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# ANALOGUES OF *Stealth*

by

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## IN BRIEF

The U.S. Department of Defense plans to invest hundreds of billions of dollars in stealthy aircraft over the next several decades. Will low-observable (LO) capabilities incorporated in military aircraft such as the B-2 bomber, the F-22 air superiority fighter and the F-35 joint strike fighter prove as successful and enduring as submarine stealth? To address that question, this paper briefly explores antisubmarine warfare, examines the development and fielding of low-observable aircraft, and suggests analogues between stealthy platforms in the sea and in the air.

When those analogies are drawn, many of the same reasons the submarine has proven so difficult to detect, track, fix, and destroy also pertain to stealthy aircraft. The friction of combat, the platform operators' ability to modify their tactics, the technology of denying more than fleeting contacts, and the problem of looking for small things in large volumes all apply. The submarine's long-term success suggests that properties inherent in low-observable combat platforms provide an enduring competitive military advantage to those who produce, maintain and continually improve them. It stands to reason, therefore, that stealthy aircraft should maintain an enduring edge over anti-aircraft defenses, providing their sponsors constantly study and exploit the environment, and take prompt and sustained corrective actions to negate enemy countermeasures.

<sup>1</sup> This paper adopts the same title and thesis presented in an article the authors published a decade ago, but explores the issues quite differently. See "Analogues of Stealth" in *Comparative Strategy* (Vol. 10, No. 3) pp. 257-271. Copyright 1991, Taylor and Francis. Now, as then, we acknowledge James G. Roche for encouraging us to examine the similarities between stealthy submarines and aircraft. We would also like to thank our colleagues in the Northrop Grumman Analysis Center for their assistance, especially John Backschie, Mary Hubbell and Adam Siegel.

## INTRODUCTION: ANALOGUES OF STEALTH

Recent claims regarding the detection and vulnerability of low-observable aircraft like the B-2 bomber are reminiscent of similar reports issued over the years postulating the demise of the submarine's stealth. Comparing submarines and aircraft employing stealth—low-observable technologies and tactics—results in several analogies useful in refuting these claims:

- Each system operates in a three-dimensional environment facilitating low observability: vast stretches of sea and sky.
- They can use terrain features (ocean trenches, mountain ranges) to mask their presence from sensors.
- They can vary their immersion within the environment (depth, altitude) and use its characteristics (i.e., temperature, weather, or darkness) to add measures of stealthiness.
- They can reduce to varying degrees their observable signatures (through sound-deadening techniques, infrared shielding, or cooling).
- They can avoid or attack active means of detection (sonar, radar) and make themselves less detectable by spoofing or jamming those systems.
- Finally, owing to these properties stealth provides, they each enjoy the tactical advantage of choosing when to engage the adversary in combat.

With these analogies in mind, this paper explores similarities between low-observable submarines and aircraft with the purpose of examining the staying power of stealth.<sup>2</sup> To accomplish that, we first briefly review the history of anti-submarine warfare (ASW)—a story of the search for countermeasures against a platform that from the outset was designed to use the environment to mask its presence. Yet, ever since submarines entered military operations, claims have emerged that some new technology will make them obsolete. Time and again those claims have proved baseless. With continued modernization and modification, the submarine's signature has been reduced to the point where the “noisy” nature of its operational environment hides its position and dramatically reduces or neutralizes the effectiveness of various detection means. Indeed, every nuclear-powered U.S. submarine was quieter, that is, more stealthy, when decommissioned than when it was launched.

It is our contention that low-observable aircraft, when they reach the end of their service life, should also be retired in a more stealthy condition than that of their first flight. Seeking to support that contention, the paper next outlines the development and employment of airborne stealth. Although the story of air defense begins with observers on the ground and in the air, since World War II air defenses have relied primarily

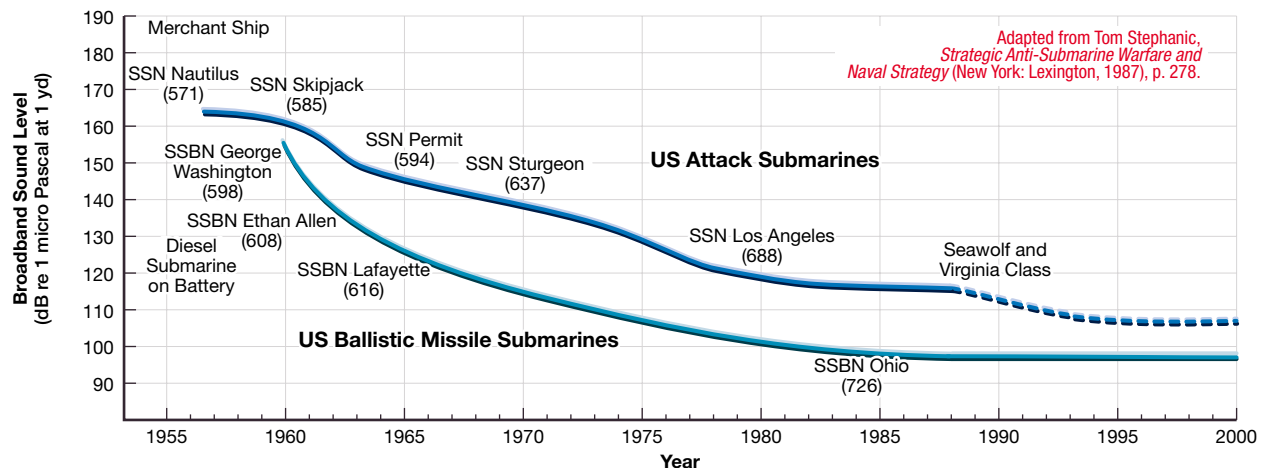


Figure 1. This estimate of total radiated sound levels for US nuclear submarines suggests a noise reduction of 60 dB over 45 years. Modern submarines emit about one-millionth of acoustic energy as did their predecessors.

<sup>2</sup> There are differences as well, most notably that the submarine achieves its stealth primarily by submerging, while a stealthy aircraft operates in the same medium as non-stealthy planes. We believe the comparisons far outweigh the contrasts, particularly with regard to the mutual need to counter detection technologies and the operational advantages that accrue to stealthy combat platforms whether in the sea or in the air.

on radar to detect, track, and subsequently engage hostile aircraft. That said, optical detection is still pursued, as are detection techniques seeking other aircraft signatures such as heat, radio communications, and even turbulent wakes in the atmosphere.

Although the atmosphere provides some natural hiding places for aircraft, such as clouds and darkness, an airplane's signature must be lowered to survive in a hostile environment. Using stealth technology, aeronautical engineers reduce an aircraft's susceptibility to radar detection and mitigate its observable infrared, electromagnetic, visual and acoustic signatures. Indirect or passive measures diminish the contrast between an aircraft's profile and its physical or electromagnetic surroundings. For example, camouflage paint allows an aircraft to blend into the background, while aircraft threat-warning systems enable search radar evasion. Countermeasures include presenting an incoming anti-aircraft missile with a false signature to lead it astray, using focused light, flares or lasers to lure an infrared seeker, and employing active jamming or deploying a towed decoy to deflect radar terminal guidance. Using these multi-spectral signature reduction techniques, low-observable aircraft deny current detection methods to a degree comparable to the modern submarine's ability to counter anti-submarine warfare capabilities.

Finally, we draw analogies between the game of measure and countermeasure characterizing the hunt for stealthy platforms in the air and beneath the sea, speculate on future challenges, and conclude with some implications for the long-term competitive advantage stealth provides. A theme throughout the paper implies that those forecasting the impending demise of low-observable aircraft may be falling into the same sort of traps as those who wrongly predicted the degradation of the submarine's stealth. But we hasten to warn that maintaining a combat platform's stealth is neither a naturally occurring nor a self-sustaining phenomenon. As a proven and essential capability of future U.S. power projection forces, stealth, to

survive, must be accorded the attention and the resources it deserves.

### Anti-Submarine Warfare: Countering Underwater Stealth

Attempts to degrade the submarine's inherent stealthiness through ASW have evolved through numerous techniques and technologies. Initially, ASW relied on a submarine compromising its stealth by operating in a non-submerged mode or raising its periscope above the ocean's surface. Before World War II, technological innovations led to active means of detection (e.g., sonar) to search for submerged submarines. During World War II, ASW exploited the nonstealthy aspects of a submarine's behavior by employing radar when the sub was required to operate on the surface,

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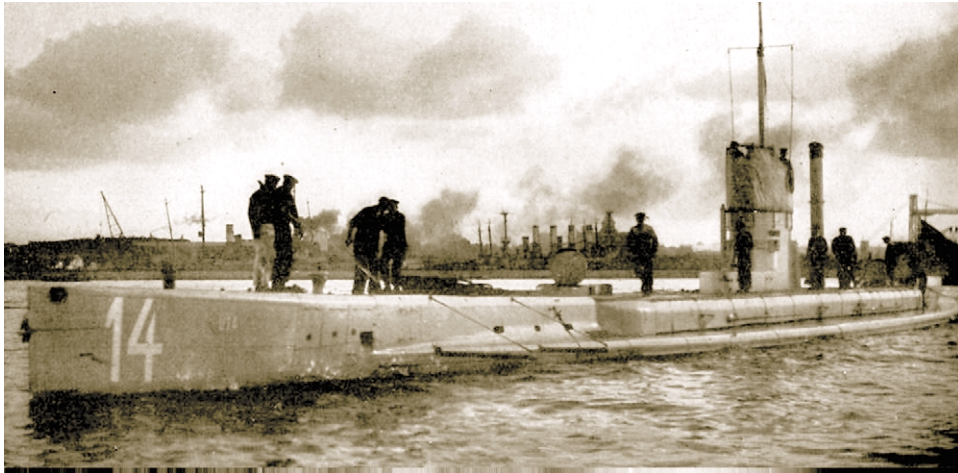
and by using direction-finding equipment when submarine transmissions broke radio silence. Finally, since World War II, more sophisticated detection

techniques have emphasized passive detection technologies, such as listening for the sounds of a submarine, detecting its metallic hull, or picking up the trail it leaves behind.

*Seeking nonstealthy signatures.* Although some observers anticipated the submarine's military potential before World War I, a more typical opinion was that the submarine was a cowardly weapon employed only by weak naval powers. Even after three British cruisers had been torpedoed and sunk in a matter of minutes by a German U-boat on September 22, 1914, the media coverage about the event concluded that the submarine threat was likely to be short lived. "Mining harbors, torpedo nets, better armor, careful lookouts (including aircraft) and high speeds and frequent course changes" were seen as countermeasures likely to negate any advantages the submarine could achieve by wrapping itself in the cloak of the sea.<sup>3</sup>

The 1918 British development of sonar, for *SOund Navigation And Ranging*, strengthened the belief that the submarine would become

<sup>3</sup> "Modern Submarine Warfare: Methods of Guarding Against the Latest Form of Underwater Attack," *Scientific American*, November 1914, pp. 376-77.



*The German U-14 heads out to sea during World War I.*

increasingly detectable by its armed adversaries. Sonar apparatus generates a pulse of acoustic energy in the water and utilizes directional listening for the signal's return when it bounces off the submarine's hull. However, submariners had discovered that near-surface temperatures increase from sunlight late in the day, creating a refractive layer in the water. Like a prism, this layer directs sound downward and adversely affects the horizontal ranges of sonar detection. Tactics were developed to take advantage of these refractive layers, including those well beyond the depth of daily solar heating, thus directing the sound away from the receiver and making it difficult for sonar operators to hear the submarine's return echo.

Despite these early stealth-enhancing tactics, the submarine's military utility was questioned during the inter-war period. If the Naval Institute's *Proceedings* journal can be considered as a bellwether for fleet perceptions, experienced naval officers regarded the submarine's capability as extremely limited, owing to its perceived vulnerability to a growing antisubmarine threat. Between the World Wars, the conventional wisdom among the Navy's leadership was that the submarine would ultimately prove to be vulnerable in combat.<sup>4</sup>

**Active submarine detection.** When airborne radar sets became operational in mid-1942, German submarines deploying into the Atlantic and returning on the surface became vulnerable to sudden and unexplained attack in the Bay of

Biscay. Admiral Doenitz, commander of the German U-Boat fleet, deduced properly that the submarines were being detected by radar, and his U-boats were outfitted with a radar receiver fed from an improvised antenna consisting of wire wrapped around a wooden frame.

Among the first pieces of electronic support measures equipment, this "Biscay Cross" permitted the detection of a threat signal in more than enough time for a submarine to submerge before the transmitting platform could locate and

attack it. When the British later decided to convert terrain-profiling air force radar to ASW use, the Biscay Cross could not intercept that frequency, and losses resumed.

By early 1944, the snorkel (a mast-mounted device allowing the submarine to ingest air for diesel engine operation while at periscope depth) returned stealth to the submarine. The exposed portions of the snorkel mast were also coated with radar-absorbent material (RAM), reestablishing stealth as a defense and allowing the U-boats to operate in the English Channel again. An unexpected benefit of these submerged transits was, since submarines then had to surface to transmit radio messages, their physically enforced radio silence deprived the Allies of their most productive source of detection and localization.

Despite technological advances in underwater stealth, the most successful ASW applications in both World Wars came from surface tactics—convoy escorts by numerous ASW ships—negating those improvements. Because a submarine could attack only one ship in the convoy at a time, it exposed its position to the ASW ships, which formed a concentrated and effective defense. The German tactical response to convoys in World War II was the "Wolfpack"—attacking the convoys with multiple submarines in a coordinated, swarming assault. Massing stealthy platforms, however, creates the risk of multiple exposure, and while the submarines were successful in

<sup>4</sup> See "Submarine Capabilities and Limitations," Naval Institute *Proceedings*, Aug. 1925, pp. 1398-1407.

sinking ships, they also suffered major losses from counterstrikes. This experience influenced U.S. Navy strategy and force planning through the Cold War, generating requirements for large numbers of surface ships to escort trans-Atlantic convoys.<sup>5</sup>

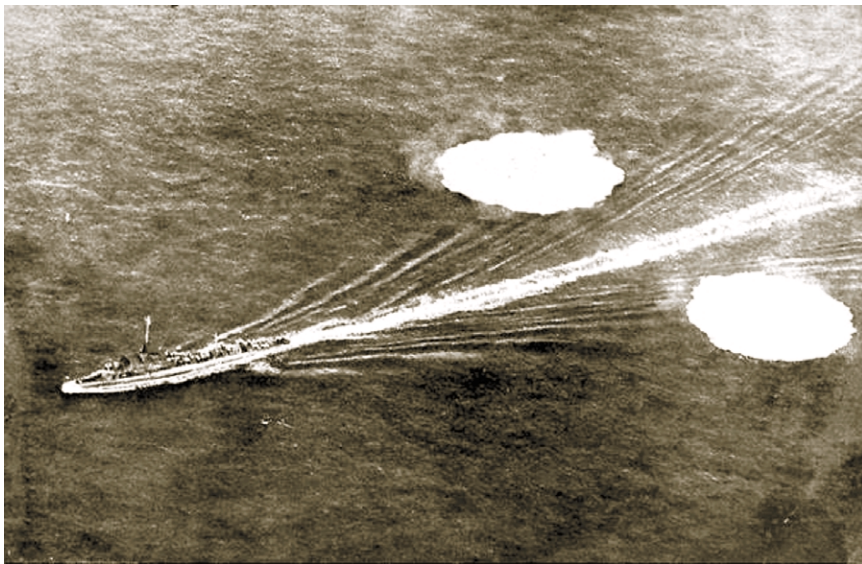
The development of nuclear-powered submarines during the Cold War altered the balance between surface and sub-surface combatants. By greatly limiting their vulnerability through stealthy tactics and technologies, nuclear attack submarines (SSNs) gained the initiative against surface ships under almost all circumstances. The U.S. Navy, having invested significantly in the fielding and practice of ASW, found that SSNs successfully attacked surface ships in exercise after exercise. Thus, from the 1960s on, it was generally acknowledged that the only consistently effective defense against a submarine attack was another submarine defending the force, and submarine barriers in the Greenland-Iceland-UK gap became important additions to the forces defending Atlantic convoys.

*Acoustic and non-acoustic ASW.* Sound and sonar have been the primary focus of efforts to counter the submarine's stealth since World War II. Acoustic technology improved the capabilities of active sound measurement and led to the devel-

opment of whole new systems based on passive techniques. Sophisticated sonobuoys, bottom placed sound arrays, towed sonar systems, and helicopter-dropped arrays were deployed to detect submarine-generated noise. Sonar systems grew larger, longer and more powerful to seek out increasingly quieter submarines. However, U.S. submarines were able to respond to and counter these threat improvements and retain their acoustic advantage by using sonar to provide threat information, reducing equipment-radiated noise, and employing various types of hull coatings analogous to RAM (inasmuch as they reduced the strength of a submarine's sonar return). Tactics also helped to defeat sonar detection, or to break the kill chain linking that detection to an effective attack. Thus, the submarine, alerted to a momentary breach in its low observability, might deploy a noisemaker or launch a decoy to confuse the source trying to track and engage it.

While acoustic techniques have remained the dominant means of locating submarines, the Cold War saw attempts to exploit other phenomenologies. Airborne magnetic anomaly detection (MAD) equipment was viewed as a great breakthrough in ASW when it was first used during World War II. But, with very limited range and frequent false readings, MAD proved to be a poor search mechanism, and today serves primarily as a localization device when an approximate position of a submarine is already known. The low altitudes needed for MAD employment also result in a coupling of the aircraft's noise to the water, serving to alert any submarine around.

Technologists have also devised a number of systems in an attempt to detect the family of elements or compounds shed, pumped, activated or



*Allied destroyer dropping twin depth charges in World War II.*

<sup>5</sup> A typical force generation package for the escort mission included 10 surface combatants per convoy. Planning four convoys per month, and adding a carrier battle group to each task force, could generate total ship requirements of 167 ships, not including submarines, just in the Atlantic.

otherwise released from a modern submarine. One detection mode investigated aboard ASW aircraft was to detect hydrocarbons released into the atmosphere in the exhaust of a snorkeling diesel-electric submarine. Although expectations mounted after limited success under controlled conditions, open-ocean testing saw very high false alarm rates, especially in areas where other hydrocarbon-emitting shipping was present (a likely place for patrolling submarines). As a result, this “sniffer” equipment had minimal operational impact.

Hydrodynamic principles, such as a Bernoulli “hump” or a Kelvin “wake,” offer other detection means—sensing effects on the sea surface resulting from a submerged, moving body. Most of these methods, enabled through radar- or laser-based scanning of the ocean’s surface, could theoretically detect shallow, fast submarines. “Shallow and fast,” however, is a seldom-populated portion of the submarine’s total operating envelope. Although the Navy has expended significant efforts attempting to exploit these theoretically observable phenomena, the “noise” surrounding them remains significant in any kind of sea state, and there is little promise for future success when the submarine operates to optimize its stealth. Although several of these technologies are currently lacking, the view of the submarine community is to “expect the unexpected” and to hedge against the surprise threat that can’t immediately be countered. Such an approach supports analogous research in non-traditional areas to counter emergent threats to airborne stealth.

### Developing and Employing Airborne Stealth

Airmen appreciated the value of aircraft survivability and tactical surprise—stealth’s primary operational benefits—long before the relatively recent advent of low-observable technology.

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first and completing an attack  
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Although the mantra chanted by supporters of the stealthy F-22 air superiority fighter is “first-look, first-shot, first-kill,” the importance of seeing the opponent

first and completing an attack without being detected has long been the goal of would-be aerial aces.<sup>6</sup> As far back as World War I, air combat doctrine recognized that “the deciding element in air combat is usually surprise.”<sup>7</sup> But in those days of early combat aviation, when the primary means for detecting enemy aircraft was a visual sighting, there were few, if any, technological aids to evasion. Rather, airmen of the time placed a premium on tactics to achieve surprise, such as hiding in clouds or approaching their adversary from out of the sun’s glare.

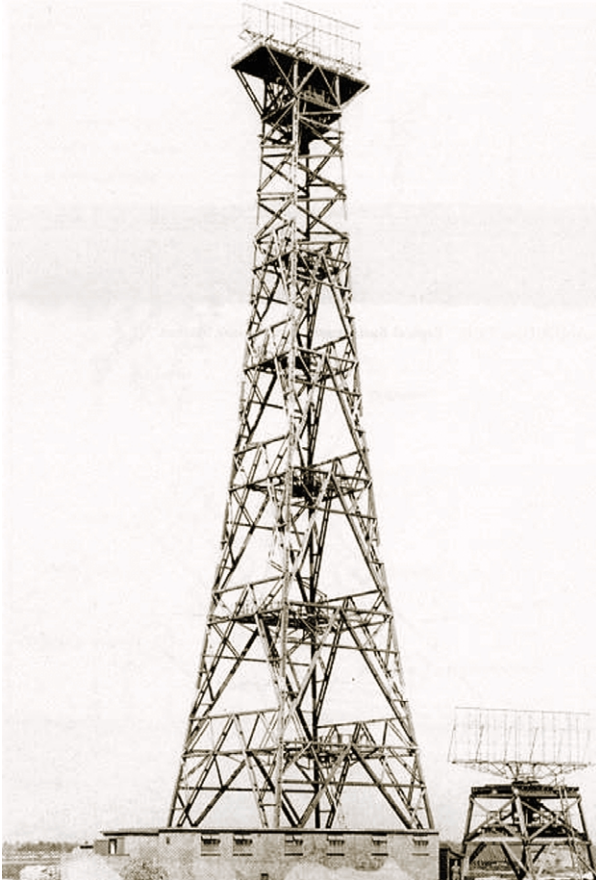
From World War I through the inter-war period, visual observation—an inherently limited capability—remained the primary means of aircraft detection. During this time, attackers retained, especially in air-to-ground engagements, a significant competitive advantage over defenders, giving rise to such absolute assertions of offensive airpower’s dominance as, “the bomber will always get through.” But this imbalance did not last. Eight years later, radar’s operational debut as a primary aircraft detection tool marked the beginning of a pronounced tilt backward to the defender.

*The Radar Game.* Radio Detection And Ranging, or radar, was developed in England in the mid-1930s and is credited with giving the British an important competitive edge during the Battle of Britain in 1940. Later in the war, the Germans also exploited radar to gain a significant defensive advantage, using it to inflict heavy losses on U.S. and British bomber formations. Tactics and techniques applied during World War II opened a new era in air combat in which the survivability of an airborne force was now dominated by radar in the detection phase.<sup>8</sup>

<sup>6</sup> See, for example, Bill Sweetman, *Stealth Aircraft: Secrets of Future Airpower* (Osceola, WI: Motorbooks International, 1986), p. 7. The advantage of a stealthy aircraft in an air-to-air engagement is that it provides an edge in situation awareness, proven to be the single most important factor in fighter duels. For a discussion of that, see Barry D. Watts, *Clausewitzian Friction and Future War* (Washington, D.C.: NDU Press, 1994), pp. 96-104.

<sup>7</sup> Rebecca Grant, *The Radar Game* (Arlington, VA: IRIS Independent Research, 1998) quoted William Sherman, “Tentative Manual for Employment of the Air Service, 1919” printed in *The U.S. Air Service in World War I*, Volume I (Washington, D.C.: Office of Air Force History, 1978), p. 369.

<sup>8</sup> Grant, p. 15.



185-foot British “Chain Home Low” radar tower, circa 1940.

After radar’s advent, U.S. aircraft designers wasted little time in pursuing counters to radar-based defenses. Indeed, the post-World War II period ushered in a fundamentally new approach to aircraft survivability—one in which aircraft were designed from inception to avoid detection. By the 1950s, radar-absorbing materials developed to mask antennas on submarines were being applied to help shield conventionally designed aircraft from radar detection. Thus, the Lockheed U-2, optimized for long range and high altitude based on an F-104 fuselage design, was later fitted with radar absorbent paint and radar-scattering wire to hamper detection by the improved early warning, tracking and fire-control radars the Soviets were then incorporating into their surface-to-air missiles.<sup>9</sup>

In addition to these quick fixes to conventional

platforms, there was a growing realization that aircraft could be designed to diminish the power of the radar return, thereby allowing the aircraft to delay, or deny entirely, detection by radar. In 1953, the U.S. Air Force specified that a new reconnaissance aircraft be designed to minimize radar detection.<sup>10</sup> The SR-71 later evolved from a series of designs to replace the U-2 for the CIA, including a prototype “Blackbird” aircraft, designated the A-12, the first production aircraft to incorporate a stealthy shape. The radar reflectivity of the SR-71, roughly that of a small private aircraft according to its designers, was “significantly lower than the numbers the B-1B bomber was able to achieve twenty-five years later.”<sup>11</sup> Key to the design of stealthy aircraft was the concept of “radar cross section” (RCS) that summed the major reflective components of the aircraft’s shape, with much of the pioneering research being supported by the U.S. Air Force Avionics Laboratory.<sup>12</sup>



The Lockheed SR-71 Blackbird, above, was the first military aircraft designed from inception to minimize radar cross-section.

<sup>9</sup> See Ben Rich, *Skunk Works* (Boston: Little Brown, 1994), pp. 152-160.

<sup>10</sup> Grant, p. 22.

<sup>11</sup> Rich, p. 215.

<sup>12</sup> Mark A. Lorell and Hugh P. Levaux, *The Cutting Edge: A Half Century of U.S. Fighter Aircraft R&D* (Santa Monica: RAND, 1998). For an account of early Air Force research on stealth technology see William F. Bahret, “The Beginnings of Stealth Technology,” *IEEE Transactions on Aerospace and Electronic Systems* (October 1993).

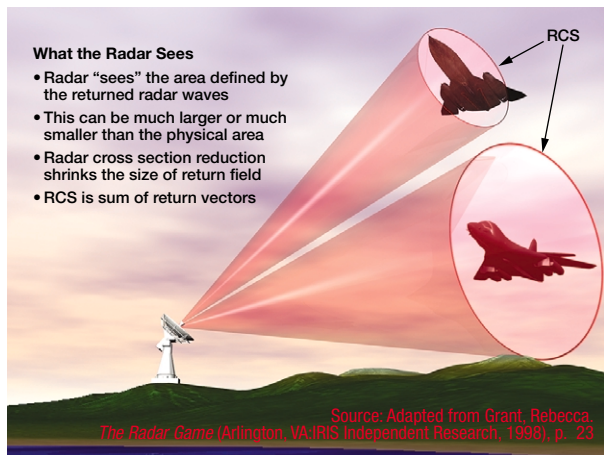


Figure 2. Radar Cross-Section: What the Radar Sees

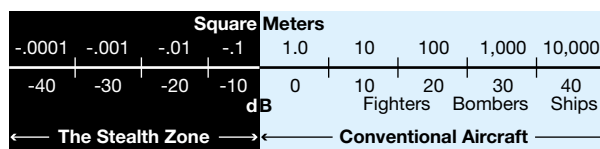
When the “Blackbird” aircraft were designed in the late 1950s, only the gross effects of different shapes on radar reflectivity could be assessed. For example, it was understood that a flat plane or a cavity at right angles to an incoming radar wave would produce a very large return. But the state-of-the-art in numerical design procedures in the 1960s was not advanced enough to produce a balanced design, i.e., one in which a certain aircraft part did not produce a dominant (and thus easily observable) return in one direction. By the next decade, computer modeling had progressed to the extent that it was possible to design an aircraft with a reduced and balanced RCS, and fly-by-wire flight systems enabled control of the non-aerodynamic configurations mandated by stealth. Given these technologies, initial aircraft designs for the F-117, B-2 and F-22 featured dramatically reduced radar cross-sections.<sup>13</sup>

Despite design tradeoffs between aircraft performance requirements, cost, and radar cross section, there is little evidence of a leveling off in the capability to continue to develop and produce very low radar signatures on aircraft. Clearly, continued growth in the computing power required for stealthy aircraft design and development does not necessarily equate to proportional reductions in RCS. However, government and industrial test facilities reportedly now can measure radar signatures as low as one ten-millionth

of a square meter—something like a speck of dust. Thus, while today’s advanced stealthy aircraft can be detected at close range by the most powerful ground radars, continued advancement in RCS reduction should make future aircraft even less detectable.<sup>14</sup>

*Seeking other signatures.* With emerging radar advances unlikely to yield near-term, dramatic improvements in detecting low-RCS aircraft, those interested in countering stealth must pursue capabilities detecting other observable phenomena. Here, the stealthy aircraft and submarine share several properties susceptible to detection, including infrared, visual, acoustic, or electromagnetic emissions.<sup>15</sup> Although, historically, none of these is as useful as radar for detecting low-observable aircraft, each must be minimized to ensure that none can be used to obtain a defensive advantage. For example, a stray electronic emission could result in vectoring air interceptors to a stealth aircraft’s general vicinity, increasing the probability of close-in visual, infrared, or radar detection and tracking.

Infrared, or IR, is one of the most difficult signatures for a stealth aircraft to suppress. Aircraft generate heat in two basic ways: via the engine (both the engine exhaust and internal engine heat coupling to the aircraft skin), and through increases in surface area temperatures resulting from atmospheric friction. To reduce engine-generated IR signature, subsonic stealthy aircraft such as the B-2 bury the engines within the aircraft fuselage and mix cold ambient air with the engine exhaust to lower its escape temperature. High-speed flight’s enhanced IR signatures pose additional challenges to low-observability. To reach supersonic speeds, stealthy fighters such as the JSF must employ afterburning engines,



Source: Grant, *The Radar Game*, p. 27

Figure 3. Radar Cross-Section Size by Platform Type

<sup>13</sup>These observations rely on “Fundamentals of Stealth Design,” a 1992 unpublished article by Alan Brown, program manager of the F-117. Brown is credited with the quote that the secret to stealth “was to design a very bad antenna and make it fly.”

<sup>14</sup>Sweetman, Bill, “How LO can you go?” *Jane’s International Defense Review*, January 2002, pp. 22-23. See also J. Paterson, “Overview of Low Observable Technology and Its Effects on Combat Aircraft Survivability,” *Journal of Aircraft*, Vol. 36, No. 2, March-April 1999, pp. 380-388.

<sup>15</sup>See John J. Kohout III, “Stealth in Context,” *The B-2 Bomber: Air Power for the 21<sup>st</sup> Century* (New York: University Press of America, 1995), pp. 141-144.





*The F-22 “Raptor” stealth fighter, above, has been outfitted with special technologies, such as leading-edge cooling and special surface paints, for infrared signature reduction at high-speeds.*

which, even with shielding, dramatically increase the heat trail created by engine exhaust. Once at supersonic speed, an aircraft’s surface heats up markedly owing to the increased friction between the atmosphere and the skin of the aircraft. The F-22, uniquely capable of flying at supersonic speeds for extended periods in non-afterburning “supercruise,” must incorporate additional measures, such as leading-edge cooling and special surface paints, to counter this phenomenon.<sup>16</sup>

Stealth critics and advocates alike point out that low-observable aircraft are not invisible, and as hundreds of thousands of witnesses at college football games and parades will attest, they are easily seen in conditions where a stealthy aircraft’s mission is to show off. But visual detection has been made more difficult by diminishing the aircraft’s size and shape, treating its surface with non-reflective coatings, and minimizing the trail of engine smoke or condensation through technology and operating procedures. Clearly, the most submarine-like tactic that a stealthy aircraft can adopt is to operate under the cover of darkness to reduce the probability of visual acquisition, and that concept of operations has been

used exclusively, thus far, in combat operations. How limiting a factor this is will depend on the mission’s purpose and priority, as well as aircraft type. In part to give the B-2 bomber a “24/7” capability during the first few days of an air campaign, for example, the Air Force developed the “Global Strike Task Force” concept of operations. Composed of stealthy F-22s and B-2s, this plan provides a stealthy daylight air superiority escort to defeat any enemy interceptors that might acquire the B-2 visually before integrated air defenses are degraded. Given that concept of operations, any added B-2 vulnerability resulting from an increased probability of visual detection would seem to

occupy a very narrow slice of the battlespace: enemy interceptors operating deep in their territory beyond the F-22’s operating radius during the day in clear weather.<sup>17</sup>



*The B-2 “Spirit” stealth bomber, above, and the F-22 stealth fighter form the lethal centerpiece of the Air Force’s new “Global Strike Task Force” concept of operations.*

<sup>16</sup> Sweetman, “How LO can you go?” p. 22.

<sup>17</sup> See Christopher J. Bowie, “Destroying Mobile Ground Targets in an Anti-Access Environment,” *Northrop Grumman Analysis Center Papers* (December 2001), p. 9.

As those same football fans watching a stealth fly-over would point out, when contrasted with fighters plugging in their afterburners the B-2 is disappointingly quiet—and deliberately so. All-aspect stealth design includes diminishing the ability of acoustic sensors to locate the aircraft. In addition, sound in the atmosphere is subject to irregularities similar to anomalies submarine-seeking sonar encounters owing to thermal layering in the ocean. As one student of airborne stealth concluded, “Wind, ambient noise, atmospheric layering, and rather rapid dissipation in the atmosphere all combine to make sound a rather unreliable and indeed expensive approach to detecting an attacking force.”<sup>18</sup>

Radio or radar signals transmitted by a stealthy aircraft could also give away its position. Therefore, techniques to decrease the probability of intercepting those signals, such as controlled and moderated electronic pulses that do not exceed the range of the target, and frequency-hopping radios and radars, are used to deny electromagnetic detection. As in the case of the submarine, radio silence is the dominant concept of operation for stealthy aircraft, and the use of passive receivers, including links from satellites, can provide a comprehensive operating picture while obviating external transmissions requesting navigation, targeting, or order-of-battle information.

*Stealthy aircraft in combat.* For many years, designers and builders of stealthy aircraft had to content themselves with computer-based simulations and flights over radar ranges to judge aircraft low-observability. Even the first combat use of the F-117 in Panama was against an adversary ill equipped to test conventional aircraft, much less the stealthy *Nighthawk*. Since then, however, we have seen stealthy aircraft employed in hostile skies over Iraq, Serbia and Afghanistan. As a result, we can conclude that airborne stealth works.

On the first night of *Desert Storm* according to the *Gulf War Air Power Survey*, “...the F-117s that attacked the first targets in the capital...flew into, over, and through the heart of the fully operating air defenses of Baghdad with no sup-



*The F-117A “Nighthawk” stealth fighter, above, was the star of the Gulf War air campaign.*

port from electronic countermeasures.”<sup>19</sup> But the airmen planning that war’s first attack were not willing to bet on unaided stealth technology, and requested electronic jamming support in the form of three EF-111 aircraft over Baghdad. However, Iraqi air force activity forced one of the *Ravens* to divert, while the other two arrived later than planned and were forced to begin jamming well beyond the desired range.

It is not clear from available evidence whether that radar jamming aided the F-117s in avoiding detection over Baghdad. We know that no follow-on F-117 strikes received direct jamming support, but we also can assume that these attack operations benefited from the battlespace confusion generated by indirect jamming and other air attacks on Iraq’s integrated air defenses. As Chris Bowie has suggested,<sup>20</sup> two principal conclusions can be drawn from this combat use of stealth. First, the F-117s were able to penetrate relatively sophisticated air defenses without standoff jamming support, and did so repeatedly early in the war. Second, although available electronic jamming may be desirable and planned to support stealthy strikes, if that support is disrupted the attack can probably continue as planned without greatly increasing the risk that the stealth aircraft will be detected, tracked and engaged.

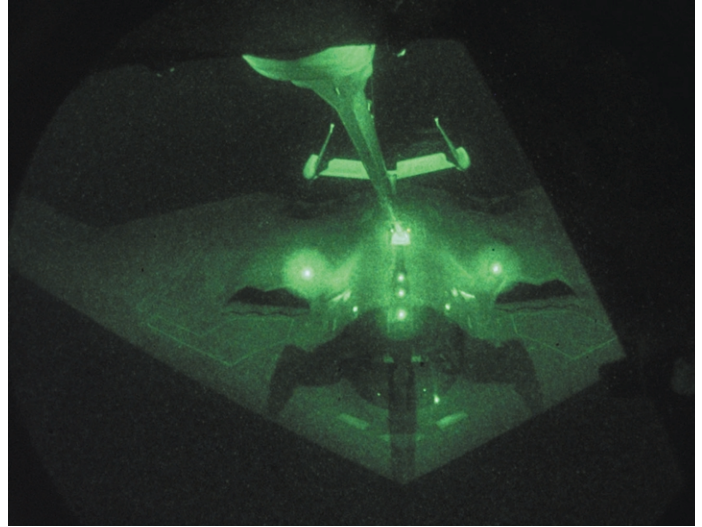
<sup>18</sup> Kohout, p. 143.

<sup>19</sup> Office of the Secretary of the Air Force, *Gulf War Air Power Survey: Operations and Effectiveness*, Vol. II (Washington, D.C., U.S. Government Printing Office, 1993), p. 124.

<sup>20</sup> Chris Bowie, *Untying the Bloody Scarf* (Arlington, VA: IRIS Independent Research, 1998), p. 16.

The B-2 stealth bomber's performance over Serbia during *Operation Allied Force* mirrored the F-117's success over Iraq. Because the B-2 would penetrate uncorrupted air defenses on the war's first night, mission planners constructed a rigid flight plan, known as the "blue line," designed to optimize both the B-2's low-observable characteristics and the support available from jamming, defense suppression, and air superiority aircraft.<sup>21</sup> As a precaution, and because the option existed at relatively little cost, this approach to B-2 mission planning continued throughout the campaign, and defensive support was provided when available. Nevertheless, at least one B-2 mission was executed autonomously during the conflict, when bad weather forced the cancellation of all the planned escort and support sorties in the theater. After the war, Air Force officials were quick to underscore their confidence in the B-2's ability to avoid detection on its own, while arguing that providing the stealthy bomber with available in-theater support was still a prudent, if conservative, concept of operations.

Together, the B-2 and the F-117 put on an impressive display of offensive dominance during *Operation Allied Force*. For most of the war they were the only two aircraft to deliver direct-attack munitions against heavily defended Belgrade. During the first eight weeks of the war, a total of six B-2s operating out of Whiteman AFB,



*A B-2 bomber refuels under the cover of darkness before entering Serbian airspace during 1999's OPERATION ALLIED FORCE.*

Missouri flew only three percent of the allied combat sorties but destroyed 33% of the targets. Using the Joint Direct Attack Munition (JDAM) and augmenting that weapon's through-the-weather accuracy with its on board GPS-aided radar, B-2s hit 84% of their targets on the first strike and averaged 15 targets attacked per sortie. Not only were no B-2s lost; there is no evidence that they were even detected, much less tracked and fired upon by Serbian air defense. The B-2

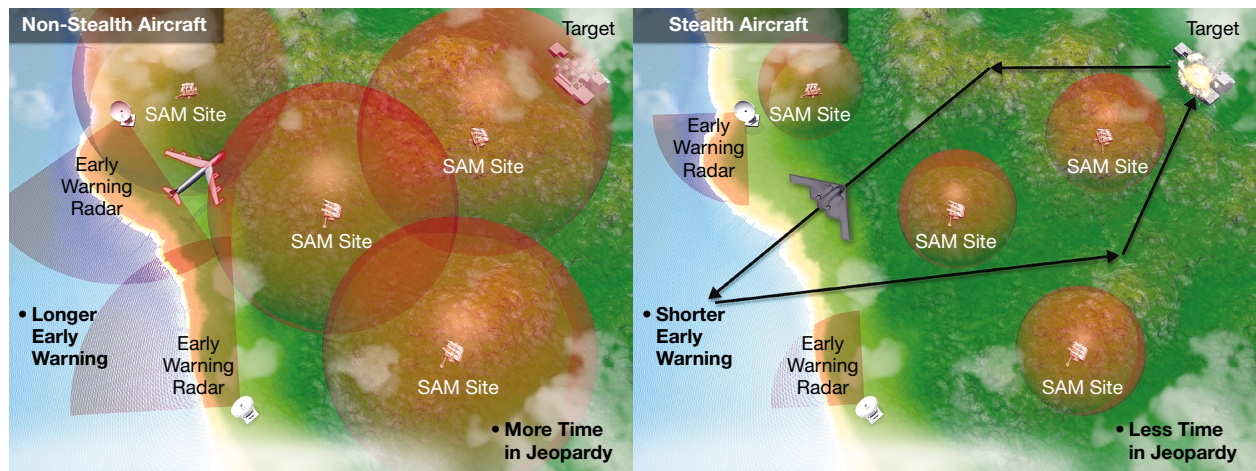


Figure 4. *Stealth Strike*

Source: Adapted from Grant, *The Radar Game*, p. 37

<sup>21</sup> Because the Air Force had retired its EF-111s after the Gulf War, the electronic jamming mission fell to the jointly operated EA-6Bs. Those aircraft not only provide standoff jamming, but also fire anti-radiation (HARM) missiles at any radar attempting to acquire a US aircraft. F-16 fighters equipped with HARM capability also contributed to defense suppression, firing their missiles in both reactive and preemptive modes. Finally, combat air patrol (CAP) air superiority fighters were available to thwart any enemy fighters.

was judged by the air war's commander to be the "superstar" of the Kosovo campaign.<sup>22</sup>

What, then, should be made of the Serbs downing an F-117 with a barrage of Russian-made SA-3 surface-to-air missiles (SAMs)?<sup>23</sup> Although an authoritative public accounting of the shoot-down is not available, numerous factors probably contributed to the loss. Support assets may not have been positioned properly, the missile site was either unknown or the SAM had been moved from a previously known location, the F-117 was flying along a route repeatedly used to strike key targets, (thus allowing the enemy to anticipate the aircraft's location based on dead reckoning from a known point and time), and some operator error or technical malfunction may have kept the bomb bay doors open longer than planned, providing a targetable radar return.<sup>24</sup> In any case, the downed F-117 is a dramatic reminder that stealth aircraft can be shot down, and that survival against sophisticated defenses requires continual attention to all-aspect low observability and innovative tactics. In this regard, stealthy aircraft are not much different from stealthy submarines, which have had their share of losses when stealth was compromised, however briefly.

In the air operations supporting *Operation Enduring Freedom* over Afghanistan, stealthy aircraft played a limited role for two reasons. First, the unavailability of land bases to support relatively short-range fighter aircraft meant that the Air Force fighter contribution to the battle, including the F-117, was minimal.<sup>25</sup> Secondly, the very modest air defenses possessed by *al Qaeda* and the Taliban meant that stealth was not required after a brief "kick down the door" operation at the start of the air war to destroy air defenses, fighter aircraft and command and control centers. Those strikes were executed by B-2s launched from their American bases. After this enabling mission, they turned over the ensuing strike missions to the non-stealthy B-52s and B-1s.<sup>26</sup>

## Drawing Analogies: (1) Future Challenges

What sorts of analogies are useful to draw between stealthy submarine and aircraft combat employment and the wide range of countermeasures deployed—or envisioned—to lessen their combat advantage? Proponents of the military use of stealthy aircraft would not have wanted to search for analogies with the submarine at the end of World War I. At that time, the perceived vulnerability of the submerged submarine, given an accurate attack on it, was overemphasized. Overlooked was the fundamental element of the submarine's defenses—its stealthy nature—that reduced its susceptibility to detection and greatly diminished the probability of such an attack occurring at all.

Simply put, the true operational capabilities of a stealthy platform in any media are not self-evident when the system first appears, and adversary and advocate alike misunderstand the technology. The adversaries apply traditional perspectives often mixed with a resistance to change, and fail to appreciate the system's potential. The advocates push their innovation, but often overlook the range of applications and technologies likely to reshape the strategies and tactics of warfare. In the case of the submarine, it first took the German snorkel-equipped U-boat during World War II and, ultimately, nuclear power, before the greatest combat leverage could be gained from stealth. Today, low-observable technologies applied to reduce an airplane's signature are already comparable to those of the modern submarine, but the implications of that revolutionary technology are only just beginning to be included in manuals of air combat.

What lessons might a low-observable aircraft advocate have drawn from the use of the submarine during World War II? The first lesson was that a stealthy platform will perform best in a manner that preserves its low-observable properties—working alone or in very small numbers<sup>27</sup>,

<sup>22</sup> Grant, p. ii.

<sup>23</sup> Lambeth, Benjamin S. *NATO's Air War For Kosovo: A Strategic and Operational Assessment* (Santa Monica: RAND, 2001), p. 116.

<sup>24</sup> Sweetman, "How LO can you go?" p. 21.

<sup>25</sup> One report, quoting unpublished Pentagon statistics, stated that USAF bombers dropped 69% of the weapons over Afghanistan, Navy fighters launched from carriers dropped 24%, and USAF fighters dropped 7% of the ordnance. See "Fly by Night," *Aviation Week and Space Technology*, March 18, 2002, p. 23.

<sup>26</sup> See John A. Tirpak, "Enduring Freedom," *Air Force Magazine*, February 2002, pp. 32-39.

<sup>27</sup> Some would argue that being in an environment where there are numerous other targets with strong returns, or when jamming is present, would improve the survivability of a stealthy aircraft. But all those returns will also result in increased attention to that sector of the sky. See Paterson, p. 386. Submarines operating closely with surface battle groups in the littorals would also seem more susceptible to detection.

under mission-type orders, being given considerable latitude in terms of time and space constraints, operating with tactics that may seem to violate traditional principles of force application, and with absolute attention to all aspects of operational security. A second lesson is that since insufficient resources require the pooling of assets and a subsequent loss of low observability in employment, stealthy systems must be acquired in numbers adequate to get the job done.<sup>28</sup> A third lesson is that a system able to commence an attack unobserved and to disengage at will has a multiplier effect on required enemy defenses.

Analogies can also be drawn between post-World War II ASW efforts and the hunting of stealthy aircraft. The search for a substitute for sonar as the dominant ASW detection technique has proved fruitless. Radar enjoys that same dominant position when it comes to finding airplanes, and other techniques provide only limited assistance under ideal conditions. Nevertheless, an important similarity to be illustrated is that neither the stealthy submarine nor the low-observable aircraft can be assured of its future survivability. Each will continue to face challenges to its successful combat operation. Each must continue to be improved.

*Future challenges to underwater stealth.* Active or passive acoustic detection of submarines has long been the *sine qua non* of ASW techniques, and acoustic engineers continue to develop measures to reduce vulnerabilities in these areas. For years it has been understood that, to minimize acoustic energy coupled to the environment, a submarine's propeller should have an odd number of blades to preclude reinforcement of the perturbations caused when these blades intersect the turbulent flow behind an even number of control surfaces (rudders and stern planes). It was further understood that reducing the range to which such acoustic events would propagate required more blades rather than fewer. More recently, a British innovation called a "propulsor" has been developed to stabilize the flow from the rotating blades. In this concept, a multi-vented rotating device is surrounded by a shroud containing fixed blades which "untwist" the flow from the rotating

blades, creating an axially stable thrust similar to exhaust from a jet engine. Other methods of damping acoustically detectable flow noise, such as vortices from hull discontinuities, rely on form shaping—analogue to the stealthy design techniques of the F-22 and B-2.

Taking a lead from Russian innovations, hull coatings have been developed to significantly reduce a ship's "target strength"—the acoustic analogue to RCS. These not only reduce the echo returned from an active sonar but also have the secondary effect of lessening the amount of structure-borne vibration noise coupled to the ocean.

Some potential observables from a submarine, such as internal waves, thermal discontinuities or chemical/nuclear activation by-products, tend to stay at the depth at which they were generated, thus requiring a three- rather than two-dimensional search. Even with such a search, these submarine "footprints" dissipate quickly. For example, owing to the ocean's immense thermal conductivity, temperatures can be restored to normal just a few ship lengths behind a submarine dispersing megawatts of heat energy into the water. On the other hand, internal waves or entrapped chemical/isotopic signatures persisting for days or even weeks simply indicate that a submarine, at one time, passed through those waters.

Other theories of submarine detection suggest that high-powered acoustic sources operating at very low frequencies could illuminate thousands of square miles under the ocean's surface. Like an acoustic tomographic version of an MRI, the seemingly chaotic echoes from the entire area could theoretically be collected by a large number of geographically dispersed sensors, processed at a central location, and correlated to develop a common operational subsurface picture. Such a system is analogous to the bistatic radar challenge to stealthy aircraft discussed below. Submarine presence could probably be detected by these multiple sensors and receivers, because it would be impractical to apply the thick acoustic hull coatings required to reduce reflectivity from the long wavelengths associated with the low frequencies involved. However, the technologies and resources

<sup>28</sup> Proponents of stealth in combat aviation argue that the U.S. has not capitalized on its substantial investment in stealth technology in its acquisition of limited numbers of aircraft. Only 59 F-117s were produced, and the B-2 buy was cut from a planned 132 to 21. The original plan to acquire 750 F-22s has been pared to less than 300, and the JSF is also facing program cuts.

necessary to put such a system in place are presently well beyond the capabilities of credible adversaries.

Since the late 1950's *Skipjack*, single-hull construction has long been a characteristic of U.S. submarines—meaning that the entire pressure hull isn't encased within a larger superstructure containing the main ballast tanks. Proposals to revert to a double-hull construction, allowing a much greater payload to be carried, are also being evaluated in terms of stealth. An included benefit of this change in shipbuilding philosophy, for example, would be a tripling of surfaces available for coatings to further mitigate active/passive acoustic signatures.

Non-acoustic detection vulnerabilities will also remain a challenge in the future. Many of these are hydrodynamic in nature, either within the water column or at the air-water interface. The submarine force well understands these potential detection phenomena, and applies the tactics of stealth to meet emerging ASW technologies. Thus, to keep “Bernoulli humps” or “Kelvin wakes” from being observable at the surface, the guidance might be: “Don't go faster than XX knots if shallower than YYY feet and sea state is less than Z.” As sensor and processor capabilities improve, and smaller signals are recoverable from noise, a constant review and modification of detection-free operating envelopes will remain an essential element of stealth.

As a rule of thumb, RF energy penetrates seawater to only a small fraction of a wavelength. A notable exception to this is at a small sliver of the spectrum in the blue-green visual domain. This phenomenon has long been a source of speculation and engineering, not only for detection, but also for communication with submerged submarines. However, blue-green lasers have tended



*The Virginia-class attack sub (SSN-774), above, will incorporate the latest in submarine stealth, along with a wide range of new offensive capabilities, to support the littoral warfare mission.*

to be either very inefficient or very expensive. Some recent solid-state advances have made these lasers more feasible and affordable, prompting the requirement for hull-borne early warning sensors to provide advance warning.

In sum, there are numerous known detection modes for modern submarines, all of which are kept under very close scrutiny. The submarine force must be the first to note a disruptive technology and initiate efforts to counter or mitigate its impact. A continuing process of action-reaction has occurred in which potential upgrades in threat capabilities are countered by improvements in platform stealth. It is through these improvements that submarine survivability and effectiveness have been maintained.

*Future challenges to airborne stealth.* Stealthy aircraft such as the F-117 and B-2 have proved highly successful in combat against current radar detection technology, monostatic radar, wherein a single radar functions as both transmitter and receiver. Although the B-2 is considered to be a generation ahead of the F-117 in RCS reduction, both aircraft rely on the same principle of scattering the reflection of incoming radio frequency waves from the transmitter, thereby reducing the size of their radar return when the transmitter and receiver are collocated. Theoretically, detection of stealthy aircraft could be enhanced by separating the transmitting radar from the receiving antenna in a configuration known as bistatic radar. In this concept, the receivers, geographically separated from the transmitter, must be properly aligned to catch the radio waves scattered by the low-RCS aircraft.

While simple in concept, bistatic radar detection faces significant technical and operational challenges. Because stealthy aircraft are observable only from a very small number of angle combinations, the aircraft will be reflected only if an ideal alignment exists among transmitter, target and receiver. Providing conventional radar the coverage needed to ensure sufficient reception of the scattered signals might require placing radar transmitters every few miles—a cost-prohibitive approach. Coordinating the interception of multiple radar beams and collecting and analyzing radar return data from a number of transmitters and receivers would also require massive computing

power. Therefore, considerable skepticism exists that a practical, stealth-detecting bistatic radar system will be deployed.<sup>29</sup>

Increases in computing power and the proliferation of commercial radio waves as a by-product of the information revolution have given rise to another challenge to stealthy aircraft. In the days before cable, many television viewers could vouch for the fact that an aircraft flying nearby could momentarily disrupt the antenna-generated image on their TV screen. That phenomenon is the basis for a recent series of articles and interviews alleging that “passive coherent location” (PCL) or “passive bistatic” radar systems using TV, radio, or mobile phone transmitters, coupled with sensitive receivers, could track stealthy aircraft. The theory behind this concept is that a radar system could be designed to exploit radio signals already plentiful in the atmosphere rather than generating its own targeted beams. Systems based on cell phone signals as well as radio and television waves have recently been touted as breakthroughs capable of defeating airborne stealth.<sup>30</sup>

However, analysis and testing have determined that the performance and capability of such systems are considerably less than that of common commercial and early warning radars. The U.S. Air Force does not regard PCL/passive bistatic systems as possessing a “counter-stealth,” capability, notes the large number of false tracks these systems generate, and has concluded that jamming or other techniques could degrade the performance of passive detection systems even further.<sup>31</sup>

Perhaps the most problematic of counter-stealth technologies for airborne targets will be continuing improvements in infrared search and track (IRST) systems. Heat generated by engine and exhaust systems is one source of detection, and airborne IRST systems in fighter airplanes have routinely been able to detect afterburning engines at a range of 30 miles. IRST systems that concentrate in a higher range of the infrared spectrum to

detect surface heating resulting from atmospheric friction may prove to be more effective, with the most advanced systems credited with picking up a conventional target at ranges up to 50 miles. Although IR-suppressing paint, exhaust shielding and cooling, and heat tolerant fuels will all be used in lowering a stealthy aircraft’s thermal signature, the plane’s surface will always be hotter than that of its environment, and a temperature differential as low as one degree may be sufficient to cue other sensors to look more closely. Nevertheless, the problem of searching large volumes of space for small differences in temperature in varying atmospheric conditions still applies. According to the Air Force, the F-22 will have a “low-aspect IR signature under sustained supersonic conditions.”<sup>32</sup> Infrared detection of stealthy aircraft is sure to remain a game of measure and countermeasure.

Finally, there is the challenge of maintaining stealth logistically once it has been achieved operationally. As stealthy air vehicles age, increased LO maintenance is required to prevent signature degradation of unique design features. Both the F-117 and the B-2 have suffered from low “mission capable rates,”—that is, the amount of time that the aircraft is judged to be combat-ready—owing to excessive down times to replace and repair LO-related structures and surfaces. Those problems have been exacerbated by shortages in the skilled labor force needed to do the work and the training demands to fly the limited number of aircraft acquired, thus postponing needed aircraft maintenance.

On the B-2, the application of alternate high frequency material (AHFM) now underway will result in more durable and effective low observability, while dramatically reducing labor hours per maintenance action. Other actions to replace stealth treatments around windows and doors and to deal with hot trailing edges and tailpipes are also essential to keeping the aircraft in a combat configuration. Despite these continued improvements in stealth technology, it seems certain that the supersonic, aerobatic F-22 and the

<sup>29</sup> John Schaeffer, *Understanding Stealth* (Marietta Scientific: Marietta GA, 1997), p. 15.

<sup>30</sup> Bill Sweetman, “Stealth Threat,” *Popular Mechanics*, February 2002.

<sup>31</sup> Office of the Secretary of the Air Force, “USAF Analysis of Passive Coherent Location Systems,” Secretary of the Air Force Public Affairs, Washington, D.C., June 15, 2001.

<sup>32</sup> Sweetman, “How LO can you go?” p. 22.



*Carrier basing may pose environmental and logistical challenges to LO maintenance of the F-35 Joint Strike Fighter, shown above.*

carrier-based F-35 will face environmental and logistical challenges to maintaining their stealth when deployed forward.

We conclude that, as long as the submarine can deny the opponent an acoustic track and the stealthy aircraft can deny the opponent a radar lock, each low-observable platform will remain highly survivable, even in the most hostile environment. Implicit in this assertion, however, is that the designers and operators of these stealthy platforms will pay careful attention to the status of disruptive technologies and will exercise tactical innovation, modify and update subsystems, and vary operational modes to minimize any emerging vulnerabilities. If left unimproved, a stealthy system is likely to fall victim to technological improvements in those sensors from which they were designed to be secure.

### Drawing Analogies (2): Conclusions and Implications

After World War II, the U.S. Navy concentrated on exploiting the submarine's stealthy characteristics. Now the U.S. Air Force and the U.S. Navy, facing a new century with a new capability, could be on the threshold of leveraging low-observable aircraft with analogous tactics and technologies.

As they cross that threshold, they should ponder and seek to emulate the submarine's success. No new or improved technologies have created the "transparent ocean." The submarine's ability to remain stealthy, and the potential for low-observable aircraft to duplicate that experience—despite the enormous intellectual and monetary capital dedicated to defeat stealth—can be attributed to one or more of the following considerations:

**The real environment in which forces operate differs significantly from the presumed or laboratory conditions in which new detection techniques are developed.**

- Regarding ASW, enthusiasts lacked an appreciation for the geographic scale of looking for small things in large, noisy volumes. Furthermore, the superiority of properly employed stealth has never been a marginal issue, as in the "guns versus armor" case, where the relative advantage has periodically swung from one side to the other. There are few technical or operational reasons to think that this condition will change. In the end, when exploitable observables are reduced to nearly the background levels of the vast expanses of sea and sky, the adversary is forced to try to pull faint signals out of noise. The physics of such a problem are inherently skewed in favor of the stealthy platform.
- Similarly, critics of stealth aircraft are quick to note that the aircraft is not likely to prove completely invisible to some radars and fail to appreciate that there is sequence that applies to airborne (or undersea) intercepts or attacks. To shoot down a stealthy aircraft, an opponent must identify and track it with a long-range sensor, then pass the target's track to an airborne interceptor or ground-based anti-aircraft system. That system must then locate, track, acquire and lock on to the aircraft. But the stealthy aircraft's reduced radar detection range makes it difficult to launch and vector the attacking system before losing contact, and places demands well beyond the specified accuracy and fusing parameters of missile seeker heads to the point where destruction is highly unlikely. This required synergism of multiple sensors of varying granularity to derive intelligence is fully understood by any middle-aged person wearing trifocals: a lens to drive to the library, a second to find the book, and a third



to read the text. Remove or degrade the optical system at any level, and the sequence necessary to get to the final solution is broken.

- For both stealthy submarines and aircraft, the synergy in combining tactics and technology makes defense doubly difficult. Although both platforms must sacrifice their stealth during attack—launching torpedoes or opening bomb bay doors—these events offer limited opportunities for counter-attack. Moreover, additional action can be taken by the stealthy platform during the attack phase to further lower its susceptibility to detection. Submarines, for example, could launch a decoy, change course and run in a silenced mode. Stealthy aircraft could launch a defensive missile (such as a miniature air-launched decoy) or an offensive one (such as an anti-radiation weapon) to confuse or suppress the adversary.

**Operational or technical intelligence on new anti-submarine and anti-stealth techniques is available to submariners and aviators, allowing them to modify their tactics to negate those techniques.**

- The submarine has shown that stealth has a sweeping impact because it goes to one of the fundamental success variables of warfare: the ability to see the opponent (be it target or threat) before being seen. In an operational context, history has shown that this enabled the submarine to evolve an entirely new set of operational tactics and doctrine, particularly the ability to operate alone deep within enemy territory for extended periods with minimum outside support.
- Stealth provides the advantage that tactics can be as useful as technology in achieving this all-aspect low observability. One can detect the threat and maneuver around it or one can present the platform to the opponent in a way that defeats his sensor.
- A nearly universal truth is that the commander of the stealthier platform always retains the initiative to attack or not. A corollary to these observations is that a defender's detection of a stealthy platform can be considered *prima facie* evidence that an attack is in progress, because the attacker has obviously made a conscious decision to risk that detection. Because of this, there is an extraordinarily high (and sometimes

frenzied) rate of ordnance expenditure in real counter-stealth scenarios. For example, the Royal Navy, faced with the threat of only one small coastal defense submarine off the Falklands, expended—fruitlessly—nearly the entire fleet's inventory of ASW weapons. Against a stealthy aircraft, plagued by false alarms and unable to precisely locate its adversary, ground-based air defenses have similarly fired at extraordinarily high rates, as evidenced by CNN's displays of anti-aircraft artillery in the skies over Baghdad during the first nights of Desert Storm.

**Stealth provides a long-term competitive advantage.**

- The existence of a stealthy force creates an enormous burden on the defense. Whether or not the platforms are being employed, there is a major requirement for a prepared response, because the defender is never sure where or when the threat will surface. Stealth thus contributes to virtual attrition of enemy forces by causing the adversary to maintain a high and expensive level of readiness.
- The virtual attrition property of stealth suggests the opportunity cost of defending against low-observable platforms. During World War II the allies invested in thousands of ships and hundreds of thousands of people in defending against U-boat attacks. Theoretically, extremely high concentrations of air defense systems could provide some capability against stealthy aircraft, but the B-2 was designed to negate that enormous investment made by the former Soviet Union in air defenses. Any potential U.S. adversary faces an enormous opportunity cost to develop a system to defend itself against stealthy ships and aircraft while attempting to engage the U.S. military in other arenas. Thus the U.S. investment in stealth (an asymmetric advantage in its own right) poses a significant allocation dilemma for potential adversaries—invest enormous amounts to counter stealth (and neglect other areas) or spend elsewhere (and remain vulnerable to stealth).

**The submarine or aircraft, as a stealthy system, is a noncooperative target able to manipulate its observables and reduce its signature by constantly reviewing and correcting emerging deficiencies.**

- Had the nature of the submarine threat remained constant, more might have been expected from ASW efforts over the years. However, stealthy platforms have strong operational forcing functions to evolve technologies at a rate capable of maintaining their covert nature in a relative sense, and have an intrinsic advantage of being able to “sense the sensor” (or the platform upon which it is carried), and respond accordingly.
- Another lesson is that true stealthiness involves all aspects of a platform’s design and operation. Decades of evolution, sometimes with hard lessons learned through losses, have shown that every potential source of signature must be controlled. Reflections of the adversary’s energy (sonar or radar) have to be reduced; energy radiation from the low-observable platform (self-generated signature) has to be minimized; and operational practices (use of active vice passive radio communications) have to be controlled.
- In submarine warfare, when complacency was avoided, where counter-stealth R&D programs were aggressively maintained, and when operational desires were not allowed to encourage nonstealthy behavior, stealth has prevailed. The implicit issue here is that stealth was the only variable judged immune from design and development tradeoffs. The Navy might accept bigger, slower or shallower, but each new class, or variant, had to have the same or less radiated noise characteristics than that of the preceding boat. All of these considerations are transferable to low-observable aircraft.
- It was noted earlier that every U.S. military submarine, on decommissioning, left the water stealthier than it entered. Indications are that owners of stealthy aircraft have not yet learned that lesson. LO modifications to the F-117 and B-2 have not been granted priority in comparison with other upgrades, with an attendant decline in mission-capable rates. Even more troubling is a retreat from maintaining an aircraft’s stealth to enhance other capabilities. Proposals to hang external ordnance on the JSF or to turn it into a standoff electronic jammer are illustrative of this trend, as are suggestions to stretch the F-22 and diminish its stealth to give it an air-to-ground capability. Clearly, tradeoffs will occur between low observability and mission requirements, but related tactics and operational procedures must offset any stealth technology surrendered.

## CONCLUSION

The analogies drawn between the stealthy submarine and low-observable aircraft suggest the following:

- Stealthy airborne platforms will maintain a long-term edge over defenses, providing that its sponsors continue to study and exploit environmental phenomena and opponents’ countermeasures, and take prompt and sustained corrective measures.
- Continued operation of stealthy airborne platforms will prompt new tactics, techniques and procedures markedly different from conventional concepts of operations. For example, the World War II bomber streams numbered in the hundreds of aircraft both for protection and to muster the firepower necessary to accomplish the mission; it was impossible to conceal such a signature. Similarly, the massive strike packages into North Vietnam provided a wealth of warning to the opponent, and were structured to smash directly through enemy air defenses rather than to avoid them. Single-ship B-2 missions over Serbia and Afghanistan illustrate the value of stealth in avoiding these costly tactics. Converting the B-2 and the SSBN from their strategic nuclear roles to providers of long-range, precise conventional firepower may be one of the most telling analogies of all.
- Stealthy and nonstealthy aircraft will have to develop special techniques for operating together, so that nonstealthy aircraft will benefit while stealthy ones will not lose their inherent advantage. Working together, however, does not mean collocated in space or time. The submarine conducting forward offensive operations is working with the approaching carrier battle group by destroying or diverting potential attackers. The stealth aircraft, operating in front of a larger, nonstealthy force, defeats air defenses to allow a greater penetration probability for the following force, and frees up supporting resources (air superiority, escort, and electronic countermeasures aircraft) for other uses.

- Numerous innovative countermeasures to stealthy aircraft will be proposed, but few, if any, will have lasting impact even though they may achieve momentary headlines.
- Low-observable aircraft, in which stealth has been added to the intrinsic mobility of the airplane, will prove as revolutionary as the nuclear submarine, where mobility was added to inherent stealth.

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