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Radar Detection and Stealth Bomber:  
What Future for Stealth Technology?

Andrea Pezzati

85003 - TECHNOLOGY AND INTERNATIONAL RELATIONS

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# Radar Detection and Stealth Bomber: What Future for Stealth Technology?

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## Introduction

It was December 17, 1903 when Orville Wright flew the first motor-powered airplane in history, designed and built together with his brother Wilbur<sup>1</sup>. A few years later, the aircraft appeared for the first time in warfare, used by Italy in Libya during the Italo-Turkish War (1911-1912)<sup>2</sup>. Early warplanes consisted of a wooden framework braced with wire and covered externally by cloth, with wings supported by wires and struts. Some aircrafts were built using a mixture of wood and metal and, lately, all-metal planes started to be experimented<sup>3</sup>.

Despite being archaic, the airplane demonstrated to be decisive. In particular, heavy bombers proved immediately useful for ground-support bombing operations. They were used to bomb key infrastructures like docks, harbors, bridges, railways, factories, and cities. Annihilating enemy's resources and morale through strategic bombing is an anchorage in air doctrine since about a century. The heavy bomber was so powerful and determinant that, at the end of World War I (WWI), many theorists thought that air power should be used in an offensive role only<sup>4</sup>.

The power of aircrafts has been considered undisputed for at least two decades<sup>5</sup>. Initially, the sole way to detect an incoming aircraft formation was through visual detection. The naked eye can see, in optimal weather conditions, few miles away. In addition, attacking warplanes concealed themselves in the middle of clouds or flew at night to avoid being detected. The surprise effect played in the attacker's favor, until mid-1930s. In fact, during interwar period, a new technology was developed and would have transformed air warfare forever: the radar. The capability to detect and track an aircraft from hundreds of miles was a huge turning point for defenders, as the Battle

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<sup>1</sup> Laurence K. Loftin, *Quest for Performance: The Evolution of Modern Aircraft* (Washington, D.C.: NASA Scientific and Technical Information Branch, 1985), 3.

<sup>2</sup> Richard H. Kohn et al., *The Command of the Air* (Tuscaloosa, AL: University of Alabama Press, 2009), <https://ebookcentral-proquest-com.ezproxy.unibo.it/lib/unibo/reader.action?docID=835669&query=command+of+the+air>, 3.

<sup>3</sup> Laurence K. Loftin, *Quest for Performance: The Evolution of Modern Aircraft* (Washington, D.C.: NASA Scientific and Technical Information Branch, 1985), 7-8.

<sup>4</sup> David Jordan et al., *Understanding Modern Warfare*, 2nd ed. (Cambridge University Press, 2016), 238-239. Pioneers of air warfare like Giulio Douhet, Billy Mitchell, Paul du Peuty and Hugh Trenchard were all convinced that gaining control of the air (i.e. air supremacy) by the means of pursuit aircrafts to pave the way for bombers was crucial to win a war. Giulio Douhet stood out among the others for his hardline belief. He was so certain about the power of strategic bombing that the enemy centers of gravity should include, for him, civilian population to bring about the collapse of enemy morale.

<sup>5</sup> That is, throughout the whole World War I until the early phases of World War II.

of Britain in 1940 amply demonstrated. The invention of radar brought about a change in air warfare doctrine. Reaching an enemy territory to destroy its centers of gravity became much trickier and more perilous for heavy bombers, as the survivability of the aircraft collapsed with respect to WWI bombers. A counter- counter measure was needed. Therefore, as the Cold War began, the United States started to work out a new, revolutionary technology: stealth. Stealth, also referred to as low observable (LO), can be defined as a process that allows the reduction of the radar cross section (RCS) of the aircraft through the use of radar absorbing material (RAM) or the shaping of its structure, with the aim of decreasing the range of detection of a radar. Being at the forefront for the development of stealth aircrafts, the United States has manufactured striking LO aircrafts like the SR-71 (reconnaissance aircraft), the F-117, the B1, the B-2 (bombers), the F-35 and the F-22 (fighters).

The coexistence of these two trailblazing technologies, radar and stealth, has instigated a hider-seeker competition between attacking aircrafts and ground-based early warning radar systems and radar guided surface-to-air missile (SAM) systems. Both radar and stealth are under constant development. Some anti-stealth technologies have already been created but they are still unripe and present many flaws. On the contrary, stealth seems a step forward. The United States does not stop to innovate and its last creation, the B-21 heavy bomber, could be a fearsome adversary for its alleged ability to penetrate even the densest air defense environments in the world.

The paper tries to examine the relationship between radar detection and stealth aircraft, focusing on U.S. low observable bombers. First, because the United States is an avantgarde developer of stealth. Second, because the bomber is the aircraft whose primary mission is the penetration of highly defended, heavily armed enemy territory to strike a key target. Nowadays, it is necessary for a bomber to turn into a stealth machine as anti-access area-denial (A2/AD) environments are mushrooming and strengthening.

The first section is mainly narrative, and it briefly illustrates the history of the invention of the radar and the impact it had on air warfare. The second section explains the relationship between radar and stealth, and how they work. The third section briefly describes the role of U.S. heavy bombers and the introduction of stealth technology in the production line of defense industry. The fourth section assesses the future of stealth technology in relation to the improvement of radar technology. The last section concludes the paper.

## The Breakthrough in Air Warfare: The Invention of The Radar

World War I was crucial for the development of air power doctrine and aviation technology. At the end of the conflict the use of fighter and bomber aircrafts proved so successful that some air power thinkers, like Giulio Douhet, asserted that air forces would become the primary instrument to win wars, supplanting both land and sea forces in the future<sup>6</sup>. However, this optimistic assumption could be reasonable only at a time when anti-air defense was almost nonexistent, and method of detection was mainly visual. Indeed, pioneer fighters and heavy bombers carried out several tactical and ground-support bombing operations successfully<sup>7</sup>. The ability of archaic heavy bombers like the Gotha G.IV and the Hedley Page 0/400 to raid key infrastructures (docks and harbors, bridges, railways, plants) deep behind enemy lines emphasized the importance of offensive air power for wearing out enemy morale. Survivability, defined as “the ability of the aircraft and aircrew to accomplish the mission and return home”<sup>8</sup>, was not much at stake in front of enemy defenses. The archaic airplanes of WWI had a fragile structure, generally made of fabric, wood and steel, and they relied on gunners and armor plates for self-defense against enemy fighters. Although friendly fighters and bombers had to survive dogfights and enemy ground fire, aircrafts’ loss rates were mainly due to accidents, structural failures and bad weather<sup>9</sup>. The fear of being detected and tracked was not a concern at that time. The only way to signal the presence of an aircraft was through visual or acoustic detection (Fig. 1). The defenders constantly struggled to anticipate an air attack, and this favored the attackers:

The lack of long-range detection ... meant that for the most part, air operations in World War I did not encounter well-organized antiaircraft gun defenses. Enemy aircraft defenses could be severe at times and nonexistent at other times. For the attacker, the survivability duel with ground



**Figure 1.** German sound location, 1917. A German junior officer and a soldier wear combined acoustic/optical locating apparatus. The small-aperture goggles were apparently set so that when the sound was located by turning the head, the aircraft would be visible (Available from: <https://rarehistoricalphotos.com/aircraft-detection-radar-1917-1940>).

<sup>6</sup> David Jordan et al., *Understanding Modern Warfare*, 2nd ed. (Cambridge University Press, 2016), 250.

<sup>7</sup> Laurence K. Loftin, *Quest for Performance: The Evolution of Modern Aircraft* (Washington, D.C.: NASA Scientific and Technical Information Branch, 1985), 47.

<sup>8</sup> Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), 8.

<sup>9</sup> Grant, 10.

defenses was one over which pilot felt they were the masters<sup>10</sup>.

At the end of WWI one thing was clear: the control of the air would have become a tenet of future warfare because it allowed to assist ground forces' offensives and to carry out strategic bombing to annihilate the centers of gravity of the enemy and, consequently, to crush its morale. Throughout interwar years, aircraft designs and technology had undergone many advancements. For example, the Martin B-10 rendered all previous bombers obsolete<sup>11</sup>. Nevertheless, what was about to change air doctrine and warfare forever was “the invention that changed the world”, as journalist Robert Buderer calls it: the radar. The origins of the radar can be traced back to the last quarter of Nineteenth century (Fig. 2).

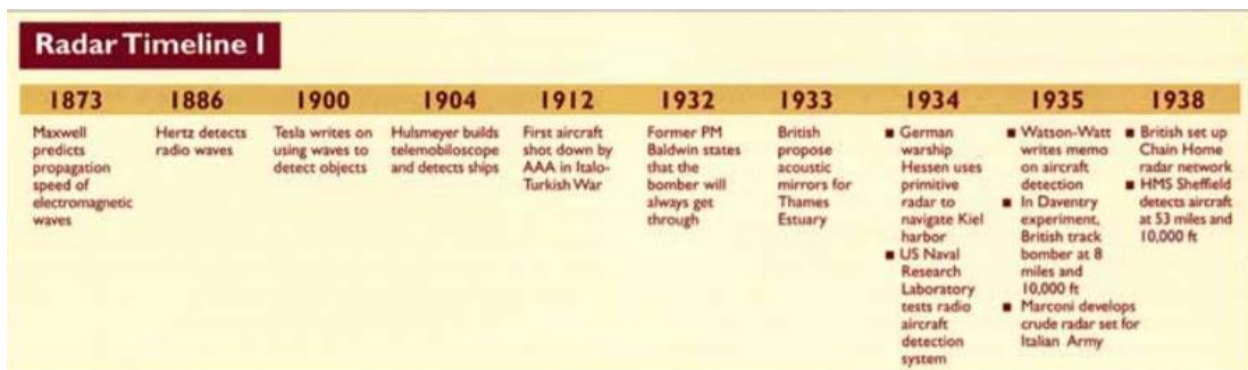


Figure 2. Radar Timeline (1873-1938)<sup>12</sup>.

The first detection of an aircraft using continuous wave equipment was in 1930 by three scientists of the Naval Research Laboratory (NRL), United States<sup>13</sup>. During the interwar period, the NRL had carried out several important experiments for the development of pulsed-echo detection, but the turning point occurred on the other side of the Atlantic.

<sup>10</sup> Grant, 12.

<sup>11</sup> Jerry Hendrix and James Price, “Higher, Heavier, Farther, and Now Undetectable? Bombers: Long-Range Force Projection in the 21st Century” (Washington, D.C.: Center for a New American Security, 2017), pp. 3-70, 14. The Martin B-10 was America’s first large all-metal monoplane, with a range of 1,400 miles and a top speed of 207 mph. The U.S. Army Air Corps ordered 14 B-10, entering service in 1934.

<sup>12</sup> Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), 15.

<sup>13</sup> Randall DeGering, ““Radar Contact!” The Beginnings of Army Air Forces Radar and Fighter Control” (Maxwell AFB, AL: Air University Press, 2018), pp. 1-109, 17.



**Figure 3.** *The Daventry Experiment: 25 February 1935.*  
Painting by Roy Huxley.

The United Kingdom worked hardly and hastily on radar technology because it felt vulnerable to air attacks from the continent, in particular from Germany's Luftwaffe<sup>14</sup>. In 1935 Robert Watson-Watt, a Scottish engineer, was appointed by the British government to carry out an experiment in order to demonstrate the feasibility of using shortwave radio illumination to detect an aircraft. The test took place in Daventry, 75 miles from London (Fig. 3). Watson-Watt and his team positioned a van with a radio receiver inside it. A RAF Handley Page Heyford bomber

flew up and down the transmitter's beam and was successfully detected at a range of about 8 miles<sup>15</sup>. Radio Detection and Ranging, best known as RADAR, was officially practicable and ready to change air warfare forever.

## Radar versus Stealth: Scramble for "Invisibility"

**T**he development of radar has changed the dynamics and the doctrine of air combat indelibly. The new technology could detect, locate and establish the altitude and direction of an aircraft any time of the day and in all weather conditions<sup>16</sup>. The defender has since acquired the capability of long-range detection which allows to pass information about approaching enemy aircrafts to command and control (C<sup>2</sup>) and ground-based defenses, which in turn can target and engage opposing aircrafts before they can reach the objective to strike.

Radar capability of long-range detection in all-weather condition has made it "the cornerstone of modern air defense since its introduction"<sup>17</sup>. The basic principles of radar technology are not complicated (Fig. 4). Radar typically involves the radiation of a narrow beam of electromagnetic energy into space from an antenna. The antenna beam scans a region where targets are expected. When a target is hit by the beam, it intercepts some of the radiated energy

<sup>14</sup> DeGering, 22. Germany showed its intention to expand its bomber force up to 4000 units, while Britain's RAF could count on only 600 fighters.

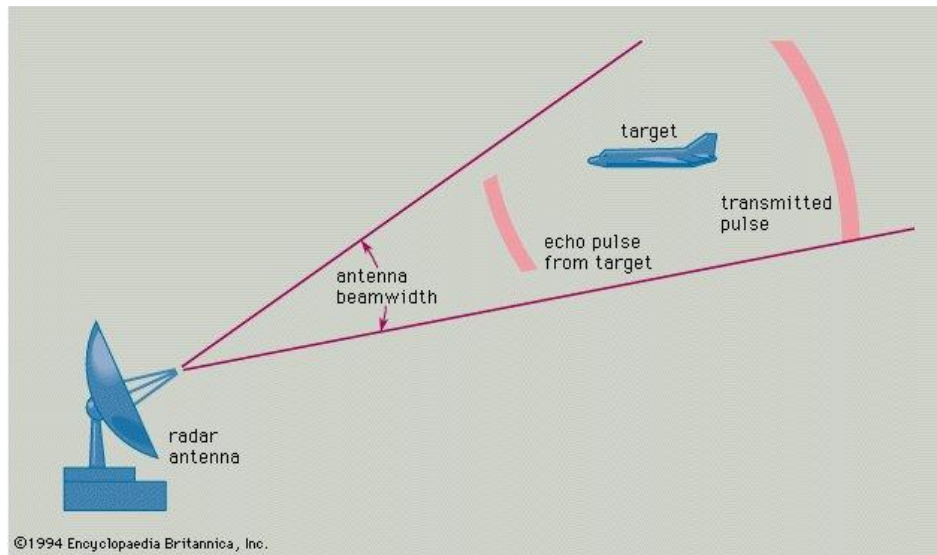
<sup>15</sup> Laurence Cawley, "The Daventry Experiment: Commemorating the Birth of British Radar," BBC News (BBC, February 26, 2015), <https://www.bbc.com/news/uk-england-northamptonshire-31634132>; DeGering, 24.

<sup>16</sup> Mark Barrett and Mace Carpenter, "Survivability in the Digital Age: The Imperative for Stealth" (Arlington, VA: The Mitchell Institute for Aerospace Studies, OAD), pp. 1-35, 2.

<sup>17</sup> Barrett and Carpenter, 3.



and reflects a portion back toward the radar system<sup>18</sup>. The transmitted radiation consists of electromagnetic waves (EW), which are generated and transmitted in the radio-frequency sector of the electromagnetic spectrum. A modern radar can determine the position, speed, altitude, and other features of a flying object because the speed of radio wave propagation is a known constant<sup>19</sup>.



**Figure 4.** *Principle of radar operation.* The transmitted pulse has already passed the target, which has reflected a portion of the radiated energy back toward the radar unit (Available from: <https://www.britannica.com/technology/radar>).

The arrival of radar and its immediately proven effectiveness in WWII<sup>20</sup> opened a new era, characterized by additional improvements in radar technology and resulting countermeasures to avoid detection. Among other things, the beginning of the Cold War led to a competition in the field of anti-air (AA) defenses between the United States and the Soviet Union. Ground-controlled radars capable to enable surface-to-air missile (SAM) batteries guaranteed the security of the air environment against a nuclear strike by a strategic bomber. Electronic countermeasures (e.g. chaff, jamming) did not suffice to deceive or disrupt a dense radar-guided AA defense environment. The United States emerged as a key player in developing a technology that, since its first introduction,

<sup>18</sup> Merrill I. Skolnik, "Radar," Encyclopædia Britannica (Encyclopædia Britannica, inc., May 7, 2020), <https://www.britannica.com/technology/radar>.

<sup>19</sup> Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), 16.

<sup>20</sup> For example, during the Battle of Britain (1940), the Chain Home early warning radar system of the United Kingdom allowed the Royal Air Force to forestall Germany's Luftwaffe air attacks. Those radars were capable of detecting approaching enemy aircrafts from 100 miles. The new technology enabled Britain to overcome the air power superiority of Germany. See Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), 18.



has been proving decisive for misleading air defenses based on radar guidance. This technology is known as “stealth”.

A stealth or low-observable (LO) aircraft can be defined as an aircraft that combines design, structural and technical properties to lower its radar signature in order to minimize the chance to be detected, tracked and engaged. Reducing the radar signature means reducing the aircraft’s radar cross section (RCS), which is crucial to decrease the defender’s radar range (Table 1) and, in turn, to increase the attacker’s survivability. The physics of radar scattering is largely dependent on the relationship between the size of the radar wavelength and the size of its target. The detection range is proportional to the fourth root of the radar cross section. This means that, in order to reduce detection range by a factor of ten, it is necessary to reduce the target aircraft’s RCS by a factor of 10,000 or 40 dBs<sup>21</sup>.

RCS (m <sup>2</sup> )	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 smaller RCS impacts on radar range<sup>22</sup>.

The most advanced LO aircraft design permits to control the electromagnetic spectrum (EMS) in order to reduce radio frequency, infrared, electro-optical, and acoustic sensor capabilities<sup>23</sup>. A very small radar signature can create gaps even in a dense AA defense network, allowing the aircraft to bypass overlapping SAM ring coverage<sup>24</sup>. Indeed, all SAMs take time to detect, track, acquire and fire. A stealth aircraft that reduces the range of early warning systems and fire control radars can achieve its target, strike, and come back home safely<sup>25</sup>. However, it should be recalled that stealth is not a synonym of “invisible” because, at least to date, it is

<sup>21</sup> Crickmore, Paul. *Lockheed F-117 Nighthawk Stealth Fighter Manual*. Air Vanguard. Oxford, U.K.: Osprey Publishing, 2014, 27.

<sup>22</sup> Mark Barrett and Mace Carpenter, “Survivability in the Digital Age: The Imperative for Stealth” (Arlington, VA: The Mitchell Institute for Aerospace Studies, 2017), pp. 1-35, 3.

<sup>23</sup> Barrett and Carpenter, 8.

<sup>24</sup> Barrett and Carpenter, 8; Grant, 43.

<sup>25</sup> Grant, 43.

impossible to nullify the RCS of an aircraft. The chance to be detected, even if minimized, is always present. Stealth is not a panacea.

## The Master of Power Projection: U.S. Stealth Bomber Fleet

Long-distance power projection<sup>26</sup> is a bedrock of U.S. defense policy. Power projection can employ air, land and sea forces to enlarge a country's military reach. In particular, the capability of long-range strike is an important instrument of power projection:

With vital interests on the line, U.S. leaders must prioritize solutions that efficiently modernize America's military and ensure it will have the most effective tools available to execute the U.S. national defense strategy . . . Chief among these tools is global long-range strike—the ability to attack targets anywhere, at any time. When paired with an effective campaign strategy aimed at vital targets on which an enemy's military enterprise greatly depends, long-range strike is one of the most effective tools available to America's military commanders<sup>27</sup>.

The bomber had given remarkable contributions to the U.S. defense posture during the Cold War. The Strategic Air Command (SAC) bomber force was the mainstay of the nation's strategic deterrent. Albeit, over the years, ICBMs and SLBMs assumed increasingly central roles in the U.S. strategic nuclear arsenal, the bomber was still considered dependable because it provided adequate target coverage and hard-target coverage<sup>28</sup>. As already mentioned, the advent and the constant improvements of radar installations and Anti-Access/Area-Denial (A2/AD) weapon systems made the task of strategic bombers more difficult. For this reason, U.S. defense contractors started to concentrate their R&D on stealth technology.

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<sup>26</sup> The ability to conduct expeditionary warfare with the aim of intimidating other countries and implementing policy through the use, or the threat, of force in an area distant from homeland. See "Power Projection," Military Wiki, accessed July 7, 2020, [https://military.wikia.org/wiki/Power\\_projection](https://military.wikia.org/wiki/Power_projection).

<sup>27</sup> Mark Gunzinger, "Long-Range Strike: Resetting the Balance of Stand-in and Stand-off Forces" (Arlington, VA: Air Force Association, 2020), pp. 2-45, <https://www.mitchellaerospacepower.org/single-post/2020/06/18/Long-Range-Strike-Resetting-the-Balance-of-Stand-in-and-Stand-off-Forces>, 10. It should be clear that aircrafts, ships, submarines and land platforms are all able to launch long-range missiles but this paper focuses on air power, especially on strategic bombers.

<sup>28</sup> Michael E. Brown, "The U.S. Manned Bomber and Strategic Deterrence in the 1990s," *International Security* 14, no. 2 (1989): pp. 5-46, <https://doi.org/10.2307/2538853>, 8. ICBMs are Intercontinental Ballistic Missiles, SLBMs are Submarine-Launched Ballistic Missiles.

The stealth era opened between the 1960s and the 1970s. Two contractors stood out as innovators in “niche specialty-aircraft areas” such as stealth technology: Lockheed and Northrop<sup>29</sup>. Before the stealth revolution, Lockheed had already built two technologically advanced reconnaissance aircrafts: The U-2 and the SR-71 (Fig. 5 e Fig. 6)<sup>30</sup>. It must be considered that the U-2 and SR-71 were reconnaissance aircrafts. Both bomber and fighter aircrafts require different characteristics to fulfil their missions. Pushing performance features to the limit may be a necessary but not sufficient condition to avoid radar detection. The Vietnam War is a blatant example of the problems of survivability U.S. aircrafts had against well-organized radar guided SAMs batteries.



**Figure 5.** Lockheed U-2 (Flickr, Lockheed Martin. Available from: [https://www.flickr.com/search/?user\\_id=10062223%40N06&view\\_all=1&text=u-2](https://www.flickr.com/search/?user_id=10062223%40N06&view_all=1&text=u-2))

<sup>29</sup> Mark A. Lorell, *The U.S. Combat Aircraft Industry, 1909-2000: Structure, Competition, Innovation* (Santa Monica, CA: RAND, 2003), pp. 97-117, 98.

<sup>30</sup> The stealthiness of the U-2 was due to its capability to fly at very high altitudes. Built in 1955 and still in service today, it can reach a ceiling of 70'000 ft, it has a range of 3000 nautical miles unrefueled and a cruise speed of 475 mph. The SR-71, introduced in 1966 and retired in 1998, remains one of the most advanced aircrafts ever built, with a maximum speed of Mach 3+ and a ceiling of 85'000 ft. Compared to the U-2, the SR-71 can be considered the first stealthy military aircraft. Indeed, it was assembled with radar-absorbing materials (RAM) for structural edges and radar-absorbing coatings for the fuselage. When a first U-2 was torn down by Soviet SA-2s in 1960, and a second two years later, it was acknowledged that high altitude did not suffice to avoid radar-guided SAMs. Lockheed resolved part of the problem by building an aircraft that could combine both high ceiling and high altitude: the SR-71. However, it was clear that pushing performance features to the limit was not the solution. See “U-2 High-Altitude Reconnaissance Aircraft, United States of America,” Airforce Technology, accessed July 8, 2020, <https://www.airforce-technology.com/projects/u-2-aircraft/>; Mark A. Lorell, “The Stealth Revolution,” in *The U.S. Combat Aircraft Industry, 1909-2000: Structure, Competition, Innovation* (Santa Monica, CA: RAND, 2003), pp. 97-117, 101; Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), 25.



**Figure 6.** *Lockheed SR-71* (Flickr, Lockheed Martin. Available from: [https://www.flickr.com/search/?user\\_id=10062223%40N06&view\\_all=1&text=sr-71](https://www.flickr.com/search/?user_id=10062223%40N06&view_all=1&text=sr-71))

## Lockheed F-117 “Nighthawk”

On April 1976, Lockheed won a competition against Northrop to design and produce a combat aircraft with low RCS configurations and materials. Under a program named “Have Blue”, the Skunk Works<sup>31</sup> started to work on two experimental projects (XST, Experimental Survivable Testbed)<sup>32</sup>. The end product was astonishing: The F-117 “Nighthawk” (Fig. 7). Its maiden flight was in 1981 but it was made public only in 1988.

The F-117 was an attack bomber, the first operational stealth aircraft in the world. The main feature was its unusual, highly faceted design which accounted for its low observability.

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<sup>31</sup> The Advanced Development Programs (ADP), better known as “Skunk Works”, is the division of the Lockheed Martin Corporation which deals with experimental projects. Most of their programs are kept secret.

<sup>32</sup> Mark A. Lorell, *The U.S. Combat Aircraft Industry*, pp. 97-117, 104.





**Figure 7.** *Lockheed F-117 “Nighthawk”*. It had a length of 65 ft, a height of 12 ft and a wingspan of 43 ft. It could reach high subsonic speed (617 mph) and it had an unrefueled range of 1070 miles (Flickr, Lockheed Martin. Available from: [https://www.flickr.com/search/?user\\_id=10062223%40N06&view\\_all=1&text=f-117](https://www.flickr.com/search/?user_id=10062223%40N06&view_all=1&text=f-117))

The F-117 had an extraordinarily low RCS:  $0.0025 \text{ m}^2$  (Fig. 8). To make a comparison, the B-52 Stratofortress has an RCS of  $100 \text{ m}^2$ . The slab-sided aspect of the F-117 safeguarded from specular reflection and reduced diffraction, minimizing the total radar return. Swept wings protected the front of the plane from radar energy and the shielded canopy prevented radar reflection. Furthermore, the radar cross section was further reduced by radar-absorbing materials that covered the whole body<sup>33</sup>. Engine inlets were placed above the wings and inlet ducts curved very slightly down to the compressor, acting as a shield. Moreover, engine intakes were protected by grids to impede radar waves from entering and reflecting back to the receiver<sup>34</sup>. Cockpit’s windows were metalized to prevent radar energy reflection after hitting corner reflectors<sup>35</sup>. Other

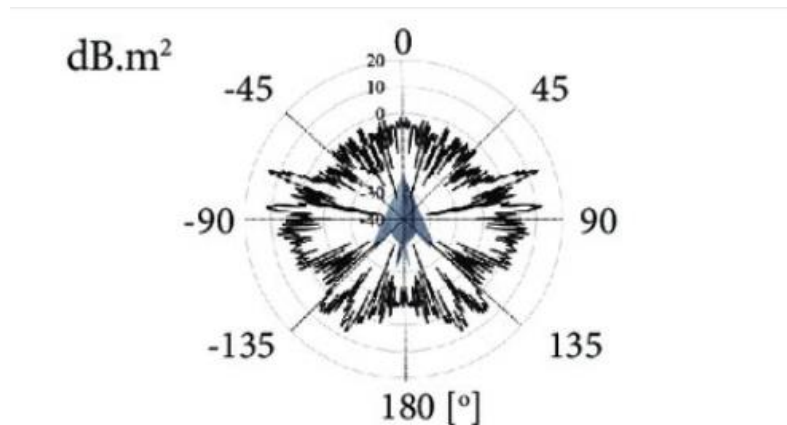
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<sup>33</sup> Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), 34-35.

<sup>34</sup> Crickmore, Paul F. *Lockheed F-117 Nighthawk Stealth Fighter*. Vol. 16, Osprey Publishing, 2014, 27-28; Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), 34-35.

<sup>35</sup> Crickmore, Paul F. *Lockheed F-117 Nighthawk Stealth Fighter*. Vol. 16, Osprey Publishing, 2014, 27-28.

important stealthy elements were the absence of right angles in the tails, of exposed ordnance and of gaps or seams in the entire surface.



**Figure 8.** *F-117 Radar Cross Section (RCS)*<sup>36</sup>. It can be noticed that signature reduction is smaller in front and rear aspects whereas it is larger on the sides. This type of signature is called “bowtie”.

The F-117 demonstrated what a stealth aircraft is capable to achieve. Indeed, it has a near-perfect combat record: it took part to six different military operations and, over the 59 produced, only 1 was shot down<sup>37</sup>. The loss of an F-117 in Kosovo by an old SA-3 ground-to-air missile shocked the United States Air Force (USAF). Stealth technology discovered to have limits. If the highly advanced F-117 could be tore down by a non-sophisticated radar-guided SAM, what could happen in future, as radar systems and guided weapons will make progresses?

### Rockwell B-1B Lancer

The F-117 was an attack bomber and, therefore, not ideal for nuclear deterrence. That task is carried out by strategic bombers. Throughout the Cold War, the Strategic Air Command had been searching a new strategic bomber to replace the illustrious B-52 Stratofortress. Between

<sup>36</sup> Kuizhi Yue, Shichun Chen, and Changyong Shu, "Calculation of Aircraft Target's Single-Pulse Detection Probability," *Journal of Aerospace Technology and Management* 7, no. 3 (2015): [PAGE], accessed July 9, 2020, doi:10.5028/jatm.v7i3.470).

<sup>37</sup> The F-117 was employed in the Operation Just Cause (1989-1990), Operation Desert Shield (1990-1991), Operation Desert Storm (1990-1991), Operation Allied Force (1999), Operation Southern Watch (1992-2003), and Operation Iraqi Freedom (2003-2011). During the Operation Desert Storm, its service record was remarkable. No F-117 was lost and neither damaged. It flew 1271 sorties with an 80% mission success rate. Although it represented only 2% of all combat sorties, it covered 40% of strategic targets. The aircraft seemed so unbeatable that was the only one allowed to enter Baghdad's boundaries to carry out a mission. The F-117 managed to deceive the dense IADS of Iraq. Its invincibility ended in 1999, during Operation Allied Force, when one F-117 was shot down by an old Serbian SA-3 ground-to-air missile. It was retired from service in 2008.

the 1960s and 1970s, the SAC has employed two non-stealth strategic bombers: the Convair B-58 Hustler and the North American XB-70 Valkyrie. However, both aircrafts revealed to be a failure<sup>38</sup>. A supersonic bomber capable to fly at low level, avoiding Soviet SAMs, was needed. After almost two decades of trials and financial hassles, the Rockwell B-1B Lancer entered the production line in 1984 and became operational in 1986 (Fig. 9).



**Figure 9.** *Rockwell B1-B Lancer*. It has a wingspan of 137 ft extended forward and of 79 ft swept aft. It measures 34 ft in height and 146 ft in length. Its speed can amount to 900-plus mph (Mach 1.2 at sea level). (U.S. Air Force photo by Staff Sgt. Clayton Cupit)

The B1-B is a long-range, multi-role strategic bomber. It can reach a ceiling of more than 30'000 ft and it has a range of 7'500 miles. Compared to the previous version B-1A<sup>39</sup>, the B-1B is

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<sup>38</sup>Jerry Hendrix and James Price, "Higher, Heavier, Farther, and Now Undetectable? Bombers: Long-Range Force Projection in the 21st Century" (Washington, D.C.: Center for a New American Security, 2017), pp. 3-70, 41-44. The B-58 has been in service only for ten years (1960-1970), the XB-70 even less, five years (1964-1969). They were considered failed designs since their in-flight performance revealed many problems. Moreover, the two bombers fell victim of a change in the U.S. doctrine. Indeed, the B-58 and XB-70 were high speed, high altitude aircrafts but those requirements became useless against the improving Soviet's SAMs and interceptor aircrafts.

<sup>39</sup> From mid-1960s to mid-1970s a previous, similar version of the B-1 was planned and built: The B-1A. Due to high costs, government's preference on the development of air-launched cruise missiles, and the new Soviet fighter MiG-25, capable to reach very high altitudes and high speed, President Jimmy Carter canceled the program. See Jerry Hendrix and James Price, "Higher, Heavier, Farther, and Now Undetectable? Bombers: Long-Range Force Projection in the 21st Century" (Washington, D.C.: Center for a New American Security, 2017), pp. 3-70, 46.



heavier (from 395'000 lb to 477'000 lb) and slower (from a top speed of Mach 2.3 to Mach 1.2) but it can carry more ordnance (from nuclear weapons to conventional bombs). More importantly, it has a smaller RCS (one tenth of the B1-A) which totals 1 m<sup>2</sup>. This was an enormous improvement seeing as how the RCS of the “colleague” B-52 was, and still is, 100 m<sup>2</sup>.

The B-1B displays a blended wing/body configuration, variable-sweep wings and turbofan afterburning engines, which provide long range, maneuverability and high speed while enhancing survivability<sup>40</sup>. The stealthiness originates from its self-protection electronic jamming equipment, radar warning receiver (ALQ-161) and electronic countermeasures system (i.e. chaff and flares) and a towed decoy system (ALE-50); they all complement the aircraft's low-radar cross-section to form an integrated defense system that permits it to fly behind enemy lines at low altitude<sup>41</sup>.

The effectiveness of the B1-B is unquestionable. According to the USAF, the B-1B holds almost fifty world records for speed, payload, range, and time of climb in its class<sup>42</sup>. It carried out several conventional bombings during various operations in Kosovo, Iraq and Syria. The aircraft is still employed today and the U.S. bomber fleet counts 62 B1-B. However, the B-1B was mapped out to penetrate Soviet air defenses, not the modern integrated air defense systems (IADS) of today's Russia (and China)<sup>43</sup>. The B1-B did not top the U.S. strategic bomber fleet off. Stealth technology needed to be pushed to the limit.

## Northrop B-2 “Spirit”

The increasingly advanced and dense anti-air defense environment of the Soviet Union distressed the U.S. government. Therefore, in 1974 the Defense Advanced Research Projects Agency (DARPA) commissioned to Lockheed and Northrop a study on the possibility to build a stealthier aircraft<sup>44</sup>.

Northrop gathered most of its resources for the Advanced Technology Bomber (ATB) program, in which Lockheed participated too. The ATB had far-reaching goals. The next bomber should fly 6'000 miles unrefueled, carry 20 tons of ordnance and have a low radar and infrared signature<sup>45</sup>. Northrop's project won the competition against Lockheed, as its prototype was best-

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<sup>40</sup> U.S. Air Force, “B-1B Lancer,” December 16, 2015, <https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104500/b-1b-lancer/>.

<sup>41</sup> Ibid.

<sup>42</sup> Ibid.

<sup>43</sup> Mark Gunzinger, “Long-Range Strike: Resetting the Balance of Stand-in and Stand-off Forces” (Arlington, VA: Air Force Association, 2020), pp. 2-45, <https://www.mitchellaerospacepower.org/single-post/2020/06/18/Long-Range-Strike-Resetting-the-Balance-of-Stand-in-and-Stand-off-Forces>, 7.

<sup>44</sup> Jerry Hendrix and James Price, “Higher, Heavier, Farther, and Now Undetectable? Bombers: Long-Range Force Projection in the 21st Century” (Washington, D.C.: Center for a New American Security, 2017), pp. 3-70, 47.

<sup>45</sup> Ibid.

performing and “stealthier”. In 1981 Northrop started the development program of the B-2 “Spirit” (Fig.10), which entered full-scale production in 1987. Finally, the United States has its multi-role stealth heavy bomber.



**Figure 10.** *Northrop B-2 “Spirit”*. The B-2 has a flying wing structure. The wingspan measures 172 ft. It has a length of 69 ft and a height of 17 ft. It can climb to 50’000 ft in altitude and can fly at high subsonic speed (Flickr, U.S. Air Force. Available at [https://www.flickr.com/search/?user\\_id=39513508%40N06&view\\_all=1&text=b-2](https://www.flickr.com/search/?user_id=39513508%40N06&view_all=1&text=b-2))

The ultimate version of the B-2 has noteworthy characteristics<sup>46</sup>. It can climb up to 50’000 feet and fly 6’000 miles without air refueling. The bomb bay can carry more than 18 tons of ordnance. The speed can achieve high subsonic digits. The most striking feature of the B-2 is its

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<sup>46</sup> During the development of the B-2, USAF’s concern over counter stealth capabilities of the Soviet Union did not appease. Consequently, the Air Force decided to redesign the B-2 in the 1980s. The airframe was modified and strengthened, and its aerodynamics was adjusted in order to allow low-altitude flight<sup>46</sup>. However, these alterations brought about significant additional costs to an already very expensive program. Moreover, features required to fly at low altitude made the B-2 less stealthy: engineers added an extra chevron-shaped surface and extra moving parts on the trailing edges, which increased the RCS. The B-2 redesign also caused a reduction in range and payload. See Jerry Hendrix and James Price, “Higher, Heavier, Farther, and Now Undetectable? Bombers: Long-Range Force Projection in the 21st Century” (Washington, D.C.: Center for a New American Security, 2017), pp. 3-70, 47-48.

stunningly low radar cross section:  $0.0001 \text{ m}^2$ . As an all-aspect RCS reduction is only theoretical, the B-2 signature type may be the “bowtie” (see figure 8). Several features make it so stealthy. First, trailing edges are held at constant angles to guarantee that radar energy reflects away from the rear. Second, there are no vertical control surfaces. Third, the structure is covered by radar-absorbing material. Fourth, the bomb bay is located within the aircraft to avoid radar reflection. Finally, the engine inlets and exhaust are placed on the top of the aircraft and buried in order to deceive infrared (IR) sensors<sup>47</sup>.

The remarkable, stealth capabilities of the “Spirit” are described by the U.S. Air Force:

The B-2 Spirit is a multi-role bomber capable of delivering both conventional and nuclear munitions. A dramatic leap forward in technology, the bomber represents a major milestone in the U.S. bomber modernization program. The B-2 brings massive firepower to bear, in a short time, *anywhere on the globe through previously impenetrable defenses*<sup>48</sup> (emphasis added).

Therefore, what the USAF judged impossible to achieve with the B-1B is now deemed feasible with the B-2. The high survivability of the B-2 allows it to reduce its time in jeopardy and to bypass dense IADS packed of radar-guided SAMs (Fig. 11).

Only the USAF fleet of 20 B-2s is capable of penetrating advanced IADS, of which 16 are assigned to combat squadrons so they can perform their warfighting missions. Therefore, only these 16 B-2s constitute the whole of the country’s long-range penetrating strike force<sup>49</sup>. The USAF is experiencing a growing gap in its long-range strike capacity, considering that 87 percent of its bombers cannot penetrate contested, radar-controlled environments. For these reasons, the U.S. government looks at the future with apprehension. Will stealth retain its advantage against the improving radar technology and proliferating IADS? Will the new Air Force stealth bomber, the forthcoming B-21 Raider, satisfy the need of an aircraft able to face ever-growing anti-air defense systems?

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<sup>47</sup> The heat emitted by jet engines has always been a problem even for stealth aircraft because that heat increases IR signature and, consequently, the visibility to ground-based IR sensors.

<sup>48</sup> U.S. Air Force, “B-2 Spirit,” U.S. Air Force, December 16, 2015, <https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104482/b-2-spirit/>.

<sup>49</sup> Mark Gunzinger, “Long-Range Strike: Resetting the Balance of Stand-in and Stand-off Forces” (Arlington, VA: Air Force Association, 2020), pp. 2-45, <https://www.mitchellaerospacepower.org/single-post/2020/06/18/Long-Range-Strike-Resetting-the-Balance-of-Stand-in-and-Stand-off-Forces>, 12.

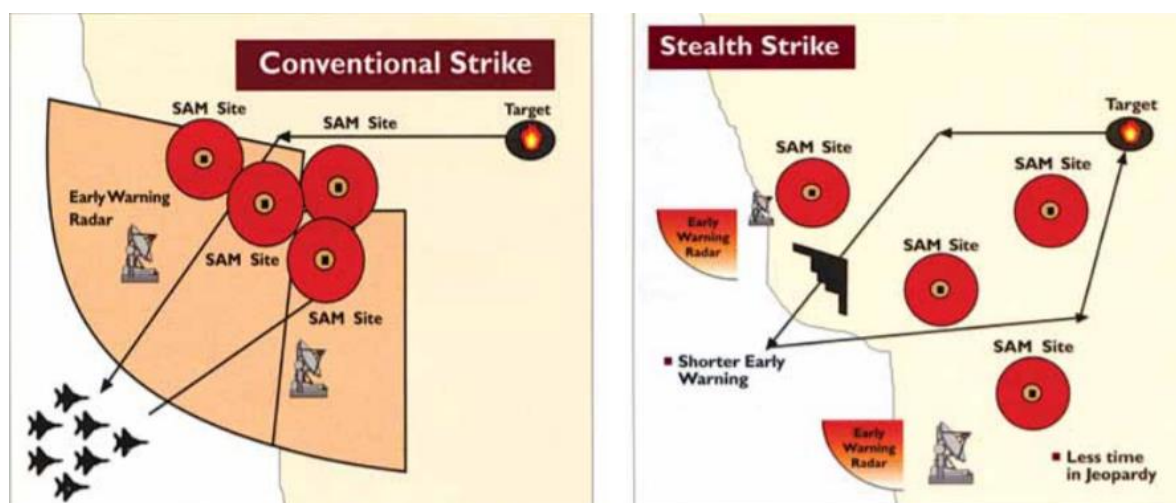


Figure 11. *Conventional strike vs. Stealth strike*<sup>50</sup>

## The Uncertain Future of Stealth

About four decades have passed since first stealth aircrafts left the production line in the 1980s. Nevertheless, nowadays United States Air Force fleet counts only 396 stealth aircrafts<sup>51</sup>. It seems that the Pentagon has held back demands to establish a conspicuous stealth fleet. Restraints to boost the number of LO fighters and bombers do not originate from a lack of resources, rather from a shortage of political will. Stealth technology is a huge financial burden for federal coffers. One should bear in mind that, for instance, the cost for a single B-2 surpasses one billion dollars. This is the main reason for the limited quantity produced. Throughout the Cold War, financial worries cushioned for two main reasons: for the sake of technological innovation and, especially, because credible nuclear and conventional deterrence was at stake vis-à-vis the Soviet Union. As Rebecca Grant underlines, “the early stealth programs were immensely complicated, but strong leadership and a clear calculation of national interest allowed the programs to press on through their difficult times”<sup>52</sup>. In recent years, the development of low-observable technology has become more a hefty burden than a purposeful instrument of national interest.

<sup>50</sup> Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), 44.

<sup>51</sup> 20 B-2s, 166 F-22s, 210 F-35s. U.S. Air Force, “United States Air Force. Fiscal Year 2019 Budget Review” (The Pentagon, VA: SAF/FM, 2019), pp. 1-40, [https://www.saffm.hq.af.mil/Portals/84/documents/FY19/FY19\\_BOB\\_FINAL\\_v3.pdf?ver=2018-02-13-150300-757](https://www.saffm.hq.af.mil/Portals/84/documents/FY19/FY19_BOB_FINAL_v3.pdf?ver=2018-02-13-150300-757), 37.

<sup>52</sup> Rebecca Grant, “The Murky Future of Stealth,” July 9, 2020, <https://www.airforcemag.com/article/0209stealth/>.

Counter stealth capabilities are being studied tirelessly since decades. Well-known techniques to contrast LO technologies consist in employing very high frequency (VHF) and ultra-high frequency (UHF) radar, and passive radar<sup>53</sup>. However, they all have some limitations. With regards to the first two, ultra-wide band radar can emit waves at different frequencies in order to



**Figure 12.** A traditional IRST system mounted on a Russian Su-27 (Available from: <https://commons.wikimedia.org/wiki/File:Regiment100thAnniversary2018-08.jpg>)

detect a stealth aircrafts but transmitting over a wide band results in a drop of power in each band, making the radar less efficient. Then, bistatic or multistatic radar like passive ones may have some advantages but also fundamental technical and operational difficulties<sup>54</sup>.

An emerging challenge for stealth technology consists of next generation Long-Wave Infrared Search and Track (LW-IRST) sensor (Fig. 12)<sup>55</sup>. The LW-IRST system will enable long range passive detection and tracking against LO aircrafts. However, the system has not spread as expected, given its flaws<sup>56</sup>. Even though the technology may

improve in future, cost and capability limitations does not make LW-IRST system a potential clincher in the radar-stealth competition in the near future.

Another potential threat to stealth technology is the “wake detection”<sup>57</sup>. It consists of detecting the atmospheric disturbances created by the aircraft when it flies through air. Wake detection can be captured by pulse Doppler radar or laser-based light detection and ranging

<sup>53</sup> Arend G. Westra, “Radar vs. Stealth: Passive Radar and the Future of U.S. Military Power” (Washington, D.C.: National Defense University Press, 2009), pp. 136-143, 138. VHF and UHF radar uses decimeter- to meter-long wavelength, instead of the usual centimeter long wavelength. If a radar beam of longer wavelengths illuminates an aircraft, the latter’s RCS increases. Moreover, the RCS increases even when the radar wavelength is in the same order of magnitude as the target because radar waves and the aircraft resonate. Thus, longer wavelength and resonance of VHF and UHF radar increase the chances to detect a LO aircraft. Passive radar is a recently emerging technology. It uses transmitters of opportunity (e.g. AM and FM radios, televisions, mobile phone networks, etc.) and it is configured as a multistatic system, as it employs three or more transmitters and receivers. The radar measures the travel time between the direct signal from the transmitter and the reflected signal from the target to determine the bistatic range. The target location is found using the intersection of the receiver-to-target bearing and the bistatic range.

<sup>54</sup> The receiver antenna beam of a bistatic radar, for example, has to intercept the transmit beam and follow the transmit pulse that is moving at the speed of light. Unless the receiver and the transmitter are in synchrony, measurement of the distance is impossible. Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), 54.

<sup>55</sup> Mark Barrett and Mace Carpenter, “Survivability in the Digital Age: The Imperative for Stealth” (Arlington, VA: The Mitchell Institute for Aerospace Studies, OAD), pp. 1-35, 24.

<sup>56</sup> Few NATO aircrafts are equipped with LW-IRST sensor whereas China and Russia have not made meaningful progress in its deployment. One reason is that infrared search and track sensors’ effective range, operational effectiveness, and field of view (i.e. search capability) face significant limitations under adverse environmental conditions. A conventional radar, instead, retains its efficacy even in bad weather. See Barrett and Carpenter, 24.

<sup>57</sup> Barrett and Carpenter, 27.



(LIDAR)<sup>58</sup>. To date, wake detection has some blemishes. For instance, radar wake detection range is less than ten miles and it suffers adverse environmental conditions as LIDAR-based, optical radar are highly sensitive.

Lastly, what also concerns the United States are SAM systems, in particular Russian S-400 (NATO codename: SA-21, Fig. 13). These missiles have greater range (250 miles), higher speed (Mach 14) and greater maneuverability than their predecessors<sup>59</sup>. S-400 is mobile and networked into a wireless system. China and Russia are also improving their fleet with fifth-generation jet fighters (J-31 and Su-57 respectively). However, without further improvements in radar technology, new SAMs and fighters will struggle to tackle stealth aircrafts<sup>60</sup>.



**Figure 13.** S-400 (Available from: [https://commons.wikimedia.org/wiki/File:S-400\\_Triumpf-34.jpg](https://commons.wikimedia.org/wiki/File:S-400_Triumpf-34.jpg))

The future of stealth is defined “murky” by Rebecca Grant<sup>61</sup>, given the proliferation of new technologies potentially able to counter stealth. However, as the latter will all improve for years to come, so too will low observable technology<sup>62</sup>. Furthermore, one must remind that stealth purpose is not to make an aircraft invisible, but to deny to the enemy the capability to detect an attacking aircraft at long ranges. Colonel Mark Gunzinger (USAF, Ret.) describes this aspect properly:

A critical point to stress is that stealth does not make an aircraft invisible to enemy sensors; it denies an enemy information required to determine an aircraft’s position, altitude, speed, and direction of flight with enough accuracy to launch a successful intercept. *Many who criticize stealth as a waning advantage due to advances in air defense technologies fail to understand this point*—it is not about completely avoiding detection but preventing an enemy from completing an intercept—dramatically increasing a stealth aircraft’s probability of survival. U.S. advances in stealth technologies continue to outpace advances in air defense threats<sup>63</sup> (emphasis added).

<sup>58</sup> LIDAR determines distance to a target by pulsed laser light, by measuring the reflected pulses. Ibid.

<sup>59</sup> Barrett and Carpenter, 17.

<sup>60</sup> Barrett and Carpenter, 18.

<sup>61</sup> Rebecca Grant, “The Murky Future of Stealth,” July 9, 2020, <https://www.airforcemag.com/article/0209stealth/>.

<sup>62</sup> Ibid.

<sup>63</sup> Mark Gunzinger, “Long-Range Strike: Resetting the Balance of Stand-in and Stand-off Forces” (Arlington, VA: Air Force Association, 2020), pp. 2-45, <https://www.mitchellaerospacepower.org/single-post/2020/06/18/Long-Range-Strike-Resetting-the-Balance-of-Stand-in-and-Stand-off-Forces>, 14.

As already mentioned, U.S. government has been hesitant on whether making huge investments on LO aircrafts. Nevertheless, the Department of Defense never really backed down. First, counter stealth measures are not mature. Second, to fulfil their mission stealth air assets will not need, still for some time, what decades ago was considered crucial in air warfare: aerospace control or air supremacy. The United States is, thus, continuing to invest in low observable aircrafts. As a matter of fact, on February 26, 2016, Air Force Secretary Deborah Lee James showed a first, computerized picture of the next USAF stealth heavy bomber: The Northrop B-21 Raider.

## Northrop B-21 Raider

Little is known about the classified B-21 project. Until 2015, the whole program was secret. Then, even if technical specifications have remained confidential, the Air Force started to divulge some information about budget, procurement and acquisition strategy<sup>64</sup>. Notwithstanding the paucity of information, some speculation has come to light.

The B-21 Raider will be a multi-role, long-range, stealth heavy bomber (Fig. 14). It will gradually replace the fleet of B1-Bs and B-2s and, in the longer term, the fleet of the legendary B-52H<sup>65</sup>. The B-21 Raider is going to be the bedrock of future U.S. air power, as its operational purpose will be circumventing enemy's anti-access area-area denial (A2/AD) systems. Indeed, countries like Russia, China and Iran have developed advanced Integrated Air Defense Systems (IADS) capable to find, fix, track, target, engage, and assess (F2T2EA)<sup>66</sup> an incoming threat from hundreds of miles away. The U.S. needed a fifth-generation long-range penetrating bomber. The decision fell on a stealth bomber with traditional range and capable of carrying precision-strike weapons, both conventional and nuclear. The B-21 will be able to carry and fire the Long-Range Standoff Weapon (LRSO), a nuclear-tipped air-launched cruise missile (ALCM) that is being developed and will replace the current AGM-86B<sup>67</sup>

One may suppose that the operative purpose of the Raider will resemble that of the B-2. As already mentioned, its task will be penetrating dense anti-air defense systems deep into the enemy territory to take out A2/AD systems, paving the way to conventional aircrafts. Moreover,

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<sup>64</sup> Jeremiah Gertler, "Air Force B-21 Raider Long-Range Strike Bomber" (Washington, D.C.: Congressional Research Service, 2019), pp. 1-14.

<sup>65</sup> Ibid.

<sup>66</sup> The F2T2EA is called "kill chain". Namely, the sequence of actions that an attacker must complete in order to fulfil its mission successfully.

<sup>67</sup> 'The LRSO is designed to keep the entire bomber force, stealthy or not, credible as nuclear deterrent well into the future'. Indeed, B-1Bs and B-2s will be updated to make them capable of carrying LRSO. See Jerry Hendrix and James Price, "Higher, Heavier, Farther, and Now Undetectable? Bombers: Long-Range Force Projection in the 21st Century" (Washington, D.C.: Center for a New American Security, 2017), pp. 3-70, 52.



the B-21 will act as “a forward-deployed sensor and communication node and as a surveillance and possible electronic warfare platform”<sup>68</sup>.



**Figure 14.** *B-21 Raider*. Rendering by U.S. Air Force.

Technical specifications are kept secret. However, looking at the official USAF illustration (Fig. 14) and with a little imagination one can discern some things. First, the flying wing design takes inspiration from the B-2. The structure is similar, but the Raider has a single chevron-shaped angle on the trailing edge, minimizing the RCS against low-frequency radar, whereas the B-2 has three of it. It also means that the aircraft is streamlined to fly at medium-to-high altitude. The outboard wing section of the B-21 is longer, which may help increasing endurance and operational altitude<sup>69</sup>. The engine inlets, like those of the B-2, seem to be located on top of the aircraft, on the sides of the cockpit; the engines will probably be buried to avoid IR sensors. The bomb bay will also be concealed within the aircraft. The body will certainly be covered with radar-absorbing material (RAM). Furthermore, B-21 will employ open systems architecture<sup>70</sup>.

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<sup>68</sup> Hendrix and Price, 53.

<sup>69</sup> Ibid.

<sup>70</sup> Open architecture is a system that allows new sensors or other subsystems to be easily integrated into the aircraft. As a result, the initial B-21 aircraft can be ameliorated more easily as advanced technologies are developed; also, it means that what might otherwise be expensive development of advanced sensors and/or other subsystems may be deferred and/or competed independent of the aircraft itself. See Jeremiah Gertler, “Air Force B-21 Raider Long-Range Strike Bomber” (Washington, D.C.: Congressional Research Service, 2019), pp. 1-14, 5.

Second, some hypotheses can be made about B-21's performances. The speed will probably touch high subsonic digits, as design properties suggest an airspeed comparable to that of the B-2. The Raider will probably be able to climb up to an altitude of 50'000 ft. The range will be comprised between 4'000 and 5'000 nautical miles. Finally, the payload will be of the same quantity of the B-2, or at least between 15 tons and 18 tons as someone claims<sup>71</sup>.

Third, the strong point of the B-21 will be its stealthiness. The RCS will presumably measure "between the size of a bumblebee and a golf ball"<sup>72</sup>. It will turn into an almost invisible entity in the sky, capable to fly through defensively dense areas. In case of detection, the Raider will have at its disposal sensors, self-jamming equipment, extremely advanced onboard computers and other kits to carry out electronic warfare.

The Air Force has announced that it hopes to acquire at least one hundred B-21s, starting probably by 2025. The Raider is going to be the benchmark of U.S. long-range, nuclear-capable, bomber force and, in addition, it will gradually replace the fleet of B-1Bs and B-2s. Moreover, the higher the number of aircrafts procured, the lower the lifecycle ownership costs<sup>73</sup>.

If it will meet expectations, the B-21 could be a thorn in the side for U.S. enemies. The very low observability, the capability to carry out electronic warfare, the capability to fire both conventional and nuclear weapons, and its alleged great flight performances will make it a fearsome deterrent. The key advantage of the Raider will be its "its ability to sit in the middle of the battlespace, hearing all, seeing all, and yet remaining undetected, choosing its moment to have effect and then silently moving on without even an annoying buzz"<sup>74</sup>.

## Conclusion

**S**tealth is a revolutionary technology because it has changed the nature of air warfare<sup>75</sup>, much like the invention of the radar in the 1930s. The coexistence of the two antithetical technologies has triggered the hider-seeker competition.

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<sup>71</sup> Mark Gunzinger, "Long-Range Strike: Resetting the Balance of Stand-in and Stand-off Forces" (Arlington, VA: Air Force Association, 2020), pp. 2-45, <https://www.mitchellaerospacepower.org/single-post/2020/06/18/Long-Range-Strike-Resetting-the-Balance-of-Stand-in-and-Stand-off-Forces>, 54.

<sup>72</sup> Jerry Hendrix and James Price, "Higher, Heavier, Farther, and Now Undetectable? Bombers: Long-Range Force Projection in the 21st Century" (Washington, D.C.: Center for a New American Security, 2017), pp. 3-70, 55.

<sup>73</sup> Jeremiah Gertler, "Air Force B-21 Raider Long-Range Strike Bomber" (Washington, D.C.: Congressional Research Service, 2019), pp. 1-14, 9.

<sup>74</sup> Jerry Hendrix and James Price, "Higher, Heavier, Farther, and Now Undetectable? Bombers: Long-Range Force Projection in the 21st Century" (Washington, D.C.: Center for a New American Security, 2017), pp. 3-70, 55.

<sup>75</sup> Kevin J. Kennedy, "Stealth: A Revolutionary Change to Air Warfare," *Naval War College Review* 46, no. 2 (1992): pp. 118-136, <https://doi.org/10.21236/ada249880>, 119.

The British were the first to discover the usefulness of the radar. The new machinery bore its fruit in 1940s, when the Royal Air Force resisted Germany's Luftwaffe air raids and numerical superiority thanks to early detection. About two decades before, visual detection was the only way to sense an incoming aircraft. The limits were evident. An aircraft can be seen to the naked eye only few miles away and in excellent weather conditions<sup>76</sup>. The famous phrase pronounced in 1932 by Stanley Baldwin – “the bomber will always get through” – stood the reason at the time. As soon as the radar was invented, this sentence lost its truth.

Usually, the advent of a countermeasure produces a scramble to find a counter-countermeasure. Research on stealth technology started between the end of the 1950s and the beginning of the 1960s in the United States. “Stealth” is the ability to reduce an aircraft's radar cross section to avoid enemy air defenses to discover, track and engage an attacking aircraft<sup>77</sup>. The United States has always been at the forefront in the development of stealth technology. Prodigious aircrafts like the U-2 and the SR-71 foretold future advancements in stealth aircrafts for the U.S. The Air Force has focused on its bomber force since the final phase of the Cold War. U.S. contractors have produced formidable stealth aircrafts over the years, such as the F-117 attack bomber, and the B-1B and B-2 long-range heavy bombers.

The traditional mission of the non-stealth heavy bomber has always been to penetrate deep behind enemy lines to strike enemy's centers of gravity. This task became more complex with the advent of the radar, due to the high risk of early-warning detection. In addition, during the Cold War, non-stealth, nuclear capable heavy bombers like the B-52 were the main nuclear deterrent against the Soviet Union, as they were able to reach the enemy territory and strike its nuclear payload. The improvements in radar sensors and the development of A2/AD with IADS tangled air power doctrine even more. Manufacturing low observable heavy bombers was extremely important because nuclear deterrence vis-à-vis the Soviet Union was at stake.

Counter stealth measures are being studied. Very high frequency (VHF) and ultra-high frequency radar (UHF) radar, passive radar, infrared sensors like the LW-IRST, wave detection and technologically improved integrated air defense systems with advanced SAMs are a threat for stealth technology. However, all these systems have proved to be at an early stage of development<sup>78</sup>. Furthermore, as radar technology improves over time, so does stealth technology. It can be claimed that, in the near term, low observable aircrafts are not in jeopardy. The next stealth long-range, heavy bomber of the U.S. Air Force, the B-21 Raider, could be able to penetrate through advanced air defenses. The combination of high performances and extremely low RCS will make it a resolute machine that could put U.S. nuclear-capable bomber fleet at a crossroad against countries like China, Iran and Russia.

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<sup>76</sup> Today, for example, an individual is able to see an F-16 at three miles in a sunny day.

<sup>77</sup> Mark Barrett and Mace Carpenter, “Survivability in the Digital Age: The Imperative for Stealth” (Arlington, VA: The Mitchell Institute for Aerospace Studies, OAD), pp. 1-35, 29.

<sup>78</sup> Actually, SAM systems can be judged well-developed and combat ready.

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