States and its NATO allies relied on their advantage in airpower to help deter Soviet aggression in Europe. A perceived high loss rate would have undermined the deterrent capability of Alliance forces. The potential capability offered by stealth—the set of technologies that could reduce the detection range of various sensors and hence increase survivability—accordingly looked very attractive at the time.

The common definition for "stealth" is the act or action of proceeding furtively, secretly, or imperceptibly. As such, stealth does not make an object completely undetectable, but stealth used with modern aircraft greatly reduces an enemy's detection range, which in turn increases survivability. The survivability of stealth aircraft is primarily a result of stealth design (the set of technologies that make the aircraft hard to detect) and tactics (the means by which operators employ stealth aircraft to maximize survivability and effectiveness). Other attributes also enhance stealth airpower, such as speed, effective nighttime operations, weather, and offensive electronic jamming. Low observable technologies allow aircraft to minimize their measurable signatures to prevent detection and tracking. The most advanced LO aircraft designs enable manipulation of the entire electromagnetic spectrum (EMS) in order to reduce radio frequency (RF), infrared (IR), electro-optical (EO), visual, and acoustic sensor capabilities. The goal of LO design is to reduce the aircraft's signatures in all areas as much as possible.

In combat operations, shrinking aircraft signatures means that an aircraft will appear very small to air defense sensors. This reduces sensor performance and improves survival probability. In addition to generating smaller signatures than a non-stealth aircraft, stealth aircraft signatures are studied by US airmen and are both known and predictable. The precise understanding of how an aircraft is seen by adversary sensors aids planners and aircrew in mission planning and execution.

Careful mission planning occurs in order to minimize the amount of time a stealth aircraft might be detected on a given mission. Together with other operational considerations (such as terrain, time of day, moon illumination, speed, altitude, and maneuvering) a precise understanding of the threats facing a particular strike package lowers risk and optimizes the chances for mission success. If an aircraft has a small enough radar signature, it can effectively create open space in an air defense network and exploit it— a practical freeway where a stealth aircraft can operate without radar detection or engagement. The illustration in Figure 1 shows an attack by conventional non-stealth aircraft on a notional Cold War-era air defense system (on the left), and a modern stealth aircraft attacking through an air defense system, shrinking its radar ranges (on the right). The right side of the figure approximates the effect of modern stealth aircraft in today's operational environment.

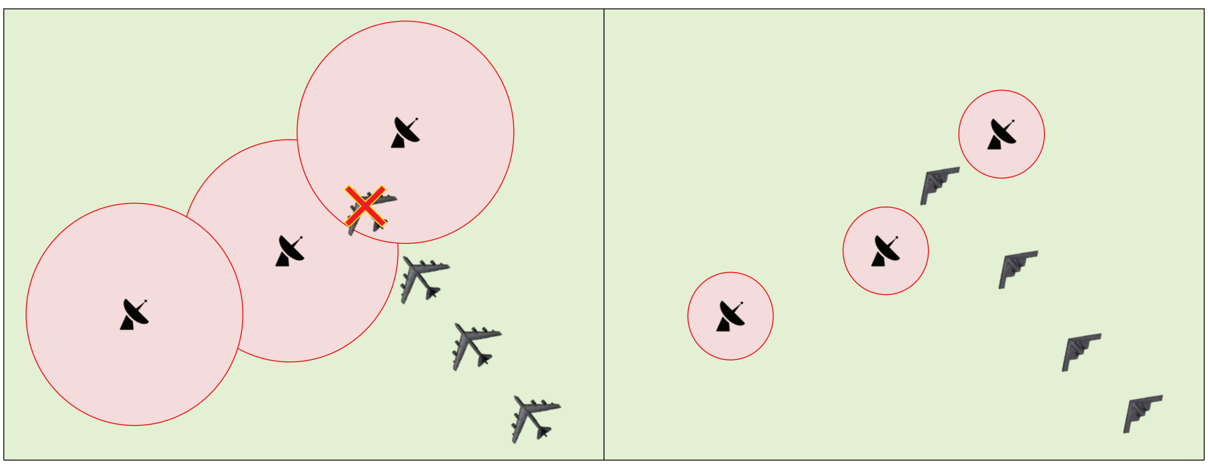


Figure 1: Notional Cold War air defense radar network versus a non-stealth platform (on the left), contrasted with an air defense network against a stealthy B-2 bomber (on the right).

The 1991 Gulf War proved a defining moment for the USAF and offered powerful evidence of the value of stealth technology. In the build-up to the war, planners had been developing large strike packages to punch through air defenses. Once F-117s were made available, however, planners rethought their concepts of operations. The stealthy F-117s could operate with minimal, if any, support. Accordingly, more strikes could be launched concurrently against a larger number of targets. On the opening night of the Gulf War, F-117s "flew into, over and through the heart of the fully operating [Iraqi] air defenses" (often without any jamming support) and struck strategic operations and communications facilities, paralyzing Iraqi command and control.[5] The Iraqis never recovered. In all, the stealthy F-117s flew just two percent of the total attack sorties but struck nearly 40 percent of strategic targets.[6]

The F-117s provided enormous leverage. Then-Lt Col David Deptula, who served as the chief attack planner for Operation Desert Storm, wrote that on opening night of the conflict a standard attack package of 41 aircraft punched its way through defenses to strike three aim points, or target areas. At the same time, 20 F-117s struck 37 aim points. Deptula pointed out the F-117s in this example provided "a 1,200 percent increase in target coverage using fewer than half the number of aircraft."[7]

Stealth offered planners the capability to execute a whole new approach to air warfare. Instead of marshaling large formations of aircraft into attack packages to strike a few targets, stealth aircraft flying at night could range an entire battlespace to strike any location without warning. And without the ability to detect and track stealth systems, an adversary had no effective defense. This in turn enhanced US deterrent capabilities. By the end of Operation Desert Storm, F-117s had flown 1297 sorties, often in the most contested environments, with no losses. Modern stealth had proved its operational value.

Stealth aircraft have now been in development and active service for over 40 years. The operational advantages offered by stealth aircraft like the F-117 resulted in stealth's widespread adoption in many US aircraft designs, prototypes, and programs. These include the B-2, F-22, YF-23, A-12, F-35, RQ-170, and X-47—and soon the B-21 next generation bomber. By 2022, approximately one-fourth of the US combat air forces will be stealthy—and the proportion should grow with each passing year as F-35s and B-21s enter service while non-stealthy aircraft retire. Today, Russia and China have also adopted stealth in a range of new aircraft designs that are currently in development, and are slated to enter production in the next decade.

By 2022, approximately one-fourth of the US combat air forces will be stealthy—and the proportion should grow with each passing year as F-35s and B-21s enter service while non-stealthy aircraft retire.

That said, a range of adversaries are also fielding advanced air defenses, comprised of long-range radars, advanced fighters, modern SAMs, and advanced command and control networks to pass information quickly between nodes. These new air defense capabilities now pose a threat to stealth aircraft, as they offer some significant new challenges:

- More powerful advanced radars: Modern radars, utilizing digital advancements, can detect aircraft at longer ranges. In addition, next generation radars can use a wider portion of the frequency spectrum, making them more flexible and capable.
- More lethal SAMs: Modern SAMs being fielded by multiple adversaries feature greater range, speed, and agility than previous generations. Additionally, the mobility of these systems makes targeting and striking them much more difficult.

- Advanced fighters: Adversaries are fielding higher performance fighters equipped with advanced radars and long-range missiles.
- Networking: Modern command and control systems use both land lines and wireless connectivity which, when combined with advances in processing and display technology, provide air defense commanders with better situational awareness and the ability to pass critical information quickly.

As with any military technology, the threats posed by technology to counter stealth are under debate. Do the advances in computational power, SAMs, and radar systems seen in the digital age undermine stealth aircraft survivability? Will stealth remain viable in future decades in the face of these technologies? Or will its effectiveness wane? Should the United States continue to invest in stealth systems or shift its approach? Discussion over these issues will increase in the coming years as spending on F-35 and B-21 increases.
This study is an attempt to provide an unclassified-level assessment of the military viability of stealth over the coming decades. To conduct this analysis, we first examine the performance of stealth against radar—the primary sensor underpinning modern air defenses. We will then discuss the impact of digital age improvements to this core sensor, and parallel improvements to stealth aircraft design. Lastly, we must examine threats posed by other sensor types, and outline some ideas and proposals for countering these threats in the future.

Beyond the Naked Eye: Radar Detection and Airpower

The development of radar, today the primary means to detect aircraft, was spurred by the fact that visual detection of aircraft proved a poor means of defense against attacking aircraft. In the early days of manned flight before radar, visual detection was the primary detection and tracking method. Air attackers of the day focused on avoiding visual detection using tactics like flying in clouds or approaching an (often unsuspecting) opponent from the rear while defenders did what they could to detect, track, and engage incoming raids. During this period, the pilots with the best vision were often the most successful. The element of surprise was, and still is, critical in air combat.

Visually searching a vast expanse of sky for an unknown object (especially an aircraft) is a difficult task. Studies have shown that even under ideal conditions when the aircraft is known to be in a particular location, visual detection ranges are limited (see Figure 2 below). For example, under ideal conditions, the visual detection range of an F-16 is just over five kilometers, or around three miles. If the F-16 is at top speed (1,500 knots true air speed), this limited detection range results in a narrow 10-second detection window.[8]

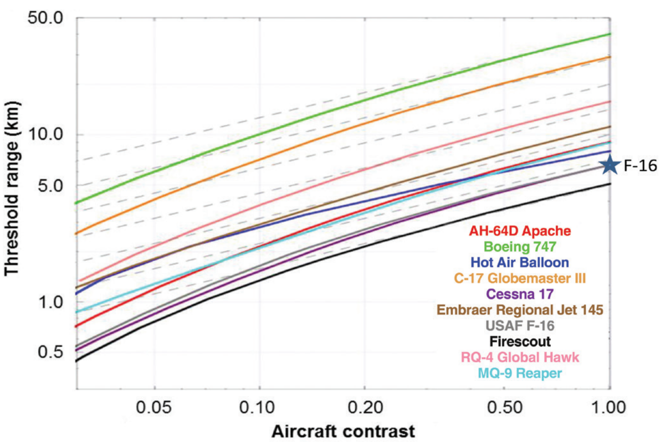


Figure 2: Predictions of aircraft visibility ranges.[9]

This data alone exaggerates the utility of visual detection. These range measurements, it must be noted, assume the location of the incoming aircraft is known. The difficulty increases significantly when an observer must find a fighter-size aircraft at an unknown location in the sky. Studies have shown that detection probabilities of 10 percent or less can be expected when searching a 180-degree area even when a fighter is within range and the sky is very clear.[10]

When an observer is tasked with scanning a smaller search area, the probability of detection goes up, but even with this improvement, a simple example illustrates the limited utility of visual detection for air defense. Consider the case of defending a 1,000-mile national border (for perspective, China has 9,000 miles of coastline). If we assume that reducing the visual search volume to four degrees results in 100 percent probability of detection of a fighter within range (a highly optimistic assumption), then the linear border an observer could reasonably cover is roughly one third of a mile. These observers would need to be airborne since the max altitude of an F-16 is well beyond visual range. Assuming that the altitude of the attacker was known, it would require 3,290 aircraft to cover 1,000 miles—roughly double the number of combat aircraft in the US Air Force. If the altitude of the attacking aircraft were not known, the defender would need to layer aircraft in a way that would add significant complexity, further increasing the number of aircraft required.

Military aircraft paint color and reflectivity is carefully chosen to further reduce the ranges at which aircraft can be detected. Add clouds and rain to the equation and the problem gets even worse for the defense, as visual night detection becomes nearly impossible. Difficulties surrounding visual aircraft detection during the First World War led to the proclamation by former British Prime Minister Stanley Baldwin in a 1932 speech to Parliament that "the bomber would always get through."[11] Put simply, visual detection offers very limited utility in developing defenses against aircraft.

The development of radar technology by both the British and Germans just before World War II changed the attacker-defender duel permanently. During the day or at night and in all types of weather, the new detection technology could determine the presence, location, altitude, and direction of attacking aircraft. Passing that information to interceptors enabled defenders to allocate and direct forces to shoot down attacking aircraft, as was demonstrated in the Battle of Britain in 1940 and German defense of the Third Reich in subsequent years.

Figure 3 shows the absolute and relative ranges of modern radar systems compared to ground and airborne visual detection capability. Radar's long-range, all-weather capability has made it the cornerstone of modern air defenses since its introduction—radar provides orders of magnitude improvement in detection ranges compared to visual means.

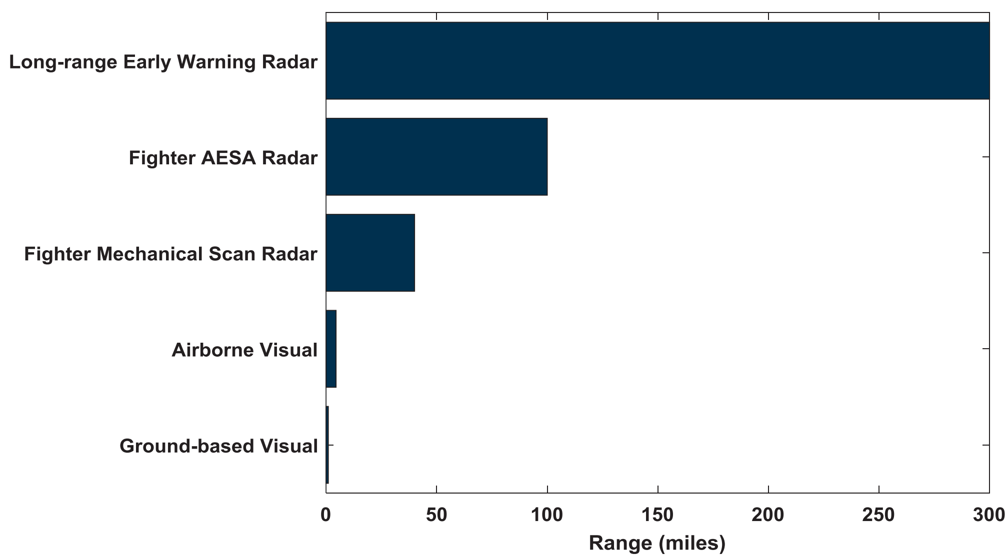


Figure 3: Comparison of radar and visual detection ranges.[12 13 14 15]

For illustrative purposes, consider the previous example of defending a 1,000-mile border. Some modern, long-range radars are mounted on aircraft, such as the E-3 Airborne Warning And Control System (AWACS) aircraft. These assets have the ability to search vast swaths of open sky very effectively. Using such a system would require a defender to use only two or three assets to detect incoming, non-stealthy attackers along the entire border. This would be a huge improvement over the thousands of aircraft required with unaided visual detection.

Outsmarting the Sensor: Stealth's Impact on Radar

Because of its capabilities, radar has historically been used as the primary air defense sensor for early warning, detection, and fire control. Therefore, avoiding detection by radar is key for an attacker. Radar cross-section (RCS) is a measure of how detectable an object is by radar. A larger RCS indicates that an aircraft is more easily detected. Reducing a defender's radar range by reducing the attacking aircraft's RCS is one way to accomplish this task.

For a non-stealth aircraft, RCS is directly related to the size of an aircraft—typically the larger the aircraft, the larger the RCS. RCS can also be changed by the design of the aircraft. Vertical tails, corners, and other aircraft design shapes and structures can generate radar reflections.

This is the most distinguishing characteristic of stealth aircraft. Radars work by sending out radio frequency (RF) electromagnetic energy from a transmitting source and looking for reflections at a receiver. The transmitter and receiver are typically in the same physical location—an architecture called monostatic radar. This type of system transmits RF energy and listens for reflections from objects, similar to an acoustic echo. These reflections behave similarly to optical light reflecting from a mirror. A modern Doppler radar is specialized radar that exploits the "Doppler effect" to produce velocity information on objects at a distance (the "Doppler effect" is the change in frequency or wavelength of a wave or other periodic event for an observer moving relative to its source). Doppler radar works by bouncing microwave signals off of objects, and determining their movement by how the frequency of the returned signal is altered. This allows radar to determine objective velocity relative to that radar. The aim of stealth design and operation is to prevent as much energy as possible from being reflected from the aircraft back toward the radar receiver.

For a non-stealth aircraft, RCS is directly related to the size of an aircraft—typically the larger the aircraft, the larger the RCS. RCS can also be changed by the design of the aircraft. Vertical tails, corners, and other aircraft design shapes and structures can generate radar reflections. The size of an aircraft's RCS is directly proportional to the distance at which that aircraft can be detected by radar (in other words, the radar's range). The relationship between RCS and the range of a powerful long-range early warning radar (like that on the E-3 AWACS) or a smaller active electronically scanned array (AESA) fighter radar is plotted in Figure 4, using the standard radar range equation.[16]

$$R = \sqrt[4]{\frac{P_{tx} G^2 \lambda^2 \sigma}{(4\pi)^3 P_{rx}}}$$, where R = range, σ = RCS in m^2

Figure 4: The standard radar range equation.

The goal of RCS reduction in a stealth aircraft design is to limit radar range to operationally insignificant distances for an effective air defense. Large RCS reductions are required to significantly impact the radar's range to distances that are beneficial for the attacker. Actual RCS performance of military aircraft is highly classified, but the lead designer of the F-117 stated the RCS of the stealth fighter was roughly the size of a ball bearing.[17] The Air Force stated in 1990 that the RCS of the B-2 was in the "insect class," indicating an even lower RCS than the F-117.[18] Twenty-five years of steady improvement to computing tools and processing power (with Moore's Law effectively doubling processing capability every 24 months) has enabled significant further reduction to the RCS of newer generation aircraft.

This reduction effectively makes a modern stealth aircraft appear smaller to radar than it actually is—moving from right to left on the graph depicted in Figure 5. For purposes here, we assume an aircraft with an RCS of one square meter (m^2) that can be detected by an airborne early warning radar at 300 miles, and AESA fighter radar at 100 miles. An F-16, for example, has an established RCS of around one to two meters, depending on weapons load out and features.

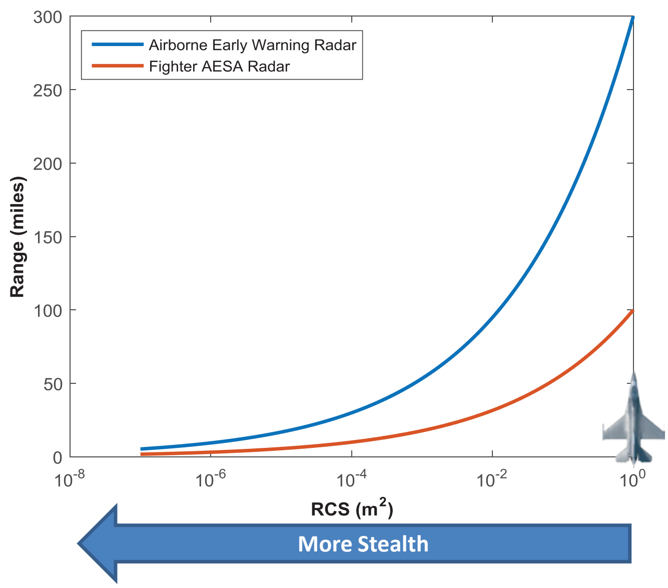


Figure 5: Radar range as a function of aircraft RCS.

For perspective, Table 2 shows how reducing RCS impacts modern long-range radars.

RCS (m^2)	RCS (dB)	Equivalent Objects	Fighter AESA Radar Range (mi)	Early Warning Radar Range (mi)
1	0	Cruise Missile (.5m^2)	100	300
.1	-10	Mallard Duck (0.1m^2)	56	168
.01	-20	Average-sized bird	32	95
.001	-30	Blue Winged Locust (.001 m^2)	18	53
.0001	-40	Medium-sized insect	10	30
.00001	-50	Alfalfa Caterpillar Butterfly (0.000063 m^2)	6	17
.000001	-60	Small-sized insect	3	9

Table 2: How detection range is reduced by smaller RCS.[19]

At the very low signatures shown in the table, radar detection range is reduced to levels similar to visual detection. Reducing radar performance to low double digit or even single digit miles gives stealth platforms many benefits, but one of the most important is the imposition of significant monetary and capability development costs on an adversary who must defend against stealth aircraft. Simply put, an adversary forced to defend against stealth is an adversary who is not investing in other military capabilities. The reduced RCS of attacking stealth aircraft pose significant cost and technical challenges to air defenders. There is clearly a relationship between the level of stealth (RCS) and the number of radar systems it would take to defend an airspace. Revisiting the 1,000-mile border from the examples above, the operational value of stealth becomes obvious.

The plot below in Figure 6 quantifies how many modern airborne early warning aircraft a defender would need to defend a 1,000-mile border against attacking aircraft with varying levels of stealth performance. For perspective, the US Air Force owns a total of 31 E-3 AWACS aircraft, of which a portion would be available in a given theater of operations.[20] As shown, detecting a non-stealth platform would only require two or three radar assets, but as stealth capability increases, it becomes clear that defending against stealth adds significant cost and complexity to air defense.

While defending a border is a thought-provoking exercise, a more realistic goal would be to defend an entire area against attack or persistent air operations. This is the objective of emerging A2/AD defenses in China, Russia, and elsewhere. However, stealth helps to mitigate the effectiveness of these types of defenses. Figure 7 shows the number of systems required to detect stealthy aircraft in a 1,000-mile by 200 mile area. The number of aircraft increases exponentially when the attacker possesses stealth capabilities.

Figure 6: Number of detection systems required to defend a 1,000-mile border, as a function of attacking aircraft RCS.

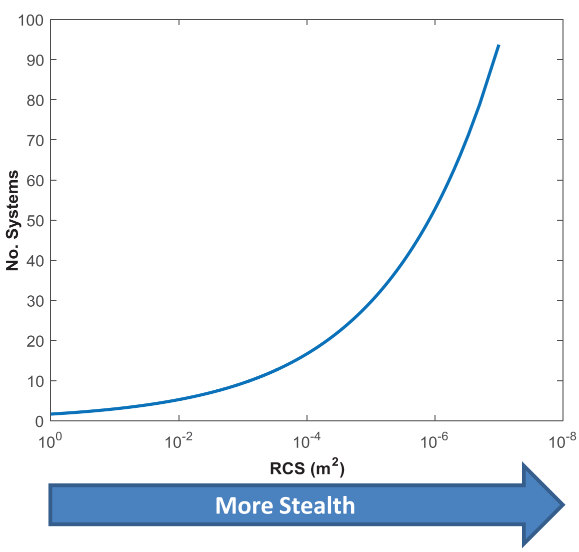
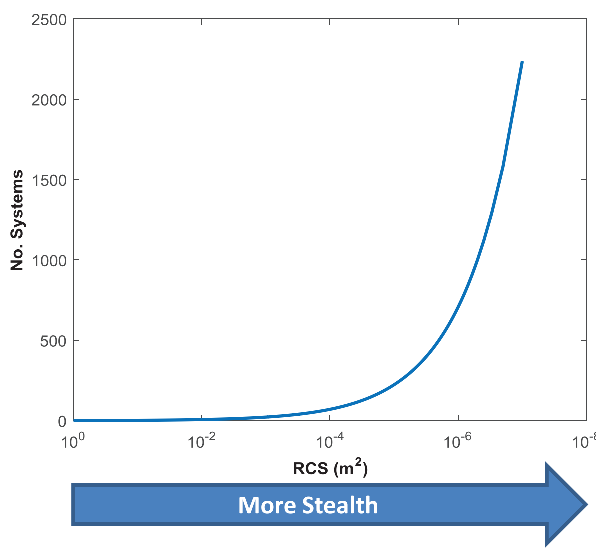


Figure 7: Number of detection systems required to defend a 1,000-mile x 200 mile area, as a function of attacking aircraft RCS.



Our analysis to this point has primarily focused on detection—the first step of the kill chain. As explained in a US Air Force unclassified paper on stealth in 1990, however, to shoot down an aircraft, a defender must successfully complete each step of the kill chain—detect, track, engage, and kill.[21] To illustrate, let's consider a very simple air defense made up of a single surveillance radar for detection, one fire control radar for tracking, and one SAM for engagement. Assume the surveillance radar has a probability of detection of 90 percent, and the fire control radar has a probability of tracking of 90 percent. Also assume the probability of the SAM being in the position to engage is 75 percent—and the probability of the missile fusing is also 75 percent (modern missiles typically rely on radar proximity fuses to detonate, which can be adversely affected by aircraft with a reduced radar signature). With this fully functioning air defense and very high probabilities of successful detection and engagement, if these elements are multiplied together the total probability of a kill comes out to just 45 percent.

Air defense is a complex endeavor, and only one link in the kill chain has to break before it all falls apart. The reality is that stealth attacks each link in turn—making the probability of a successful kill very low indeed.

If an attacker is able to disrupt just one part if this process, however, the ability to intercept the aircraft becomes very problematic for the defender. Even if an aircraft is optimized only to defeat high frequency fire control radar, this limited stealth capability reduces the probability of tracking to 20 percent. For simplicity, the surveillance radar, SAM, and fusing performance are not impacted. This single degradation in one part of the chain results in a probability of kill of only 10 percent. Air defense is a complex endeavor, and only one link in the kill chain has to break before it all falls apart. The reality is that stealth attacks each link in turn—making the probability of a successful kill very low indeed. Stealth, coupled with other attributes such as speed, maneuverability, tactics, mission planning, and jamming further decrease any successful completion of the kill chain.

Global Response to US Airpower: A2/AD and Modern Air Defenses

Air defenses in Iraq (in 1991 and in 2003), Serbia (in 1999), Afghanistan (in 2001), and Libya (in 2011) proved largely incapable of dealing with stealth aircraft. Serbia did shoot down one F-117 due to operational training shortfalls, planning errors, and luck on the part of Serbian air defenders. But potential adversaries like Russia and China are developing and fielding air defenses that take sensing and information sharing to the next level in an attempt to counter US stealth capabilities.

Russia and China are now fielding a range of more lethal SAM systems, such as the Russian SA-21. Compared to older generation SAMs, these new missiles have greater ranges (250 miles), are capable of higher speeds (Mach 14), and are more maneuverable (>20g at 100,000 ft).[22] Unlike older, long-range systems like the SA-2 and SA-5, these new generation SAMs are mobile and networked into a wireless system. This enables air defenders to use "shooting and scooting" tactics to minimize the chance of being located and engaged by attacking aircraft.

Left and below: The mobile multi-channel anti-aircraft missile system S-400 "Triumph" is designated in the West as the SA-21 SAM. Its main components include the 5P85TE2 TEL (at left) and the 92N6E Grave Stone Multimode Engagement Radar (pictured below). (Almaz)

Below left: An SA-21 nighttime launch. (Almaz)

Left: A pair of Russia's Sukhoi T-50 PAK-FA prototypes during a display. The aircraft is claimed to have a radar signature of three to four square feet. (Sukhoi)

Below: China's Shenyang J-31 at the 2014 Zhuhai Air Show. The aircraft is externally similar to the F-22 and F-35. (File photo)

Adversaries are also fielding advanced fighter aircraft to protect their national airspace. Fighters can be vectored against enemy threats, whereas SAM batteries must typically wait for aircraft to come within range.

Integration of digital technologies has steadily improved sensor range, accuracy, and the overall speed at which modern air defenses operate. The rate at which each step of the kill chain can be executed has increased significantly from legacy systems. When compared to air defenses of just two decades ago, newer systems leverage more capable sensors and better communication networks to share information faster, and often autonomously. The net effect is a significant increase in the speed at which a defender can complete the kill chain against an incoming attacker.

Without improvements in radar, however, new SAMs and fighters would be operating in the blind against stealth aircraft. Accordingly, US opponents have made significant investment and progress in controlling the EMS by leveraging improved digital signal processing and control technologies driven by the commercial electronics market. Russia and China have developed longer range, lower frequency systems that leverage complex low probability of intercept (LPI) waveforms with solid electronic protection to reduce the effectiveness of standoff jamming assets. They have also designed and fielded high power, ground, and airborne AESA radars similar to those pioneered in the US and fielded on platforms like the F-22, F-35, F/A-18E/F, surface ships, and on ground vehicles. The Russian PAK-FA stealth fighter will reportedly carry five AESAs when fully operational—clear evidence of the connection between airpower and control of the EMS. [23] [24]

In theory, AESA technology enables radar systems to focus more power in narrow beams to detect, acquire and track low-signal targets. To be effective, however, these RF beams must be accurately steered or "cued," to put the higher energy on distant targets. Stealthy targets can introduce small pointing errors and poor Doppler measurements from these systems, which can complicate tracking by requiring prolonged or repeated search scans to develop engagement quality tracks. Speed, maneuverability, electronic interference, and tactics are stealth capability multipliers in this context as well.

Older air defense systems typically used low frequency radars to detect the presence of incoming aircraft at long ranges but with poor locational accuracy. In general, the long-range radars provided indications that an aircraft was in range, but could not necessarily pinpoint what type it was. This information would then be used to alert higher frequency radars associated with SAM batteries to scan particular areas to detect and track the aircraft in question. These higher frequency (generally X-band) radars provided far better resolution and accuracy to enable missile guidance. Similar X-band radars were installed on fighter aircraft for the purposed of engagement and weapons control to be used once they were vectored to the area of an attacking aircraft. These systems were slow by today's standards and had many moving parts that allowed for disruption at each step.

Older air defense systems typically used low frequency radars to detect the presence of incoming aircraft at long ranges but with poor locational accuracy.

Today, however, the advances of the digital age are yielding radar systems capable of operating seamlessly over very wide portions of the EMS. By operating in multiple RF bands, these wideband systems improve the search, track, and targeting solutions individually and nearly eliminate the transitions from one to another. This wideband operation is critical for stealth aircraft designers to consider because an aircraft's RCS is very frequency dependent. Therefore, modern stealth designs must truly account for this expanded operational frequency of threat radar systems—a characteristic known as "broadband stealth."

In addition to wideband AESA radar, US adversaries have also integrated "bi-static" and "multi-static" radar systems into their air defense networks. These could pose some potential problems for traditional stealth designs by separating the transmitter from the receiver (bi-static) or dispersing a group of receivers (multi-static). The concept of multi-static radar systems has been established for years, but until recently, limitations on computational power and signal processing prevented viable implementation due to the complexity of architectures. Separating the transmitter from the receiver introduces synchronization challenges resulting in system noise and clutter that could not be overcome by older radar processing capabilities. While bi-static and multi-static surveillance networks may finally be enabled by improved "real-time" computational signal processing, performance analysis of these systems indicate that their bi-static or multi-static detection performance is no better than similar networks of distributed monostatic radars—the same type of radars stealth has been designed to defeat for decades. While these systems may be somewhat less expensive than traditional radar, the investments required for calibration and advanced signal processing have been equal to, or more costly, than simply deploying additional monostatic radars. Not only has this development proved extremely complex and imposed additional cost on US adversaries, but it also presents more opportunities for penetrating aircraft to disrupt the complex kill chain.

The Leading Edge: Modern Stealth Design Considerations

Over the long run, the US and its allies will be facing opponents fielding increasing numbers of powerful, digital multi-band radars. Because ground-based systems can be larger and are able to deploy larger arrays, their theoretical ranges and capabilities will be greater than those carried by fighters and airborne early warning aircraft. The ground-based systems, if they can successfully detect and locate an aircraft, can alert SAM batteries and vector fighters to the threat location – perhaps without ever losing track.

This will pose new challenges for US stealth aircraft, but there are a few factors to keep in mind in this offense-defense struggle:

- Reduction in RCS continues to offer huge operational advantages by reducing the ranges at which the aircraft can be detected. If newer radars can detect stealth aircraft at longer ranges, their ability to detect non-stealthy aircraft is also increased.
- Current operational stealth aircraft feature highly tuned systems that detect adversary radars and utilize knowledge of the aircraft's RCS to optimize routing in order to minimize the potential for detection and engagement. Stealth is not only reduced RCS but also the tactics used to employ the reduced signature in the optimal manner.
- Multi-band or broadband stealth will grow in importance as more multi-band radars are fielded. Such radars are still in their infancy, but will grow slowly in numbers over the coming decades. This will put an emphasis on larger, tailless designs such as the B-2, B-21, and X-47. Aircraft like the F-22 and F-35, which are optimized for reduced RCS against high frequency radars such as those carried by fighters, will still enjoy a huge operational advantage but will be more detectable by low frequency radars. Mission planning for fighters with vertical tails will also become increasingly complex as side-aspect detection and engagement is enabled by sensor and missile performance of SAM systems like the SA-21. However, effective use of speed, maneuverability, jamming, and a complete sensor picture of battlespace mitigate this somewhat.
- Just as radars have benefited from the advances of the digital age, so has stealth aircraft design. Nearly 50 years of working with stealth aircraft has given the US a significant advantage in the development of the next generation of stealth platforms. The US is now developing its fourth generation of stealth aircraft—and no other world power has yet fielded an operational stealth aircraft.[25] The computational capabilities that were available to design the F-117 and B-2 are dwarfed by the power now available to design teams. Simulations of interactions between designs and various threat radars are now far more accurate and realistic, allowing additional refinement of stealth design solutions before any hardware is actually built or tested. This capability should drive significant cost and schedule efficiencies in the development of the B-21, resulting in reductions in RCS beyond those already achieved on other platforms.
- Stealth aircraft will be operating in coordination with non-stealthy aircraft. The latter feature larger RCSs, which are bound to draw attention from defenses. Because of the difference, stealth

pilots understand their aircraft can become “lost” in the mix, due to their very small signature. In the high-speed arena of air warfare, defenders will be highly stressed trying to locate stealth aircraft amid large numbers of non-stealth platforms and electronic interference.

- Low observable technology, combined with cyber capability, remains a formidable challenge to potential adversaries. EW, jamming, and other tools used with stealth to reduce an adversary’s ability to engage aircraft are potent, but the inclusion of cyber engagement against threat systems can further reduce detection and engagement envelopes against stealth aircraft.
- Since the advent of radar, development of electronic warfare capabilities has steadily improved. On older generation aircraft, adversaries have fielded DRFM pods, which provide false targets to opposing radars. The small RCSs of stealth aircraft combined with advanced processing and digital control make it much easier to use low-power spoofing by on-board AESA electronic attack RF systems to execute “digital cloaking” and disappear from adversary displays. This capability, combined with general wide area jamming, will further complicate an adversary’s defense problem.

The continued offense-defense battle between modern radars and stealth aircraft will continue for decades to come. Digital age improvements to radars are counter balanced by the impact of that same digital technology on stealth aircraft design. Unlike other stealth aircraft that had to balance stealth and aerodynamic performance requirements like the F-22 and F-35, the B-21 (like the B-2) will provide what is known as “all aspect, broadband stealth” – as the emerging A2/AD threat is requiring this type of stealth, and modern computing is enabling it.

“All aspect” simply means that RCS is reduced when the aircraft is viewed from any direction, and while the detailed specifications are unknown to the public, the B-21 image released by the USAF depicts a design that does not use vertical flight control surfaces like tails. Without vertical surfaces to reflect radar from side aspects, the new bomber will have an RCS that reduces returns not only from the front and rear but also from the sides, making detection from any angle a challenge.

Aircraft like the Lockheed Martin F-22 and F-35 were designed to balance aerodynamic performance with stealth capability, which resulted in designs with radio frequency (RF) signatures resembling a “bowtie” due to increased RF returns from the sides, as depicted in Figure 8. Because of differences in the traditional missions flown by fighters compared to stealth bombers, these fighter designs essentially traded some of their side aspect stealth capability for high maneuverability (and the vertical tails required for maneuvering). A larger, less maneuverable subsonic bomber relies much more on stealth for survival than a fighter does, and the stealthiness of bomber designs reflects that.

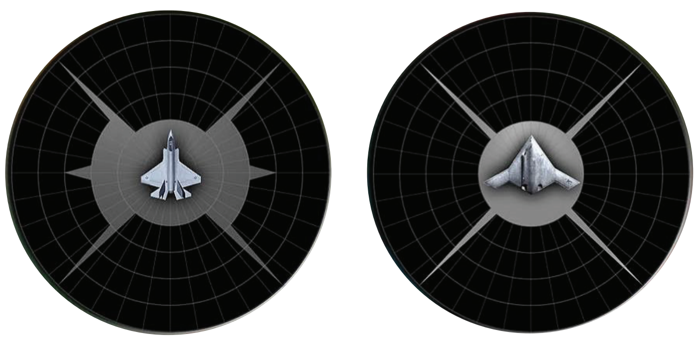


Figure 8: Notional “bowtie” RF signature of a fifth generation fighter (such as the F-35 on the left) versus a notional all-aspect RF signature of a tailless flying wing (such as the X-47 on the right).

The most advanced stealth designs today are described as "broadband stealth" designs because of the very wide frequency range over which they reduce an aircraft's inherently frequency dependent RCS. Broadband stealth makes an aircraft appear very small to all types of enemy radar — from low frequency, early warning to high frequency, fire control and missile guidance radars.

Before computational improvements enabled modern stealth modeling and analysis, the frequency dependence of RCS complicated stealth designs significantly. This complexity often forced aircraft designs to only be optimized in limited portions of the EMS to counter specific radar types. For example, the F-117 was optimized to reduce returns in the higher frequency portions of the EMS in order to counter fire control radars and missile guidance systems. While very successful, an F-117 was eventually shot down over Serbia in 1999 using a combination of low-frequency radar, a modified missile, and proficient air defenders who took advantage of USAF operational training shortfalls.[26] [27] As this incident highlighted, lower frequency systems are now capable of higher resolution tracking because their improved computational capability allows them to eliminate the signal clutter that hindered them in the past.

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Any new stealth platform must be stealthy from all angles and over a much broader frequency band to limit detection and tracking by all types of radar systems. In the current USAF fleet, only aircraft like the B-2 have this type of all-aspect, broadband stealth. This broadband capability helps to optimize the modern stealth used with other penetration assets to survive in combat against modern A2/AD defenses.

Hot on the Trail: Infrared Detection and Stealth

In addition to optimizing an aircraft's RCS to reduce the effective range of adversary radar, other sensor attributes must also be considered as they become more prominent to the overall detectability and survivability of the aircraft. After RF, the next most significant signature for any jet aircraft is the infrared (IR) signature, generated primarily by the heat from jet engines. In past stealth designs, this problem was addressed by placing the engine inlets and exhaust on the topside of the aircraft and burying the engine as far into the aircraft structure as possible (see photos below). Hot gases from the engine can be further cooled using mixing techniques in the exhaust system.

This engine position prevents ground based IR sensors from a clear line-of-sight view of the engine or its exhaust and creates thermal isolation with the skin of the aircraft. This configuration is a design challenge but one that has been overcome on numerous other platforms. The use of buried engines and stealth inlets have proved very effective against IR sensors.

Above: The topside engine inlets of a B-2 bomber, which direct air into buried engines, are clearly visible in this photograph. The use of buried engines and specially configured stealth inlets have proved effective countermeasures against IR sensors. (Northrop Grumman)

An Emerging Challenge: The Infrared Search and Track Threat

Some analysts speculate that the emergence of next generation Long-Wave Infrared Search and Track (LW-IRST) sensors will enable long range passive detection and tracking—and potentially passive (non-transmitting) lethal engagements—against modern US stealth aircraft. The reality is that advanced LW-IRSTs have not proliferated with potential adversary airborne systems as originally anticipated. While advanced LW-IRSTs have been developed and fielded in limited numbers on a few NATO aircraft, China and Russia have not made significant progress in deploying these sensors on their airborne systems. Moreover, these sensors are extremely expensive to manufacture, maintain, and sustain in the field.

Fundamentally, the physics of infrared search and track sensors limit their effective range, operational effectiveness, and field of view (and therefore, search capability) in the presence of suboptimal environmental conditions. The optimal performance of the Eurofighter Typhoon's PIRATE IRST system is depicted in Figure 9, compared to airborne radar and visual detection ranges.[28] The PIRATE system uses long-wave IR to increase range and attempts to compensate for environmental conditions and mid-wave IR to provide the resolution required to detect and engage an adversary.

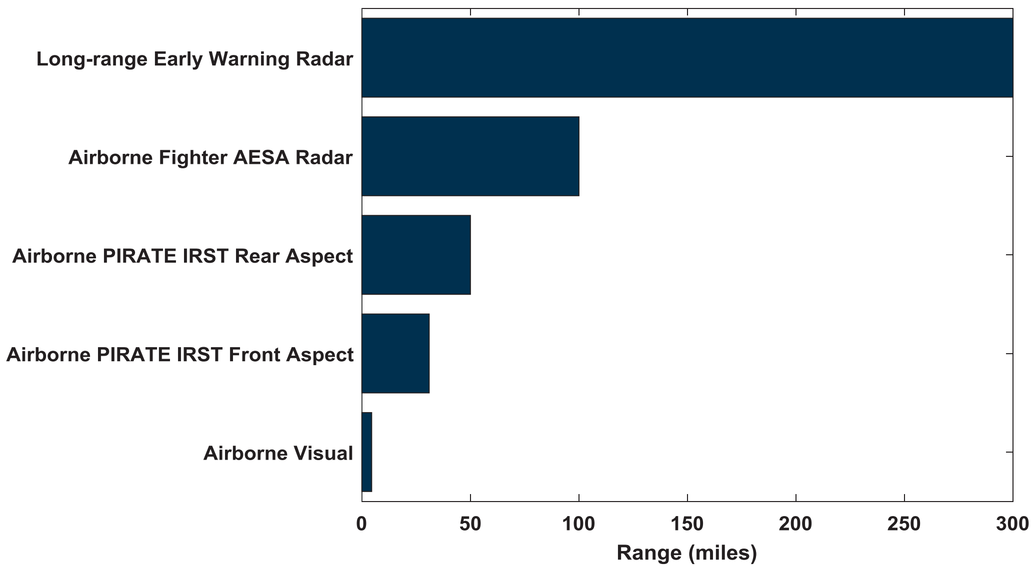

Figure 9: Comparison of radar, infrared, and visual detection ranges under optimal conditions.[29]

This simple comparison shows that IR sensors are still in a different class than modern radar. Under adverse weather conditions, the performance of IRST systems degrades while radar performance remains relatively unchanged. Due to search limitations, IRST systems must often be cued in order to acquire targets that are already within their operational detection range. While their role may expand in the future, fundamental physics indicate that cost and capability limitations reduce the attractiveness of LW-IRST systems as a near-term solution to counter stealth.

While defeating advanced LW-IRSTs with passive approaches has appeared difficult, new commercial industry advances in active thermal technologies indicate that the US defense industry has not reached any particular threshold in developing counter long-wave IR material solutions. In the same way that RF signature management has advanced over the years with improvements to both LO technologies and electronic warfare, counter-IR sensor solutions are certain to be developed to the extent the IR detection threat is realized.

Research of IR signature management (IRSM) technologies is ongoing, and the progress has been largely positive to date. Second-law IRSM (SL-IRSM) concepts related to turning heat into useable energy have progressed significantly in recent years, and nano- and micro-electro-mechanical devices (NEMS and MEMS) are showing great promise for turning waste heat into useable energy. Near term applications such as IR thermal cloaks to mask heat generated by buried facilities are being explored, and the natural extension to cloaking an aircraft is clearly evident in the thoughts of researchers.[30]

Longer term, SL-IRSM propulsion applications are also showing promise. The potential of NEMS and MEMS devices to enable active IRSM capabilities is leading some to the conclusion that "it appears possible in principle to both propel and IR-cloak aircraft using SL-IRSM technology."[31] The extent of the application of these technologies to a platform like the B-21 bomber will be determined by the emerging threat, but the physics appear very promising.

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Overall, infrared detection capabilities have ranges greater than visual detection, but not as great as modern radar. Similar to visual detection, infrared sensing is also degraded by adverse atmospheric conditions (such as rain and clouds). In addition, IR sensor hardware is expensive and difficult to maintain. All of these factors limit the overall utility of infrared sensors and have resulted in limited proliferation and employment to date. Should infrared systems overcome these deficiencies and proliferate in the future, however, means of cloaking and actively managing an aircraft's IR signature can be leveraged to minimize the threat.

Stealth and Sound: The Acoustic Detection Threat

The US Air Force is also researching other unconventional air defense approaches. There are many ideas that seem both feasible and threatening to US stealth capability. Because of this, and the importance of stealth to modern air operations, the Air Force maintains a vigorous program to assess aircraft survivability against emerging and potential threats. One of the closely watched threats over the past 30 years is the evolving threat of acoustic detection. Large jets make a lot of noise and acoustic sensors (namely, microphones) are relatively inexpensive. On the surface, using acoustic detection for air defense seems to make a lot of sense.

When the B-2 was in development, in order to better understand the threat, the US Air Force did an extensive study to assess the feasibility of acoustic aircraft detection. The USAF discovered that the effectiveness of the threat lay in the details. Similar to the exponential complexity caused by limited detection ranges in the earlier examples of this study, if a defender chose to use microphones with a range of 5 miles to cover an area defined by a 1,000-mile border and extending 200 miles inland, they would need over 2,500 detection stations. This seems potentially feasible until one considers how this number explodes to nearly 23,000 stations to cover an area defined by the approximately 9,000 miles of coastline in China, for example.

Additionally, the USAF study revealed that there were fairly obvious operational difficulties with taking such an approach to air defense. Some of those include:

- Aircraft crossing at high altitude transmit very weak acoustic signals.
- All aircraft flying over the defense would trigger alarms, not just adversary aircraft, with no method to discriminate.
- A few US cruise missiles intentionally flying along the border would ring many of the alarms and exhaust the defensive response.
- The US could destroy one of a few small segments of the fence or move a penetrating bomber force through only a few places to saturate the air defense interceptors which must necessarily cover the entire fence.

The study also uncovered technical challenges to such an acoustic detection approach:

- Acoustic sensors are severely degraded by wind noise.
- Atmospheric propagation effects can cause “quiet” zones where microphones cannot hear very well (much as layers of differing temperatures in the ocean provide hiding places for submarines).
- Snow, ice, and rain could degrade the operability and reliability of the microphones (a particular problem for adversaries like Russia where a significant part of the fence would be close to the Arctic Circle).
- The interceptors would still have a very difficult job of detecting, tracking, and killing an all-aspect, broadband stealth aircraft as discussed above.[32]

Making Waves: The Wake Detection Threat

Another unconventional detection method that is marked as a potential threat to stealth aircraft is the detection of atmospheric disturbances created when aircraft fly through air, also known as "wake detection." The so-called "Schlieren Signature" (the word is German for "streak"), also known as a wake signature, has been used to detect aircraft in wind tunnels and other controlled environments for years through a process called Schlieren photography. There have even been claims of "accidental" stealth aircraft detection using this method. But just how big of a threat is wake detection to modern stealth aircraft?

The process of Schlieren photography has been around since 1864 and was primarily developed to study supersonic shock waves. It could simply be argued that subsonic stealth bombers do not create this magnitude of atmospheric disturbance, and if no one has yet figured out a way to make this operational by now, it is not a significant threat to the viability of stealth aircraft.

Schlieren photography remains a subject of interest in modern aeronautics. NASA continues to conduct research into modernizing Schlieren photography for the 21st century, in part to improve supersonic aircraft design techniques.[33] One obvious issue to this approach for use in aircraft detection, however, is photography's reliance on a light source. Even if effective under ideal lighting conditions, advances to Schlieren photography would certainly be challenged under the cover of night or other adverse environmental conditions in the same way that operational EO sensors are challenged in these same conditions.

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Academic research continues to show promise for aircraft wake disturbance detection, but the operational realization of the concept remains distant. Wake detection can be performed by pulse Doppler radar or laser-based LIDAR (light detection and ranging). LIDAR determines distance to a target by pulsed laser light, by measuring the reflected pulses. Doppler LIDAR appears to be the most mature technology to date for wake detection.[34] A few successful experiments have been performed, but the ranges cited in scientific literature are operationally insignificant. As discussed previously, theory would indicate that radar ranges should be longer than optical LIDAR, but to date, tests have only realized radar wake detection ranges under 10 miles. This is even less promising when one considers that, in addition to being range-limited, any LIDAR-based solution will have high sensitivity to environmental conditions common to all optical systems.

When considering radar-based wake detection solutions, one obvious issue is that the most common and mature radar imaging technique—synthetic aperture radar (SAR)— relies on imaging objects that are stationary. Moving wakes present problems, and SAR's difficulties imaging ocean surface waves could be indicative of a dead end for radar-based aircraft wake detection.[35]

Another potential issue with the wake detection approach is that wake detection is quite a long way from aircraft detection, tracking, engagement, and fire control. The theory is that the aircraft's wake will point to the aircraft in the same way that the wake of a surface vessel traces all the way back to the vessel itself. This sounds simple, but this is a very difficult proposition for two reasons. First, in order to trace a wake disturbance to an aircraft, a significant portion of the wake around the aircraft must either be imaged optically (as with Schlieren photography) or recreated by other means (like LIDAR or radar) to the extent required to identify its point of origin (i.e. the aircraft). The immaturity of this imaging process has been addressed.

Even if an aircraft's wake disturbance is imaged successfully and the aircraft is tracked quickly enough, a stealth aircraft must still be engaged by an asset that can provide weapons grade tracking for fire control – a non-trivial problem, even for more mature technologies.

The second issue may be even more imposing. Even with modern improvements to computational power, image processing remains a major challenge for computers in general. Turning a wake disturbance into an image is one thing—creating enough of those images fast enough with high enough resolution and creating a computer algorithm to identify the point of origin and track it as it moves through three-dimensional space is something even more difficult. At some point, raw computational power without perception cannot overcome the complexity of the proposition. Even if an aircraft's wake disturbance is imaged successfully and the aircraft is tracked quickly enough, a stealth aircraft must still be engaged by an asset that can provide weapons grade tracking for fire control—a non-trivial problem, even for more mature technologies.

Conclusion

By all accounts, stealth, or aircraft signature reduction, will remain a viable capability into the future. Stealth is an important aspect of aircraft mission success and mission effectiveness in the 21st century. As air defenses improve, stealth will become ever more important to conducting successful air campaigns.

Reducing the ability of modern enemy air defenses to discover, track, and engage US and allied aircraft is essential. But it is important to stress that stealth is not an all or nothing military capability. Much like improved missiles and guided munitions, stealth has also advanced over the past several decades. Investments in this technology significantly improve the ability of US aircraft to penetrate enemy air defenses, and create significant costs for adversaries who attempt to mitigate US aircraft signature reduction capabilities. The costs for adversaries to attempt to offset this advantage are significant. Although highly capable, modern SAM systems such as the SA-21 are estimated to cost around $400 million per division (a division of SA-21s is comprised of 8 launchers, 112 missiles, and numerous command and control and support vehicles).

Reducing the ability of modern enemy air defenses to discover, track, and engage US and allied aircraft is essential. But it is important to stress that stealth is not an all or nothing military capability.

At the same time, stealth aircraft are more affordable than ever. For example, the F-15SG variant of the F-15E sold to the Republic of Singapore Air Force features a raft of improvements from the base F-15E Strike Eagle model, such as an advanced infrared search and track system, a modern targeting pod, and improved engines, among other features. These aircraft, delivered between 2009 and 2013, came out to around $85 million a copy for a buy of 24 airframes. In comparison, the last F-22s to roll off the assembly line before its termination cost between $90 million and $100 million a copy, and subsequent airframes could have cost even less. The F-35 is now on a cost reduction curve to get just below $90 million a copy, as production ramps up and customers begin to receive modern, operational aircraft. In light of these trends, it's important to consider capability and costs versus requirements for modern combat aircraft. Low observable aircraft are a very compelling proposition, even at a 10 to 20 percent cost premium when compared to other non-stealthy aircraft, especially in light of higher threat combat scenarios where these aircraft could face modern defenses against Russia, China, or a military equipped with capabilities from both of these potential adversaries.

In certain environments, stealth may have the ability to penetrate with very little support. In the future, there will be combat scenarios where stealthy aircraft have the ability to ingress and attack without detection. However, stealth is normally most effective when employed in concert with other aircraft and tactics. Adding stealth to multi-capability force packages, coupled with cyber operations, creates a lethal synergy. Mixing stealthy aircraft with conventional aircraft, deception, air defense suppression, and electronic jamming will complicate an enemy's defensive problem set by an order of magnitude. By reducing the enemy's ability to detect attackers, air defense efforts will become more complicated, leading to a sharply reduced timeframe for an adversary to react effectively in future campaigns.

Though modern air defenses continue to improve, stealth has improved as well. Since the development of the B-2, the US has not halted stealth research, and continues to innovate. Investments in stealth and counter-stealth technologies alike by the US and its allies have resulted in a better understanding of stealth design, materials, and supporting capabilities like mission management and EW self-protection required to enable aircraft survival against the most hostile threats. Through the life and operations of the B-2, critical capabilities like LO sensor management and LO routing have been developed and refined through various modernization upgrades to the platform. Leveraging modern computing capabilities, advances with new designs certainly appear possible.

Stealth is a central tenet of aircraft survivability in the future air combat threat environment. It gives platforms an increased chance of survival against air defenses by reducing the number of sensors that can detect, track, and shoot while increasing the time it takes them to complete these tasks. In short, stealth lowers an adversary's probability of kill. The threat scenario and associated survivability equation are more complex now than ever, but one truth remains—the laws of physics ensure that stealth will always make an aircraft more survivable by enabling it to manipulate the same EMS on which modern sensors rely so heavily.

Overall, advances in microelectronics and the commercial availability of advanced computational power has clearly helped US adversaries like Russia and China develop new threat capabilities, like wideband AESAs and DRFM jammers. However, in a similar way, the US has also leveraged these digital innovations to enhance its understanding of stealth and better optimize stealth designs more rapidly and across the broader EMS. Advanced computing has also enabled the production of materials with extremely precise electrical and physical properties, which, combined with advanced manufacturing processes (material deposition, 3D printing, etc), have not only benefitted the commercial electronics industry, but have also enabled the production of US stealth designs with much tighter electrical tolerances.

In addition to improving aircraft manufacturing, these digital advances have also enabled the creation of stealthy subsystems—RF and IR sensor and communications designs that better reduce and control their contributions to the overall aircraft sensor signatures. This occurrence alone could yield several orders of magnitude improvement in component-level RCS performance.

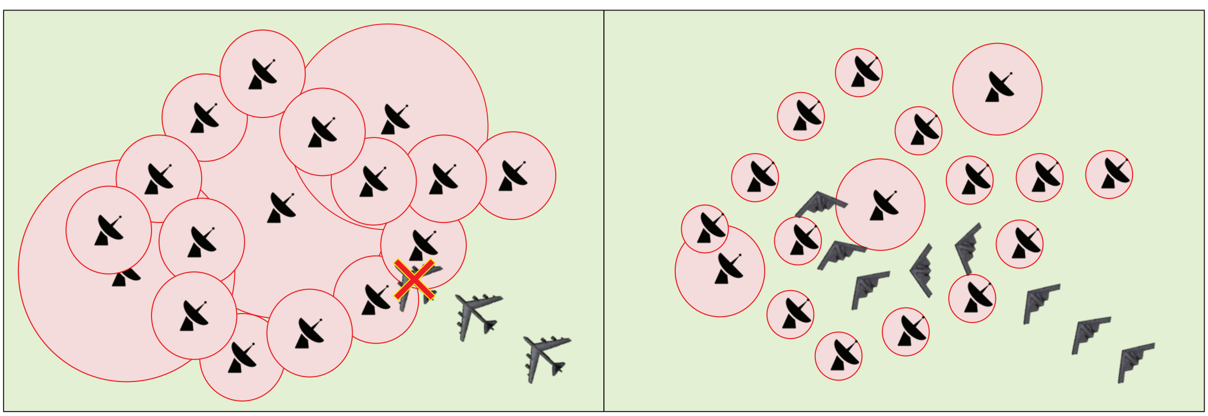

Figure 10: Non-stealth in A2/AD (left) versus stealth in A2/AD (right).

Today, the high threat A2/AD environments conceptually shown in Figure 10, on the previous page, have progressed to the point that, in some cases, completely avoiding all detection may not be feasible, but neither is it necessarily required. As discussed earlier in this study, each part of the kill chain must be effectively executed within a certain time window of opportunity in order to shoot down an aircraft. Therefore, an air defense system must be able to accurately detect, track, identify, and engage an incoming aircraft, which creates many opportunities for disruption. The new B-21 stealth bomber will undoubtedly be designed to save its kinetic disruption for strategic targets and leverage its passive stealth to manipulate the EMS and disrupt the most advanced A2/AD defenses in the world.

The emerging threat is pushing the importance of stealth technology to the forefront of counter A2/AD strategies. Not only is stealth viable in the future threat environment, it is also becoming required for a broader variety of missions than ever before. The capability to significantly reduce the range and effectiveness of modern radar and other threat sensors is becoming a basic requirement for aircraft survival as contested air space becomes more common. Additionally, stealth gives pilots and mission planners a detailed awareness of how their platform is seen by the adversary. This understanding is critical to managing risk because it enables accurate predictions, insights, and awareness of the aircraft's vulnerabilities to specific threats.

The emerging threat is pushing the importance of stealth technology to the forefront of counter A2/AD strategies. Not only is stealth viable in the future threat environment, it is also becoming required for a broader variety of missions than ever before.

In the air attacker-defender contest, however, one thing has not changed. The process of shooting down an aircraft remains a difficult task in combat. Successfully breaking the kill chain at just one point can result in mission success for the attacker. The US Air Force uses the terminology "find, fix, track, target, engage, assess" (F2T2EA) to describe the kill chain, and it remains as relevant as ever. Generations of airmen have now been trained in both executing this kill chain against targets of the US and its allies, and surviving and breaking it when they themselves are targeted.

Stealth will be closely intertwined with survivability in any future air campaign. Survivability during both world wars hinged on speed and aircraft maneuverability to evade other aircraft in dogfights where guns served as the primary weapon. Following WWII, high altitude, supersonic aircraft like the SR-71 reconnaissance aircraft were developed to avoid threats (it also used radar-absorbing composites for its leading edges, in one of the first uses of stealth technology).

By the 1970s, as radar technologies and air-to-air missiles became more reliable and lethal, the US turned to stealth's promise to avoid detection altogether. Today, digital age technologies have significantly improved US capabilities, and those of allies and potential adversaries around the world, making control of the EMS more critical than ever. Stealth in modern air campaigns is a central tenet of EMS control. Not only is stealth viable into the foreseeable future, it is clear its advantages are needed more than ever before.

Endnotes

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Artist's rendering of B-21 Raider. (USAF)

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