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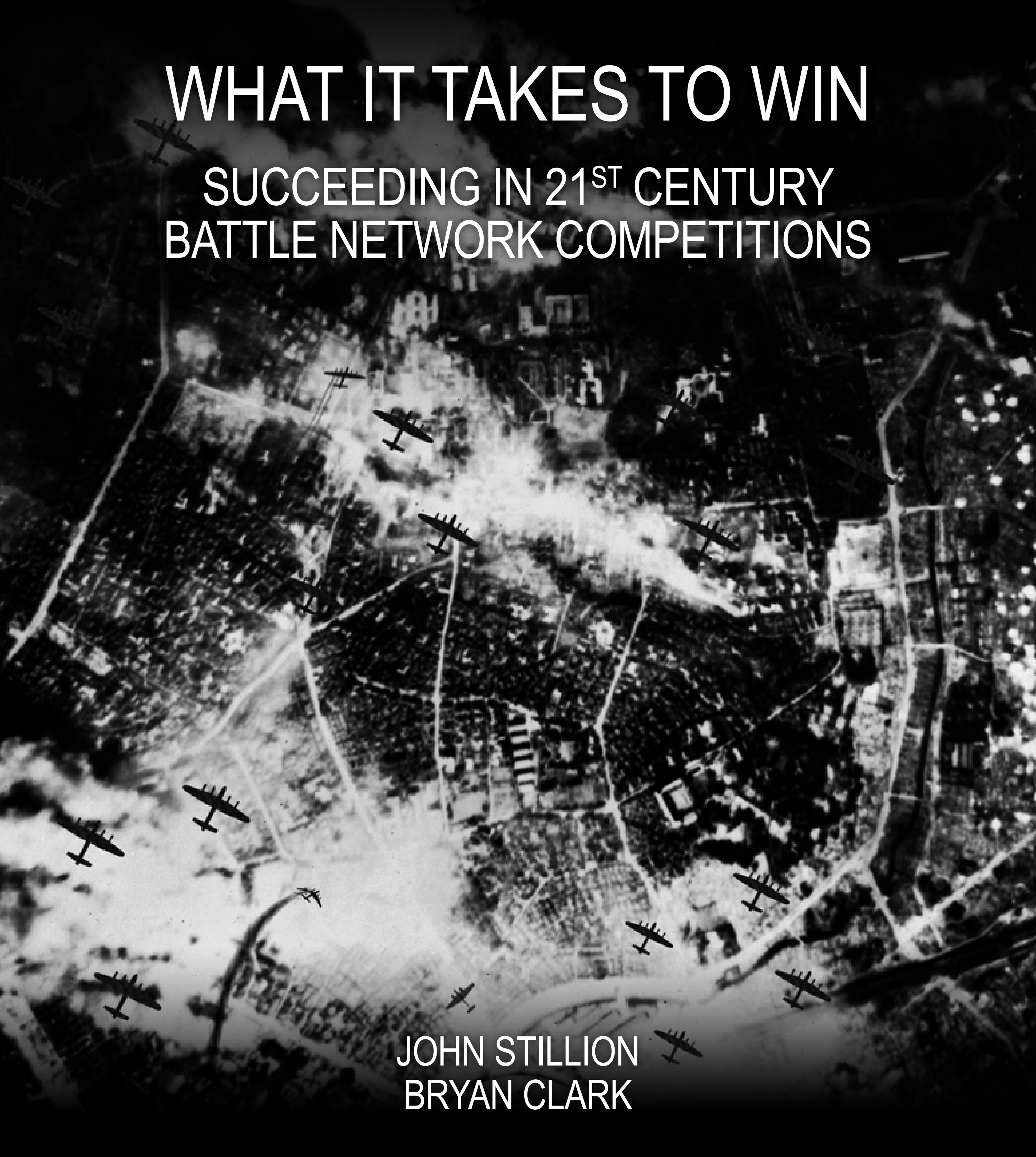
WHAT IT TAKES TO WIN

SUCCEEDING IN 21ST CENTURY BATTLE NETWORK COMPETITIONS



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2015

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The Center for Strategic and Budgetary Assessments (CSBA) is an independent, nonpartisan policy research institute established to promote innovative thinking and debate about national security strategy and investment options. CSBA's analysis focuses on key questions related to existing and emerging threats to U.S. national security, and its goal is to enable policymakers to make informed decisions on matters of strategy, security policy, and resource allocation.

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Electronic network communications play a large and increasingly important role in modern life. Over the past two decades, the decreasing cost, increasing capability, and widespread availability of network communications transformed the way many of us work, shop, and maintain contact with friends and loved ones, as well as how, when, and where we access news and information. Widespread use of electronic communications, however, is well over a century old. Successful electrical telegraph systems emerged during the 1840s. The telephone followed in the 1870s, and by 1900 over 1.3 million telephones were in use in the United States.[1] During the first decade of the twentieth century, radio communication, or "wireless telegraphy" as it was known at the time, was developed.[2] By the beginning of World War I, the armies of the Great Powers used field telephone networks and radios to transmit information and orders to ground and naval forces. The widespread ability to communicate information across great distances almost instantly led to the formation of the first battle networks.

Defining Battle Networks

For the first time, it was possible to separate the major functions of military units and systems to improve their range, survivability, accuracy, and overall effectiveness. Fundamentally, a battle network is a combination of target acquisition sensors, target localization sensors, command and control (C2) elements, weapons, weapon platforms, and the electronic communications linking them together. Prior to the advent of electronic communications and sensors, C2 and weapons had to be close enough to allow for rapid communication. As this was generally limited to the human voice, bugle calls, and, if weather and lighting conditions permitted, flag signals, dispersal options were constrained by the limits of human hearing and eyesight. Dispersing these functions in a network across a large area has a number of potential

1 U.S. Census Bureau, *Bicentennial Edition: Historical Statistics of the United States, Colonial Times to 1970* (Washington, DC: U.S. Government Printing Office [GPO], 1975), Part II, Chapter R, Table R 1, available at http://www2.census.gov/prod2/statcomp/documents/CT1970p2-05.pdf, accessed May 12, 2014.

2 The first routine transatlantic radio message was transmitted by Guglielmo Marconi on the night of December 15, 1902. See Henry M. Bradford, "Marconi's Three Transatlantic Radio Stations in Cape Breton," *Royal Nova Scotia Historical Society Journal,* 1, 1998, available at http://www.newscotland1398.net/marconi100/marconi1.html, accessed May 12, 2014.

advantages and can greatly increase their effectiveness. For example, networking allows weapon platforms to engage targets they cannot otherwise detect or track by leveraging the capabilities of distant sensor systems. Networking functions can also improve overall effectiveness by giving commanders a broader view of the overall situation, as viewed from a number of disparate sensors, enhancing their ability to prioritize missions to achieve desired operational effects and assess the effects of previous actions.

The development of indirect artillery fire techniques late in the nineteenth century is a good illustration of the advantages of a battle network. Although not generally thought of as a battle network at the time, over the course of World War I, artillery formations of the major powers rapidly developed all the characteristics of a battle network. They used forward observers on the ground and in tethered balloons (sensors) to find and identify targets,[3] fire control centers to confirm and prioritize targets (C2), and dispersed field artillery batteries (weapons) to engage targets. Each element was linked by field telephone lines that allowed targets to be engaged much faster than they could move out of range.[4]

Why Battle Network Competition Matters

Advances in communications and computer network technologies have reduced the costs and increased the benefits associated with networking military systems. This makes battle networks both more common and increasingly the central focus of competition and conflict between capable, competent adversaries. As the indirect artillery example above shows, however, battle networks and battle network competitions (BNCs) have existed for over a century. Examples of past BNCs include: the Allied anti-submarine warfare (ASW) struggle against German U-boats in the Battle of the Atlantic during World War II; the great aircraft carrier battles in the Pacific in 1942 and 1944 between the Japanese and U.S. navies; and the contest between U.S. airpower and the North Vietnamese integrated air defense system (IADS) during the Vietnam War. All of these BNCs included significant use of electronic sensors, radio communication, network penetration (code breaking), and electronic warfare. These elements are repeated in modern BNCs, making insights gleaned from historical BNCs relevant to contemporary ones.

The body of this report presents detailed analysis of quantitative historical data of two long-running BNCs. The first is the competition between submarines and ASW battle networks from World War II through the present. The second is the competition between air attack and IADS from World War II through the present. Each of these quantitative case studies will show how the introduction of new systems and/or operational concepts shifted the balance in the competitions. We chose these two BNCs for several reasons. Most importantly, they are ongoing and

3 "Caquot Type R Observation Balloon," U.S. Air Force, available at http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=281, accessed May 13, 2014.

4 Dave Wellons, *Direct Fire to Indirect Fire: Changing Artillery for the Future?* (Fort Leavenworth, KS: School of Advanced Military Studies, United States Army Command and General Staff College, 2000), pp. 1–7, available at http://www.dtic.mil/dtic/tr/fulltext/u2/a389830.pdf, accessed June 4, 2014.

are highly relevant to current and future U.S. military operations. Of almost equal significance is the degree to which the competitions are shaped by fundamental attributes of submarines and aircraft respectively. This makes it likely that many lessons from past conflicts will retain relevance well into the future. Finally, there is sufficient quantitative data available to assess these BNCs.

What Matters in Battle Network Competitions

Before launching into the battle network case studies, it is useful to highlight some of the most important common elements of BNCs we discovered during our analysis. First, BNCs tend to be defined by the fundamental attributes of the systems at the center of the competition. In the cases we explore, these are the submarine and the bomber or attack aircraft. We also found that the goals and metrics chosen for a battle network have a significant impact on its cost, complexity, organization, and effectiveness. For example, the sophistication, organization, and cost of a network designed to find and destroy all opposing submarines would be quite different from one designed primarily to enable convoys of merchant ships to avoid enemy submarines. Depending on one's strategic goals, the latter network may be "good enough" to attain a specific strategic goal and much less costly than the former. A related finding is that it is often more cost-effective to force an adversary to delay operations, decrease operational tempo, or dedicate significant resources to defense than to attempt to destroy a large fraction of an opposing force. We refer to the forced decrease in operational effectiveness as "virtual attrition" to distinguish it from the "actual attrition" resulting from destruction of enemy forces. We also noted that the pace and tempo of operations and tactical engagements greatly influences whether it is preferable to exploit an adversary's network communications or to attempt to disrupt them. For example, submarine operations unfold over days or weeks, whereas air operations tend to be completed in a matter of hours. This makes it much more likely that adversary communications can be intercepted, decoded, analyzed, and the results transmitted to submarine or ASW forces than to aircraft or IADS elements in time to influence tactical or operational outcomes. Another common feature of BNCs is that, as conflicts persist, the pace of the move-countermove cycle accelerates. Eventually it reaches a pace so rapid that one side is either unable to keep up or takes measures to force the competition into a new "competitive regime" where much of the opponent's existing battle network is rendered ineffective by reducing or eliminating the physical phenomena used to detect and localize the most important systems. An example of this is the U.S. development of stealth aircraft technology in the closing years of the Cold War. This technology greatly reduced the ability of radars to detect and track aircraft, effectively "blinding" IADS and rendering them much less effective.

The remainder of this report is organized into three sections. The next section traces the competition between submarines and ASW battle networks from World War II to the present. The following section traces the competition between air attack and IADS over the same time period. The final section summarizes the major findings briefly outlined above and illustrates how they can be used as the basis for analysis of past, present, and future battle networks.

Submarines Versus Anti-Submarine Warfare

Enduring Aspects of the Competition

Submarines and ASW have been part of military campaigns for more than a hundred years. Despite the advances made on both sides of this competition over that period, the fundamental characteristics of submarines and their targets are largely unchanged. This makes insights from past submarine-ASW competitions of forty, seventy, or even a hundred years ago still relevant today and into the future. Enduring characteristics of submarines include:

- *Submarines are slower than their targets and the platforms conducting ASW against them*. To remain undetected, submarines must travel slower than 10–15 knots. Surface ships can routinely travel at twice that speed unless they are trying to be acoustically quiet, and ASW aircraft can travel at ten to twenty times that speed.

- *Submarines have limited sensor range*. Despite advances in passive and active sonar, the systems installed on submarines cannot reliably track contacts more than 10–20 nautical miles (nm) away. In general, lower sound frequencies are detectable at longer range because they suffer less reverberation loss in air or water. Lower sound frequencies, however, require larger sonar arrays to receive them. Submarines are limited in size, so the physics of sound place a limit on the range at which they can detect sonar contacts. Submarines improve their array length with towed sonar arrays, but these provide imprecise bearings that require time to interpret. Nonacoustic sensors such as electromagnetic (EM) receivers and radar could detect targets farther away, but they have to be placed above the water to detect EM signals. To maintain their stealth, submarines remain submerged and have a limited "height-of-eye" of the masts hosting EM sensors. This limits their range to the horizon and ability to detect ships to about 10–20 nm. While they could detect aircraft radars farther away, because aircraft are above the horizon, this doesn't significantly change the submarine-ASW competition because aircraft are generally only a threat to the submarine rather than a potential target.

- *Submarines lack self-defense.* Unlike surface ships, which have air defense systems to protect against aircraft and missile attack, submarines generally lack defensive weapons to defeat incoming torpedoes or depth charges. Like aircraft, submarines have some defensive countermeasures to decoy incoming weapons, but these provide limited effectiveness and are only helpful in evading attack, as opposed to enabling the submarine to "stand and fight."

These characteristics produce enduring aspects of the submarine-ASW competition that directly impact the design and operation of submarine and ASW battle networks:

- *Submarines must preposition themselves for attack.* The maximum speed of a submarine is about the same speed as a surface ship, but to remain quiet, a submarine must travel at less than half that speed. Therefore, submarines generally cannot pursue or "chase down" a surface target. Anti-ship cruise missiles (ASCMs) expand the attack radius of a submarine to 100–150 nm from about 10 nm for torpedo attack, but this still requires the submarine to be in position to intercept the target rather than trying to catch one that is outside its current weapon radius. The longer weapon range simply gives the submarine a larger area in which it can preposition. Submarines, however, will generally have to use heavyweight torpedoes rather than ASCMs to stop large modern merchant ships, which range from 100,000 tons for Very Large Crude Carriers to more than 300,000 tons for the largest bulk carriers.

- *Surface ships can avoid submarine attack.* A corollary to the above is that surface ships can avoid submarine attack if they know the submarine's approximate position by staying outside the submarine's sensor range or, if third-party targeting will be available to the submarine, its weapons range. Surprisingly, this is easier today than in World War II or the Cold War. Modern container and break bulk ships can sustain speeds of 20–25 knots—three times that of a mid-twentieth-century merchant ship—whereas today's submarines can only travel 50–100 percent faster than their World War II predecessors if they are trying to avoid detection.

- *ASW ships and shore systems can establish a detection range advantage.* Ships and shore facilities can employ larger arrays than submarines, which can transmit and detect lower frequency sound that travels farther in water. They can also use active sonar with less concern for counter detection. Low frequency active sonar enables longer detection ranges than passive sonar against quiet submarines.

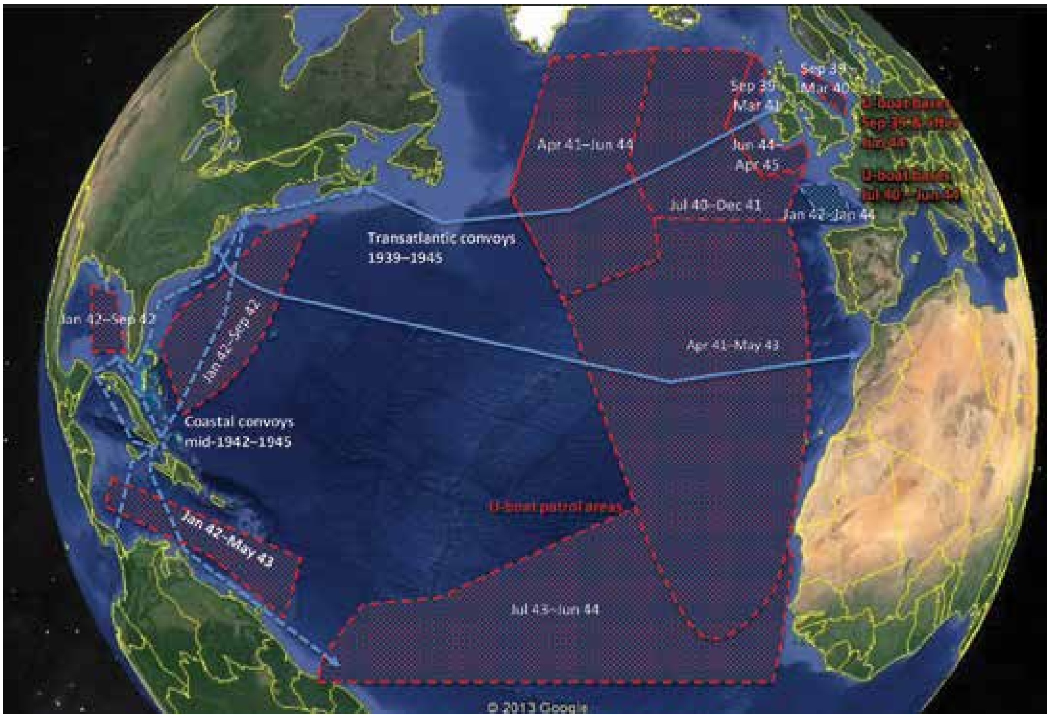
- *Submarines must "clear datum" if detected.* Submarines have limited ability to detect incoming weapons and quickly determine whether the submarine will be hit. They are also too slow to outrun attacking ships or aircraft or evade most weapons, and they cannot destroy incoming weapons; their modest acoustic countermeasures are only useful to help evasion. Together, these factors compel submarine commanders to break off operations and distance themselves from threat contacts when they believe they have been detected. Indications of detection include strong or changing active sonar signals, search platform maneuvers, and weapons launches, even if ineffective. This provides ASW forces a range of options to deny submarines confidence in their stealth and prevent them from prepositioning for an attack.

- *Submarine utility is constrained by how the other side operates.* Submarines can be used for attacks on surface ships, missile strikes against targets ashore, intelligence gathering, and ASW, but the limitations above give the other side a significant "vote" in submarine efficacy across possible missions. For example, constraints on a submarine's ability to intercept and attack surface ships prevent them from being used in this mission unless opposing targets are operated in predictable ways that enable the prepositioning of submarines for attacks. Similarly, ASW by submarines requires cueing or chokepoints through which enemy submarines must pass owing to the relatively short detection ranges possible with organic submarine sensors.
- *Submarines predominantly provide capabilities for denial.* Submarines have limited payloads and are relatively vulnerable once detected, and are thus less effective than surface or air forces in conducting power projection or shows of force. Submarines are more effective at stopping or impeding an adversary in conducting their missions. As a result, ASW metrics should focus on sustaining the missions submarines are trying to stop, rather than destroying the submarines.

The Battle of the Atlantic

The longest sustained competition of submarines versus ASW forces was the Battle of the Atlantic from 1939 to 1945. The battle started when German aggression at the outset of World War II prompted British requests for American supplied fuel, military equipment, and food. It progressed through the war as supplies from the United States kept Britain and later the Soviet Union in the fight. The Axis countries countered this supply effort by attacking Allied transport ships as they crossed the Atlantic. The Battle of the Atlantic tapered off when Allied forces invaded the European continent, capturing German submarine bases in France and driving German forces from submarine bases in Norway. The battle ended with Germany's surrender in 1945. As indicated in Figure 1, Allied convoy routes expanded with the war effort to include North Africa and the eastern seaboard of North and South America. In response, German submarine patrol areas expanded and then contracted as submarine bases were added and later lost on the western coasts of Europe.

FIGURE 1. BATTLE OF THE ATLANTIC CONVOY ROUTES AND U-BOAT PATROL AREAS[5]



The Battle of the Atlantic incorporates all the elements of the submarine-ASW competition and provides insights that apply both to other historical cases and to the future competition. In World War I, Allied forces faced a similar challenge to what they confronted in World War II. Supplies and troops needed to cross the Atlantic to assist the British and French war effort and were countered by German submarines conducting unrestricted countermaritime warfare. The submarines, however, had short endurance and stayed close to the British Isles, while the Allies only mounted a concerted ASW campaign later in the war. As a result, the World War I competition was much more limited than that of World War II.

The Cold War also featured many of the elements of the preceding submarine-ASW competitions. U.S. and NATO forces developed and fielded offensive capabilities to threaten Soviet submarines and defensive capabilities to protect allied naval forces from them. The Soviets pursued a defensive approach to protect their submarines from NATO submarines, which were primarily used for ASW. The lack of actual fighting in the Cold War limits both the ability to assess contemporary battle networks in general and future submarine-ASW battle networks in particular. Because it was long, incorporated sustained combat, and involved a full spectrum of submarine and ASW efforts, the Battle of the Atlantic enables the most robust analysis of the submarine-ASW competition.

5 Samuel Eliot Morison, *The Battle of the Atlantic, 1939–1943* (New York: Little Brown, 1947), pp. 67, 89, 107, 320.

The Electromagnetic Spectrum Competitive Regime

Sonar is most often associated with the submarine-ASW competition, yet EM-based methods were more effective in enabling submarine and anti-submarine warfare during the Battle of the Atlantic. This was because World War II submarines were actually "submersibles," rather than true submarines. They would operate on the surface most of the time and submerge only to covertly attack or evade. This made them more susceptible to detection with EM technologies such as radar or radio intercepts, rather than with the limited acoustic sensors available at the time.

Due to their sensor and speed limitations, ships and submarines required cueing to either avoid submarine patrol areas or place themselves in position to intercept transiting surface ships. In the early to mid-twentieth century, the only long-range communication technology available was high-frequency (HF) radio. HF and lower-frequency EM signals can travel over the horizon using "ducting" created by temperature gradients in the atmosphere.

This created an opportunity for communications exploitation by both sides through the decryption of messages and by geolocating transmitting ships and submarines. The Allies encrypted their convoy routing and rerouting orders but they were decoded by the German B-Dienst team from early in the war. German U-boat commander Karl Doenitz similarly used encrypted HF communications to position and reposition his U-boat "wolf packs," but these were broken through the efforts of the "Ultra" team at Britain's Bletchley Park. Intercepted and decrypted communications were used by each side in the Battle of the Atlantic to adjust their convoy routes or submarine patrol areas, creating a game of maritime "cat and mouse" throughout each trans-Atlantic transit.

The Battle of the Atlantic's EM competitive regime persisted at the tactical level as well, where both communications intercepts and radar were used to find or evade the enemy. The Allies had an advantage over the Axis at the tactical level because of the size and complexity of World War II-era EM systems and the U-boat's concept of operations. Convoys used HF communications to manage and control the convoy. Submarines could detect these emissions if they deployed HF direction-finding (HFDF) electronic intelligence (ELINT) equipment. Early HFDF and radar equipment, however, could neither be made small enough nor watertight enough to permanently mount outside the submarine pressure hull. The systems available at the time were bulky and had to be temporarily mounted on the bridge, connected via cables to the control room, which fouled the bridge hatch and lengthened the time required to conduct an emergency dive to evade detection or attack. As a result, U-boat commanders were reticent to deploy the few available HFDF systems.

The Allies' ships and aircraft, however, aggressively deployed HFDF and radar systems. HFDF was effective by leveraging vulnerabilities in the U-boats' battle network structure and "wolf pack" operating concept. The German U-boat battle network sought to make up for the limited speed and situational awareness of the submarine by placing a line of U-boats across the expected convoy path and then swarming the convoy when it was detected. This maximized the probability of at least one U-boat seeing the convoy's smoke or masts before the U-boat was detected while retaining the ability of the wolfpack to mass its attack and increase shipping losses. This tactic, however, required extensive communication among the U-boats to coordinate their search and attack. These communications were detectable by HFDF systems installed on escorts or convoy vessels starting in 1941, enabling the convoy to evade the U-boats and send escorts, or later, "hunter-killer groups," to drive off the U-boats.

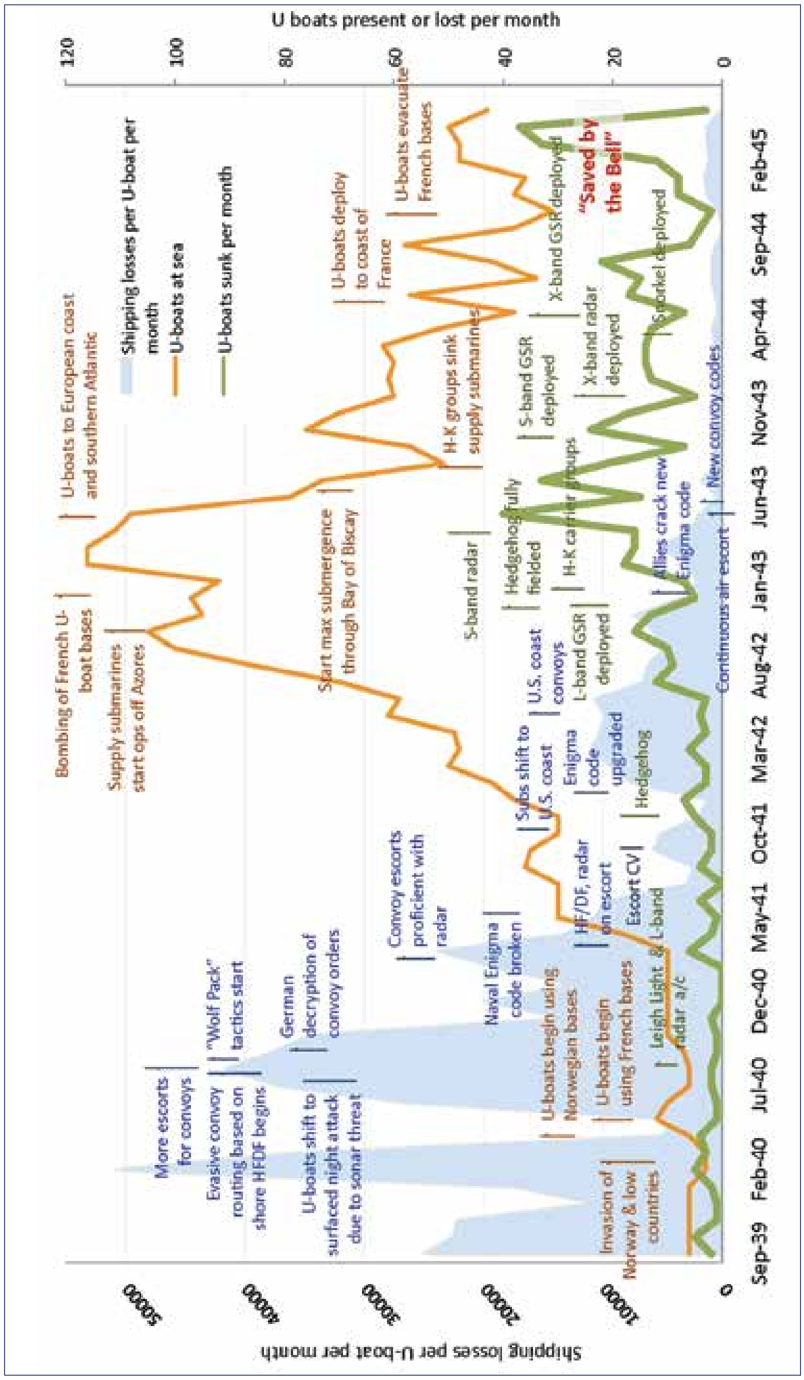
Radar was also effective at detecting U-boats, which spent most of their time on the surface and presented a discernible target against the ocean, except in high seas. German submarines did not deploy radars until late in the war for many of the same practical reasons as HFDF systems. They were bulky, fouled hatches, and had limited range due to the low height of the submarine. In contrast, the Allies' ASW radar was so effective, Doenitz and German engineers mounted a dedicated effort to develop radar receivers for U-boats. The fielding of ASW radars by the Allies and radar receivers by the Germans led to a move-countermove EM competition from 1942 through the end of the war as each side deployed progressively more accurate and higher-frequency EM systems. This development is discussed more in "Saved by the Bell" below.

Sonar, which is the centerpiece of the submarine-ASW competition today, played a minimal role in the Battle of the Atlantic. In the interwar years, Britain and the United States independently developed acoustic means for surface ships to detect and track subs. Britain developed the Allied Submarine Detection Investigation Committee (ASDIC) system and the United States developed the "sound navigation and ranging" (sonar) system. Neither system was fully tested before World War II began and both proved to have insufficient range and accuracy to be useful in even tactical-level ASW. After the systems were improved late in the war, they were able to track a known submerged submarine, but still were unable to find one without cueing.

The Importance of Metrics

One of the most significant findings of this study is the importance of metrics. The objective, or metric, of the battle network will define its structure—for better or worse. This may seem obvious, but in the Battle of the Atlantic each side sometimes employed metrics that proved suboptimal in gauging whether they were achieving their overall objectives. This resulted in battle networks that used more forces and capabilities than were needed, had multiple single points of failure their opponent could exploit, and made substantially less progress toward the desired outcome than would have been the case if more relevant metrics had been selected.

FIGURE 2. THE GERMAN VIEW OF THE BATTLE OF THE ATLANTIC[6]



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6 Morison, *Battle of the Atlantic*, pp. 400–17; Charles Sternhell and Alan Thorndike, *Antisubmarine Warfare in World War II*, Operations Evaluation Group Report No. 51 (Washington, DC: Office of the CNO, 1946), pp. 80–90, available at http://www.ibiblio.org/hyperwar/USN/rep/ASW-51/index.html#contents, accessed June 4, 2014; Clay Blair, *Hitler's U-Boat War: The Hunters, 1939–1942* (New York: Modern Library, 2000), pp. 580–600.

The German Perspective

Early in the war, Doenitz established “U-boat productivity” as his primary metric. Specifically, he focused on the number of merchant ship tons sunk per U-boat per month. This metric, combined with strict reporting procedures and C2, enabled Doenitz to track the progress of the campaign and evaluate his U-boat commanders and their ships in “real time” (see Figure 2). It also enabled him to show Hitler the effectiveness of U-boats in reducing support to Britain at the time Germany was trying to isolate and neutralize it as a launching point for a future invasion of the continent. Successfully isolating Britain would enable the Axis powers to focus their attention completely on the Soviet Union, which by late 1941–early 1942 was consuming most of the German war effort.

In retrospect, U-boat productivity was an ineffective metric with which to measure U-boat activity. The Allies started the war with more than 40 million tons of shipping. Losses per convoy averaged less than 6 percent for the whole war, except for the U.S. East Coast in early 1942, and, in the worst months, overall losses from all causes were about 1 million tons per month, about 700,000 tons of which came from submarine attack.[7] The Allies could sustain such losses for one to two years even without a robust building program. They did mount such a program, however, and were producing 700,000 tons of shipping a month by November 1942, overcoming even the worst losses to U-boats.[8]

The most significant effect of the submarine campaign was the Allied war materiel that went to the bottom with their ships, but Doenitz’s metric did not discriminate between ships carrying beans, bullets, or battalions—or ships returning empty to America. A more relevant metric would have tracked the type of cargo and tonnage sunk instead of the total shipping tonnage sunk. For example, no Allied troop ships were damaged or sunk until 1944, when six ships carrying troops and supplies were lost between England and France during the Battle of the Bulge.[9] Tankers were not accorded priority as targets, nor were they sunk at any greater frequency than other ships, although fuel losses were more concerning than losses of material for the Allied Combined Chiefs of Staff.[10] Establishing tanker or troop transport losses as a metric may have enabled Doenitz to more directly reduce the ability of the Allies to mount a successful cross-Channel invasion.

Doenitz’s metric of U-boat productivity, however, was good for identifying when U-boats were declining in effectiveness, which tracking overall shipping losses alone would not do. For example, shipping losses were steady through late 1941, while the number of U-boats on patrol increased. As a result, U-boat productivity went down. A cursory look at shipping losses would have implied the German U-boat campaign was doing fine, but the U-boat productivity metric

7 Morison, *Battle of the Atlantic*, p. 402.

8 Ibid., p. 403.

9 Sternhell and Thorndike, *Antisubmarine Warfare*, p. 35.

10 First Sea Lord, Chief of the Royal Air Staff, Chief of the Imperial General Staff, U.S. Chief of Naval Operations, U.S. Army Chief of Staff, Commander of the U.S. Army Air Corps, and the U.S. President’s Chief of Staff.

showed each submarine was accomplishing less. This would be expected if there were a finite supply of shipping targets being targeted by a growing number of U-boats. With the percentage of ships lost per convoy in the single digits, however, there should have been many targets available for each new submarine entering a patrol area. Instead, low U-boat productivity and the location of shipping losses indicated that only a few submarines in the central Atlantic were achieving the bulk of the shipping losses. In early 1942, overall shipping losses spiked to their highest levels of the war due to America entering the war without having organized convoys or provided escorts to protect East Coast shipping. Things looked promising for Germany on the surface. Doenitz's metric of U-boat productivity, however, showed the improvement was modest and short-lived. In fact, U-boat productivity was much lower than it had been early in the war.

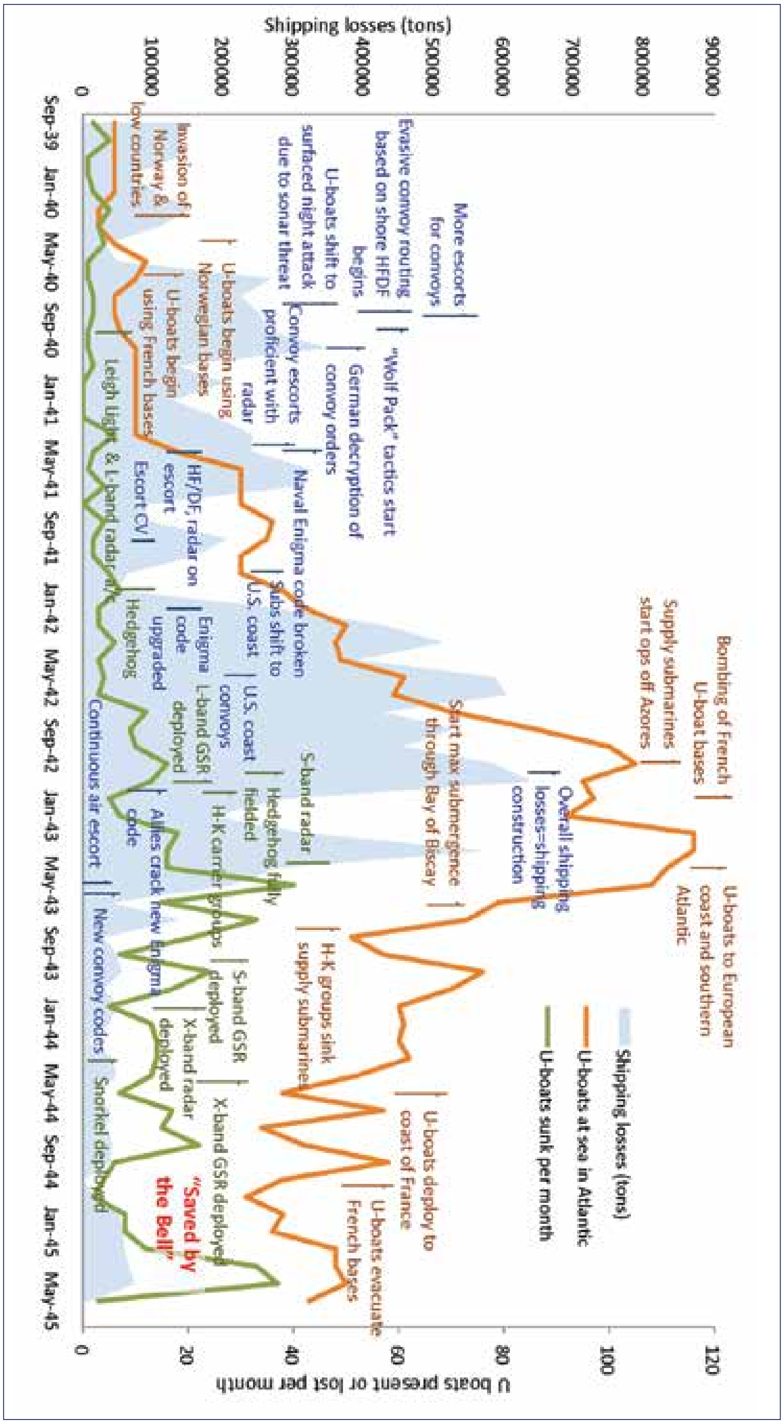
Doenitz also tracked the number of U-boats on patrol in the Atlantic. As Germany acquired forward bases, U-boat "presence," to use today's term, rose. With the invasion of Norway and later France, new submarines were able to leave German construction yards, go on their first patrol, and return to forward bases closer to the U-boat patrol areas depicted in Figure 1. Subsequent patrols could then be conducted with much shorter transits, enabling more submarines to be on patrol, as shown in Figure 2. From 1939 to 1943, U-boat construction exceeded losses, increasing the number of submarines in the Kriegsmarine to a high of about four hundred,[11] which also increased U-boat presence in the Atlantic. As noted above, however, more submarines did not translate to more Allied shipping losses, much to Doenitz's dismay. This was largely due to Allied convoy and escort tactics and capabilities.

The Allied Perspective

The Allied Combined Chiefs of Staff and convoy commanders focused on overall shipping losses (see Figure 3). This metric seemed an obvious choice between 1939 and 1942 because America was sustaining the British and Soviet war effort with food, weapons, explosives, machinery, and 80 percent of Britain's fuel. From 1942 to 1944, shipping losses also provided one way to track progress, or lack thereof, in the buildup for Operation Torch in North Africa and toward the eventual invasion of the European continent. This metric needed to be analyzed carefully, however, to ensure the correct conclusions were drawn and appropriate actions taken. With constrained time and resources, "trial and error" would not be a good approach to identify the best means to sustain the Allied war effort in the face of the German U-boat campaign.

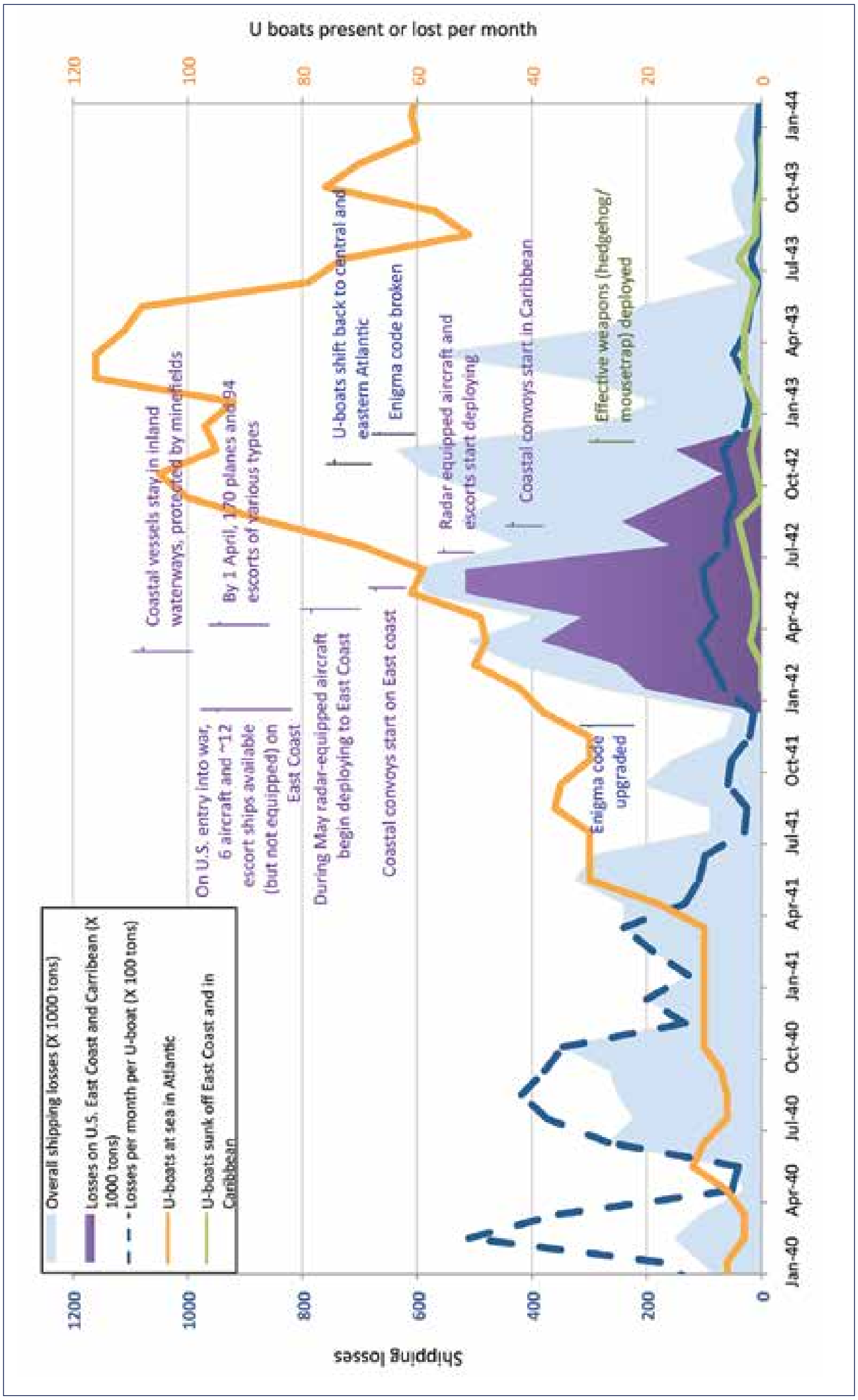
11 Morison, *Battle of the Atlantic,* p. 60; Sternhell and Thorndike, *Antisubmarine Warfare*, p. 83.

FIGURE 3. THE ALLIED VIEW OF THE BATTLE OF THE ATLANTIC[12]



12 Morison, *Battle of the Atlantic*, pp. 400–17; Sternhell and Thorndike, *Antisubmarine Warfare,* pp. 80–90; Blair, *Hitler's U-Boat War,* pp. 580–600.

FIGURE 4. SHIPPING LOSSES OFF THE U.S. EAST COAST[13]



13 Morison, *Battle of the Atlantic*, pp. 400–17; Sternhell and Thorndike, *Antisubmarine Warfare,* pp. 80–90; Blair, *Hitler's U-Boat War,* pp. 580–600.

Overall shipping losses increased from September 1939 to mid-1941 as convoy shipments increased and more submarines operated in the Atlantic. Monthly losses decreased to less than 100,000 tons by the end of 1941 as the Allies fully implemented convoys across the Atlantic and equipped them with escorts for the entire transit. Since U-boat losses remained low for this entire period and U-boat presence steadily increased, it is reasonable to conclude the introduction of convoys and escorts reduced U-boat effectiveness without sinking a sizable number of submarines.

The lull in shipping losses during late 1941 was ruptured by a dramatic increase in early 1942. As shown in Figure 4, the spike was almost entirely due to losses on the U.S. East Coast. Although America helped British and Canadian forces convoy supplies across the Atlantic for two years, the U.S. military entered the war with little ASW capability or capacity on the U.S. East Coast. Convoys leaving two to three times a week for Britain, and later, Africa, were supplied by thousands of coastal tanker and transport ships traveling from South and Central America, the Gulf Coast, and Southeastern seaboard to marshaling areas off New York City and Halifax. These ships, often traveling alone, were vulnerable to U-boat attack once America entered the war. Doenitz anticipated this opportunity based on the intelligence gained from *Milchkuh* ("Milk Cow") and other submarines operating in the western Atlantic during 1941.[14] When Germany declared war on the United States, Doenitz sent about a dozen submarines, almost half his deployed force, to the U.S. East Coast. Shipping losses grew and Americans on the East Coast got a front-row seat to the conflict as ships burned and sank within sight of Cape May, the Outer Banks, and Long Island.

Figure 4 also shows that shipping losses on the U.S. East Coast dropped almost as quickly as they had grown after the U.S. Navy implemented convoys and supplied them with escorts. These escorts were not equipped with radar, sonar, or effective ASW weapons until the end of 1942.[15] They also destroyed few German submarines. Together, this suggests that reduced shipping losses off the U.S. East Coast were the result of beginning convoys and providing escorts, rather than sinking U-boats.

Senior Allied commanders could have seen how the reduction in losses first in the central and eastern Atlantic and later in the western Atlantic corresponded with the introduction of escorted convoys rather than submarine losses. But identifying the primary causes of the reduction was difficult in real time. Germany did not report submarine losses, and escort commanders tended to be optimistic about whether their efforts to drive off submarines resulted in sinking the U-boat. Meanwhile, fleet commanders and their ASW forces wanted to kill or sink submarines. This is a natural inclination in war, especially one in which the adversary did not offer any other naval forces to attack. Most Axis surface combatants were lost early in the war, and Germany focused its wartime naval production on submarines. Significant efforts,

14 "Milk cows," or Type XIV U-boats, were larger, specialized submarine tenders for smaller U-boats, enabling them to operate near the U.S. East Coast for prolonged periods away from forward bases.

15 Blair, *Hitler's U-Boat War,* p. 525.

therefore, continued on developing an effective ASW "kill chain," especially weapons and dedicated hunter-killer groups that would prosecute submarine contacts.

In retrospect, sinking U-boats did not significantly contribute to reductions in Allied shipping losses. As shown in Figures 2 and 3, shipping losses dropped from 1940 through 1943, albeit with the increase in early 1942 described above. German submarine losses, however, were low from 1939–1942 and did not reach the point where they would impact U-boat patrol strength until spring 1943. Further, U-boat productivity dropped below 10,000 tons sunk per U-boat per month in mid-1941 and remained low for the duration of the war, even though many more merchant ships were available to be attacked. Rather than the result of sinking U-boats, Allied success was actually due to the nonlethal actions of the convoys and escorts. The reasons behind this are explored in the discussion of convoys below.

The Allies essentially "backed" into an effective ASW campaign. While capability developers and some leaders sought to kill enemy submarines, more careful analysis of metrics in real time would likely have shown they were able to reduce shipping losses simply by making submarines less effective through convoys and escorts. The sinking of submarines was secondary. This insight was not exploited until late in the war, which probably resulted in the diversion of resources away from other efforts that could have been more beneficial to achieving overall Allied objectives.

"Saved by the Bell"

Another of the major findings of this report is that BNCs operate within a certain "competitive regime" until they culminate and move to another regime. Figures 2 and 3 show this trend in the World War II submarine-ASW competition, which was an EM competitive regime involving advances in radar, radar receivers, ELINT, encryption, and decoding. Early in the war, convoy and U-boat orders were given over HF because they needed to be rerouted or repositioned during the convoy's transit to avoid (from the convoy's perspective) or create (from the submarine's perspective) contact; HF was the only method to do so once ships or submarines were at sea. These communications were encrypted to prevent exploitation by the opponent, but could be detected at long range.

The first countermove in the EM competitive regime came in late 1940 when the Germans broke the British codes used for convoy orders, enabling Doenitz to position U-boats along the planned convoy routes and reposition them in response to convoy route changes—a capability they retained for the next three years. The Allies were able to offset the German advantage somewhat when in May 1941 they broke the German Enigma code. Once each side could know the other's plans, a real-time maneuver competition resulted between convoys and U-boats. This persisted until early 1942, when the Germans upgraded the Enigma code to again deny the Allies' ability to read U-boat orders. This move was countered in December 1942 when the Allies broke the new Enigma code.

At the same time, the Allies worked to minimize the impact from German exploitation of their convoy communications by installing HFDF equipment on Allied ships and aircraft starting in mid-1941. This enabled convoys to route themselves (rather than depending on orders from headquarters) to avoid U-boats—provided the submarines were transmitting. The Germans did not launch a countermove to this advance until 1944, when they installed HFDF equipment on U-boats that could be permanently mounted on a mast or quickly installed and removed from the bridge. U-boat commanders could now find and maintain track on convoys over the horizon based on radio transmissions within convoys, which increased in frequency when the convoy had to be maneuvered away from a potential submarine contact.

Because the Germans had difficulty operationalizing ELINT technology on submarines, they mistakenly believed the Allies would also not be able to deploy an HFDF system on ships or aircraft. This shaped Doenitz's development of tactics intended to address falling U-boat productivity in mid-1941, which he determined was due to the Allies' convoy approach. Through the decoding efforts of B-Dienst, Doenitz knew the Allies' intended convoy routes and arrayed his limited number of U-boats in a line across this route. When the convoy ran across the U-boat line, one or two U-boats would be able to engage the convoy. This led to less production from the U-boats further from the convoy route. As the number of submarines at sea grew, Doenitz assessed he could increase productivity by arraying his submarines in groups, or "wolf packs," along the anticipated convoy route, a concept he developed during the interwar years. When one member of the pack identified a convoy approaching, usually by smoke, it would radio the U-boat headquarters in France and nearby U-boats, which would converge on the convoy's location. The U-boats would then coordinate their attack to get as many strikes against the convoy as possible. But the extensive radio communications needed for the wolf pack tactic were exploited by the convoy escorts' HFDF receivers; in many cases convoys were able to evade the wolf pack or send escort ships (and later, hunter-killer groups) to drive off the U-boats. Because radio communications required the U-boats be on the surface, wolf packs were also vulnerable to radar detection.

Moves and countermoves were more frequent and sustained between radar and radar receivers. At the start of the war, ASW aircraft and ships located submarines visually, so submarines could avoid detection by submerging during the day and travelling on the surface at night. This limited the U-boat's overall speed since it could only travel at about 3–5 knots submerged, while on the surface it could go 14–16 knots. In mid-1940 the British developed an L-band radar small enough to fit on a ship or aircraft. They outfitted some bombers and escort ships with radar and by spring 1941 were proficient enough with the system to locate and classify surfaced submarines at long (beyond visual) ranges and at night. The shift in the EM competition from visual to radar did not immediately increase the number of submarines being lost, but did increase the number of attacks on submarines. Doenitz and his commanders noted this, but did not understand the reason for it until a British ASW aircraft crashed off France and was recovered by the Germans. The presence of radar and depth bombs on the plane indicated to the Germans the role of radar in British ASW efforts. The German technical community went to work on a radar receiver for U-boats, known as a German Search

Receiver, or GSR. The initial systems fielded in mid-1942 were unwieldy and difficult to dismount quickly to support a "crash dive," so were not widely used by U-boat commanders. As U-boat losses increased and improved receivers reached the fleet, commanders changed their approach and employed GSRs. As a result, U-boat losses decreased.

This cycle repeated itself two more times as the Allies and Germany developed progressively higher-frequency systems—first in the S-band and then in the X-band. By moving to higher frequencies, Allied radars were undetectable to the preceding generation of GSRs. Higher frequency radars and GSRs were also smaller and could obtain more precise bearings (albeit at shorter ranges). The last radars and GSRs developed during the war operated in X-band.

Another way to view a competitive regime in which both sides are persistently seeking advantage is as an innovation cycle in the manner described by Clayton Christensen.[16] A new technology or approach is introduced, followed by improvement within that technology or approach. When that innovation yields as much improvement as is practical to extract, it is succeeded by a new innovation using a different technology or approach. Once an innovation is introduced in the conduct of a particular operation, in this case using radar instead of visual detection for ASW, improvements are made in that new technology or approach with increasing frequency. The increasing costs and reduced benefits realized in the course of progressive improvement cycles prompts each side to explore new innovations. Figure 5 shows the decreasing lifetime of each new improvement in the World War II submarine-ASW EM competitive regime. One indication that a competitive regime is nearing culmination is when the lifetime of a new improvement is shorter than the time to develop it, or when the lifetime of each new successive improvement asymptotically approaches a minimum.

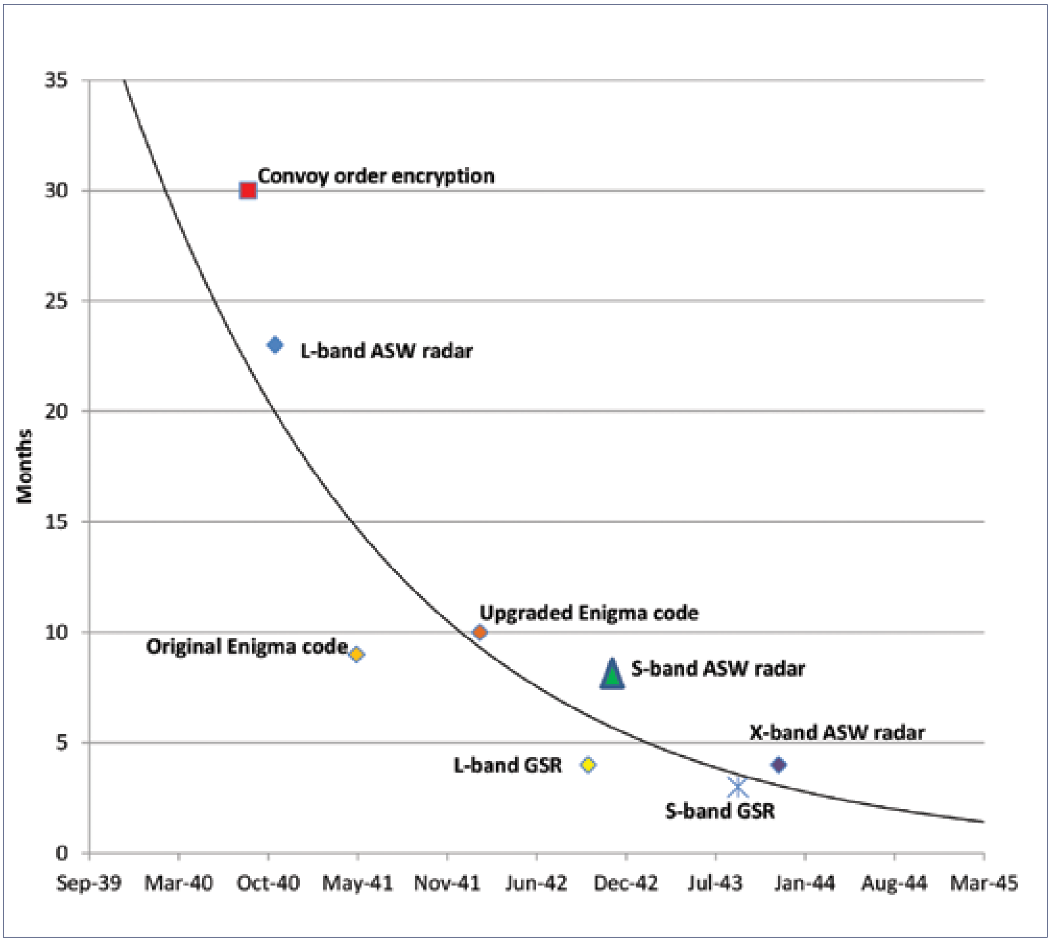
The EM competitive regime culminated in mid-1944, when Germany fielded three new technologies that would have nearly eliminated the ability of the Allies to find U-boats using EM phenomena. First was the Tunis X-band GSR, which could be employed on the surface or when the submarine was submerged at periscope depth. X-band radar was (and still is) about the highest search radar frequency that can retain an acceptable balance of precision and range. At higher frequencies, increasing attenuation will reduce the radar's range to impractical levels. As a result, U-boats would have an enduring ability to detect and potentially evade threat radars.

Second was the snorkel. Although first developed by Dutch engineers in 1939, Germany was slow to improve and deploy it on their submarines. The Type XXI U-boat, fielded in 1944, was the first mass-production submarine equipped with a snorkel, which would enable the ship to recharge its batteries while submerged. The snorkel is still detectable by radar, but is obviously much smaller than the surfaced submarine and, combined with the X-band GSR, the snorkel would make radar detection of U-boats difficult. Third was the "Kurier" burst HF radio

16 Clayton Christensen, *The Innovator's Dilemma,* 3rd ed. (Boston, MA: Harvard Business Review Press, 2011), pp. 33–68.

transmission. By compressing messages sent between and to deployed U-boats, Germany was able to reduce the vulnerability of U-boat communications to HFDF location and exploitation.

FIGURE 5. USEFUL LIFETIME OF ADVANCEMENTS IN THE BATTLE OF THE ATLANTIC EM COMPETITIVE REGIME[17]



17 Brian McCue, *U-Boats in the Bay of Biscay: An Essay in Operations Analysis* (Newport, RI: Alidade Publishing, 2008), pp. 38–42.

These advances would have almost eliminated the Allies' ability to defend convoys by routing them around submarine patrol areas or evade and drive off U-boats that neared convoys. They would also have made offensive ASW more difficult by preventing U-boat detection by radar, which was the Allies' only reliable search method—sonar being only a short-range targeting capability at this time. But the culmination of the EM competitive regime came too late for Germany. By late 1944 German industry was being savaged by Allied bombing, and German troops were in retreat.

The Allies were thus "saved by the bell" in the Battle of the Atlantic. The submarine-ASW EM competitive regime was giving way to an acoustic competitive regime for which the Allies were unprepared. After the war, the U.S. Navy aggressively pursued active and passive acoustic submarine detection technology in recognition of this change in the competition. What was not recognized, however, was what the evolution of the Battle of the Atlantic EM competitive regime implied for the nature of BNCs in general and that this dynamic of innovation-improvement-innovation would play out again during the Cold War.

Implications for the ASW Battle Network

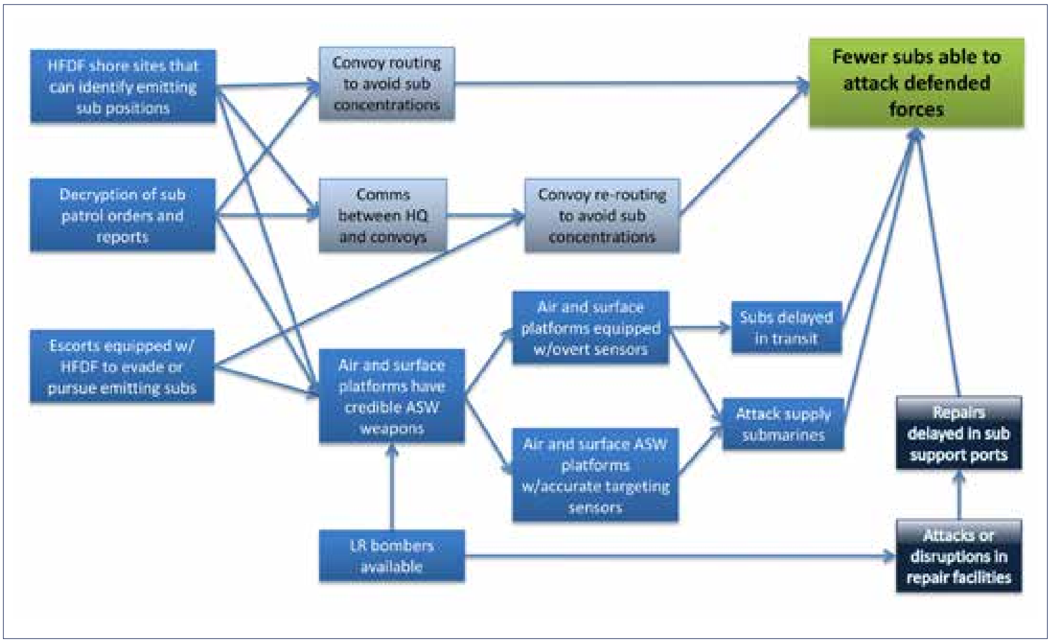
The results of the Battle of the Atlantic show that some approaches to ASW are better than others. Without destroying German submarines, the Allies were nevertheless able to reduce shipping losses in the face of growing U-boat numbers and improving U-boat tactics. This was not the result of a deliberate approach at the operational level, since commanders wanted to sink submarines. Instead, the Allies were able to render U-boats ineffective through other, nonlethal means. This has significant implications for the design of an ASW battle network, which is highly dependent upon the proper choice of the battle network's metrics, as they provide the key indicators that measure progress toward the desired objective.

For example, it turns out that the network needed if one's metric is "killing submarines" is much more elaborate than the network needed to merely make submarines ineffective. The former requires a complete end-to-end "kill chain" incorporating wide-area sensors to cue engagement platforms; localization sensors; effective weapons; and possibly multiple engagement/weapons platforms depending on their ability to simultaneously track and attack an evading submarine. Conversely, the network for making submarines ineffective in the Battle of the Atlantic only required wide-area sensors for cueing, which could be ashore since U-boats had to come to convoys, and localization sensors on convoy escorts. Highly effective weapons were not required for this network; the threat of ramming or gun attack was usually enough to compel the submarine commander to break off the engagement. When the Allies were able to field sufficient escort ships and aircraft so they could sustain pursuit of submarines after they were detected near the convoy, U-boat commanders also had to consider the possibility that a fleeting detection of the submarine would produce a prolonged pursuit, taking the submarine out of the fight for several days. This made them more likely to avoid approaching an alerted convoy.

The multiple ways in which the Allies were able to degrade the effectiveness of U-boats shows the robustness of a "nonlethal" ASW approach. As opposed to a kill chain for destroying the enemy that may have a few redundant links, the Allied ASW approach was more like a "web" with multiple independent paths to achieve the result of protecting ships.

Figure 6 shows the structure of this battle network.

FIGURE 6. THE ASW BATTLE NETWORK FOR MAKING SUBMARINES INEFFECTIVE



This ASW battle network "web" consists of several paths:

1. *Convoys:* The first step the Allies took to overcome the U-boat threat was to establish convoys of their merchant and supply ships. This was an expensive lesson of the First World War, as shown in Figure 7. Until convoys were implemented in 1917, 10 percent of transiting merchant ships were lost between America and Britain. After convoys began three years into the war, they made an immediate improvement in the number of American ships able to make it to England, reducing losses to less than 1 percent.[18]

   In the Battle of the Atlantic, the Allies were determined not to repeat their World War I experience and established convoys immediately. Convoys were beneficial because they reduced the ability of submarines to find targets, since the same number of ships transiting the Atlantic would be compressed into a smaller aggregate area. Convoys were also beneficial because submarines have difficulty attacking more than one or two ships at a

18 McCue, *U-Boats in the Bay of Biscay*, p. 16.

time, since convoys concentrate a large number of potential targets in a relatively small space and a submarine is limited in how many targets it can engage in a given time. In contrast, independent ships are easier to attack because they are distributed over the entire transit route and submarines executing a search pattern have a higher probability of running across one of them. Since the target ships are traveling alone, the submarine can attack one ship and then reposition and reset its torpedo tubes to attack the next ship. The downside of convoys is that they may be more detectable than each individual ship since in a fifty- or sixty-ship convoy, for example, at least one ship is likely to be giving off smoke, inadvertently operating lights, etc. That said, this modest increase does not make a significant difference in the probability or actual amount of convoy losses.[19]

As mentioned above, using convoys enabled the Allies to more easily route and reroute shipping to avoid U-boat patrol areas, which were being estimated via Enigma decryption and shore-based HFDF stations. And once escorts detected a U-boat, a convoy was easier to maneuver away from the threat than independent ships spread out along a shipping lane.

The vulnerability of independent shipping can be seen in the experience of Japanese shipping during World War II (see Figure 8). Japan did not convoy shipping because it did not consider the submarine threat significant and lacked enough transport ships to support convoys.

19 Sternhell and Thorndike, *Antisubmarine Warfare,* pp. 100–02.

FIGURE 7. ALLIED SHIPPING LOSSES TO SUBMARINES DURING WORLD WAR I[20]

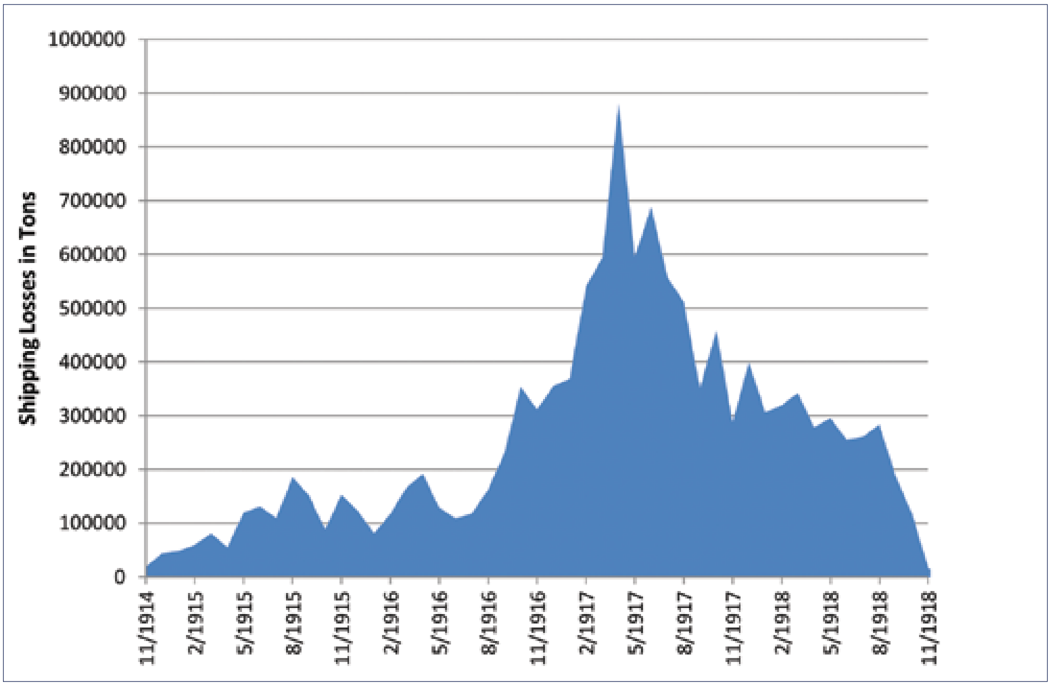
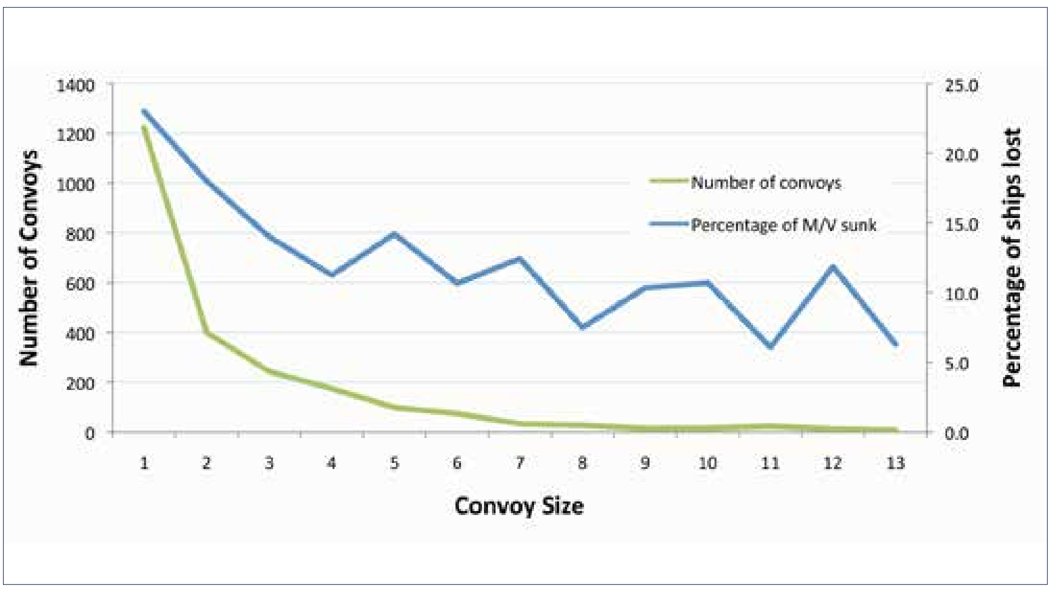


FIGURE 8. JAPANESE SHIPPING LOSSES TO SUBMARINES DURING WORLD WAR II[21]



20 McCue, *U-Boats in the Bay of Biscay*, p. 20.

21 Sternhell and Thorndike, *Antisubmarine Warfare*, p. 106.

As Japanese leaders concluded, convoying requires more ships overall than sending ships independently. Instead of ships departing as soon as they are loaded, they must wait in port for the convoy to assemble, and when the convoy arrives at its destination, ships must wait in line to unload. In the Battle of the Atlantic this inefficiency reduced transport rates from the United States to Europe by about 30 percent.[22] This can be thought of as "virtual attrition" on shipping capacity imparted by the existence of U-boats. This cost was likely worth it based on the low loss rates of ships in convoy compared to those inflicted on ships transiting independently; see Table 1. For the Allies in World War II, the inefficiency imposed by convoys would have been compensated for by reduced shipping losses after six to eight months.

TABLE 1. CONVOY LOSSES IN THE NORTH ATLANTIC, AUGUST 1942–JANUARY 1943[23]

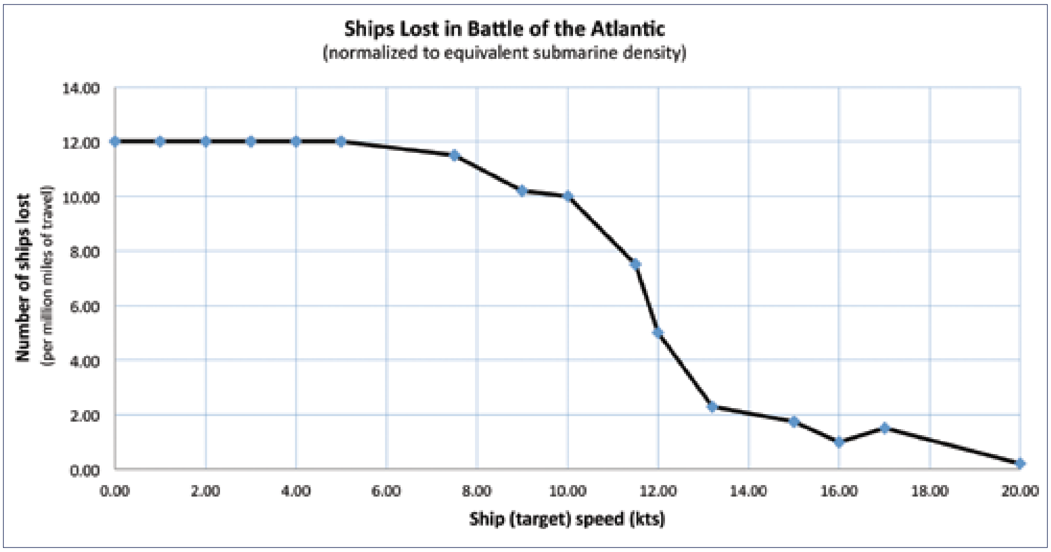
Convoy Series	Convoys	Ships	Convoys Sighted	Ships Sunk	% Convoys Sighted	% Ships Sunk
HX (9 kts)	23	923	8	12	35	1.3
SC (7kts)	24	991	14	45	58	4.6
ON (9.5 kts)	24	897	11	29	36	3.2
ONS (7 kts)	23	836	11	31	48	3.7

Table 1 also implies ship speed affects the ability of a submarine to find and successfully engage a convoy. Figure 9 further illustrates this point, taking data from across the Atlantic theater.

22 Ibid., p. 111.

23 Ibid., p. 104.

FIGURE 9. CONVOY LOSSES VERSUS SHIP SPEED[24]

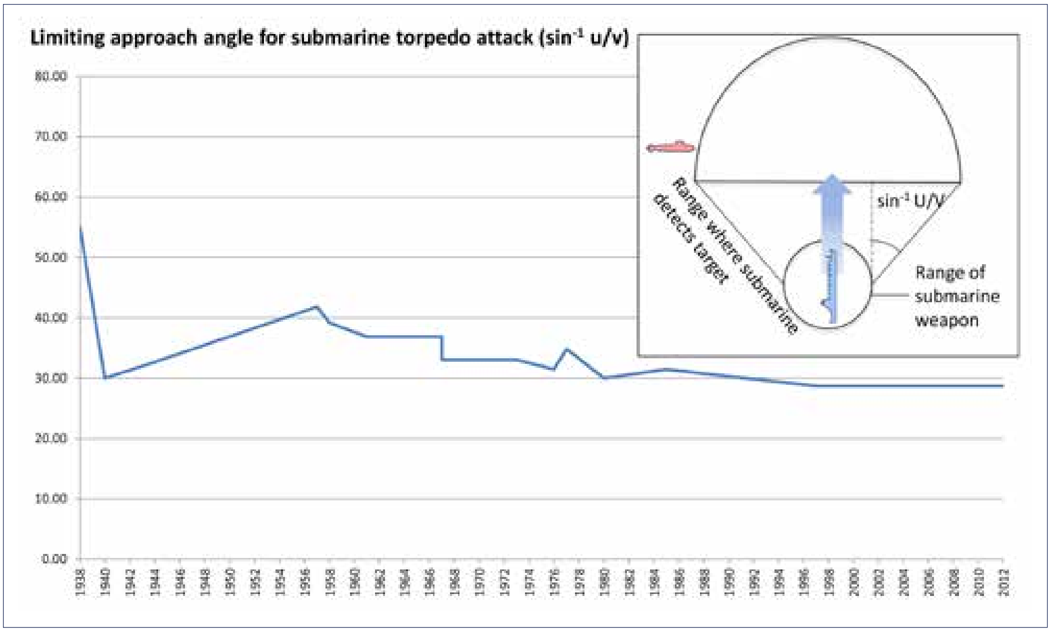


Increased convoy speed, relative to submarine speed, reduces submarine effectiveness because of the fundamental speed disadvantage of submarines. The maximum speed of a submerged submarine in World War II was about the same as a merchant ship. This, combined with the submarine's limited sensing ability, meant it would have to be prepositioned in front of a convoy to intercept it. Although the submarine was faster than the merchant ship on the surface, U-boats would usually submerge before approaching the convoy to avoid detection by the convoy or its air and surface escorts. To maximize its endurance submerged, a submarine could only travel about half the speed of the convoy, limiting the angle of approach it could take and still be able to get within weapons range before the surface ships steamed by.

Figure 10 shows how the submarine's speed disadvantage affects its ability to attack surface ships with torpedoes. As the ratio of submarine (u) to surface ship (v) speed decreases, the angle of approach the submarine can use and still be able to engage the surface ship decreases. For context, Figure 10 also shows how the angle of approach hasn't changed much since World War II as submarines and commercial ships both increased their speed. To remain acoustically undetected, submarines have to travel less than 10–15 knots, about half a commercial ship's top sustained transit speed. This continues to limit their torpedo attack approach angle to 30 degrees.

24 Ibid., p. 95.

FIGURE 10. EFFECT OF CHANGING SUBMARINE AND MERCHANT SHIP SPEED ON POSSIBLE SUBMARINE ANGLES OF APPROACH



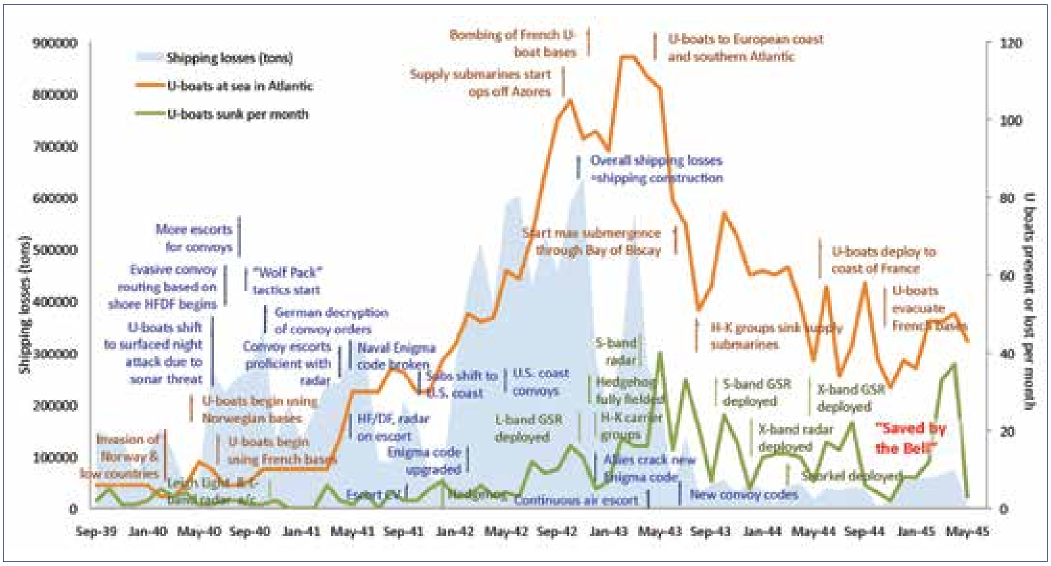
2. *Escorts and "hunter-killer groups."* While convoys in and of themselves reduced the number of losses from a given number of submarines, the Allies also escorted their convoys. Escorts were able to drive off attacking U-boats and later to intercept approaching submarines using HFDF of submarine transmissions and radar detections of surfaced submarines. Escorting convoys reduced shipping losses, but also acted as a form of "virtual attrition," taking warships away from other potential war operations. About 1,100 ships, roughly 10 percent of the combined Allied fleets, were built for escort duties in the Battle of the Atlantic[25]—ships that could have been used for other purposes had the submarine threat not existed.

   Escort vessels were generally not effective at sinking submarines, as discussed above and shown in Figure 11. Submarine losses did not exceed ten per month until late 1942 and did not reach levels that would reduce U-boat presence in the Atlantic until mid-1943. The increase in submarine losses at that time corresponded with the introduction of the three elements of an ASW kill chain: S-band radar that was not detectable by fielded L-band GSRs; hunter-killer or dedicated escort groups that were able to leave the convoy or independently pursue submarine contacts; and effective ASW weapons. During the Battle of the Atlantic, the establishment of Tenth Fleet in May 1943 gave one organization

25 Blair, *Hitler's U-Boat War*, pp. 756–757.

the responsibility of assembling all the needed elements of the ASW kill chain, and their efforts directly contributed to the increased number of submarines sunk in spring 1943.

FIGURE 11. SHIPPING LOSSES DURING THE BATTLE OF THE ATLANTIC



While they did not generally sink many submarines, escorts were effective at reducing shipping losses. In the Atlantic the introduction of escorts for every convoy in the fall of 1940 and radar and HFDF on escorts in the spring of 1941 corresponded with a reduction in shipping losses even as U-boat presence was rising. Along the U.S. East Coast, the assignment of convoys, despite their lack of radar and effective weapons, corresponded with a sharp drop in shipping losses. This dynamic directly results from the inherent nature of submarines, which are not able to stand and fight against escorts, even if the only weapons the escorts have are ramming or gunfire.

Independent hunter-killer groups cued by HFDF or decrypted U-boat messages and roving escort groups were needed to increase submarine kills because convoy escorts could not leave their charges for long to pursue a submarine contact. They could only drive a threatening submarine away and promptly return to the convoy. Also, multiple ASW platforms were often needed to effectively prosecute a submarine contact because sonar/ASDIC (the only sensor able to track an evading submerged submarine) had relatively short range. If a ship slowed so it could determine if an attack was successful, the U-boat could escape outside sonar range before the ASW ship could reacquire the submarine. Attacks conducted by multiple ships or a ship and aircraft operating in coordination were much more successful in sinking U-boats than single ships (see Table 2). This was only possible starting in mid-1943, however, because until then there were not enough escorts to spend time pursuing U-boat detections.

TABLE 2. IMPACT OF COORDINATED ATTACKS ON U-BOAT SINKINGS BY THE ALLIES[26]

Location of Attacks	Independent	Coordinated
U.S. attacks, Atlantic and Mediterranean January 1943 – February 1944		
Number of Incidents	176	18
Ships sunk or probably sunk	9	3
Percent successful	5	17
U.S. attacks, Atlantic and Mediterranean March 1944 – May 1945		
Number of Incidents	41	38
Ships sunk or probably sunk	5	21
Percent successful	12	55

Probability of Regaining Contact		
	Single Ship	Coordinated
January 1943–July 1943	0.54	0.80
August 1943–February 1944	0.68	0.90

The last piece of the ASW kill chain was a lethal weapon. The depth charge or bomb, an ASW mainstay since before World War I, was effective at driving off submarines and forcing them to evade, but it had low lethality. In large part this was because it was launched or dropped behind the ship or aircraft, which lost track of the submarine just before weapons launch, since the submarine would pass underneath the platform. Forward-firing weapons such as the Hedgehog, Mousetrap, Squid, and ASW rockets enabled the ASW platform to aim the weapon and maintain track on the submarine as it launched. As indicated by Table 3, this significantly increased attack lethality.

26 Sternhell and Thorndike, *Antisubmarine Warfare,* p. 122.

FIGURE 12. DEPTH CHARGES, MOUSE TRAP, AND SQUID

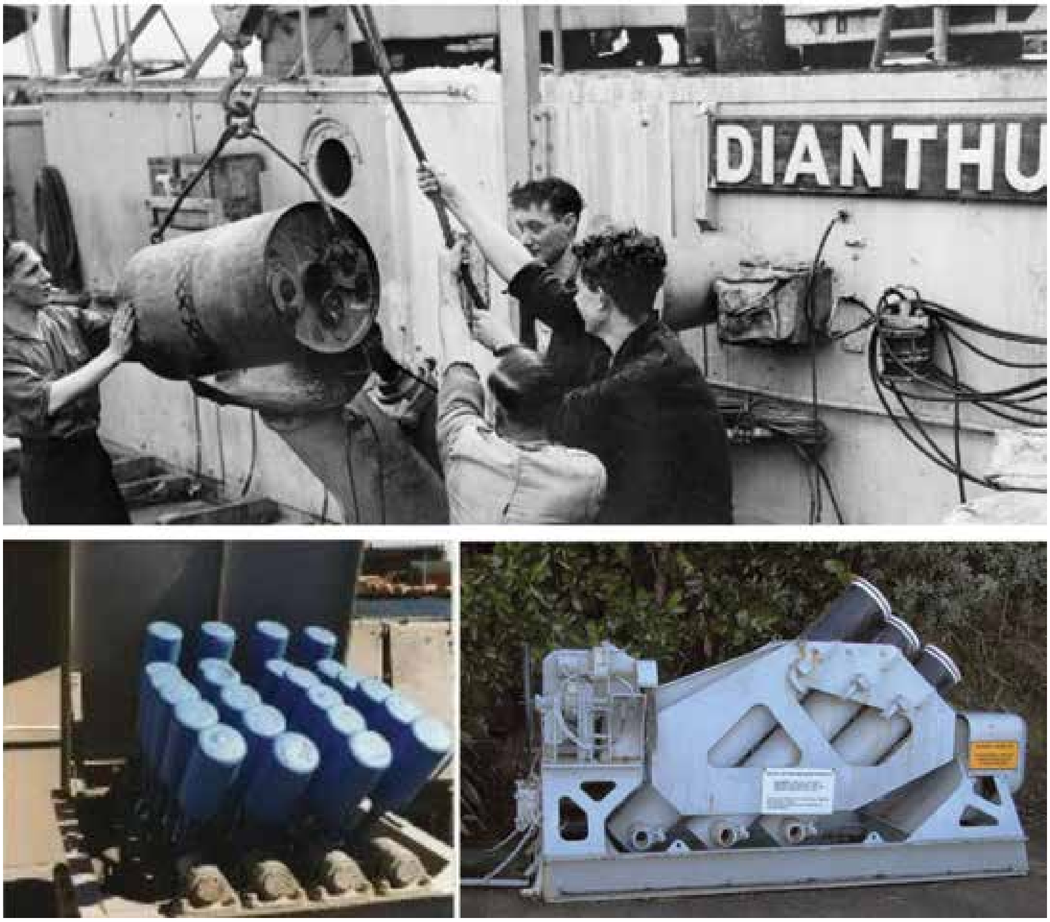


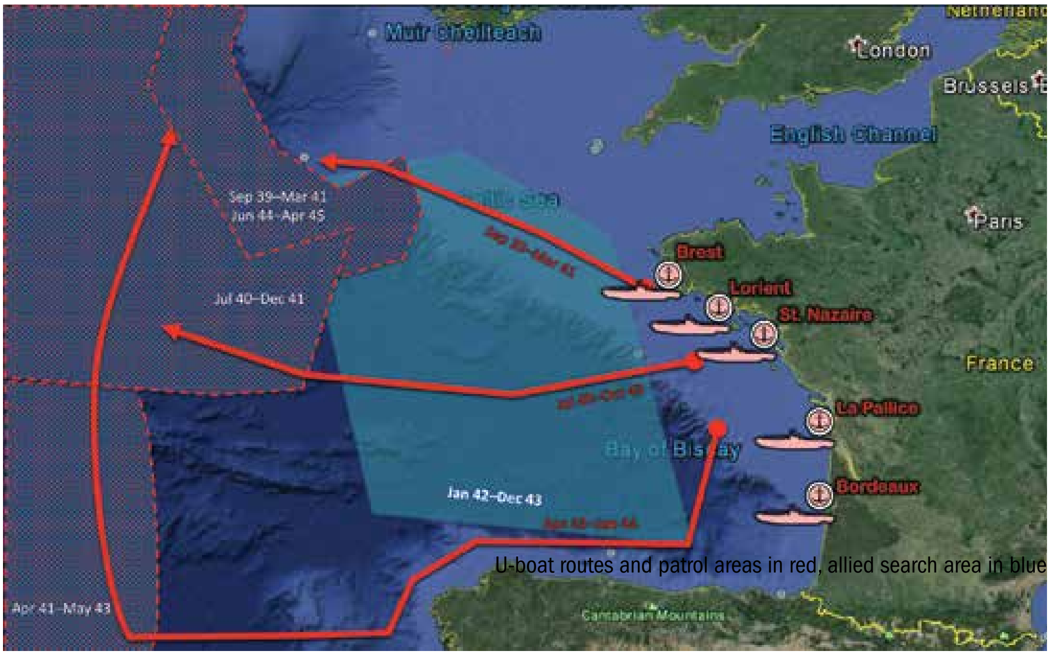
TABLE 3. EFFECTIVENESS OF VARIOUS WORLD WAR II ASW WEAPONS[27]

Weapon	Lethal Radius (ft)	# of Charges/ Barrage	Percentage of Submarines Killed per Barrage				
			1943– 1st Half	1943– 2nd Half	1944– 1st Half	1944– 2nd Half	1945– 1st Quarter
Depth Charge	21	9	5.4	4.0	6.4	5.1	7.0
Mousetrap	0	24	–	7.5	15.4	28.1	23.0
Squid	0	16	–	–	–	33.3	62.0

27 Sternhell and Thorndike, *Antisubmarine Warfare*, pp. 121, 125.

3. *Offensive ASW:* The use of convoys and associated escort or hunter-killer groups can be considered "defensive" ASW because their objective was protecting convoys. The allies also mounted several "offensive" ASW missions designed to attack and destroy submarines far from convoy transit routes. The Bay of Biscay operation during the Battle of the Atlantic demonstrates how even an offensive ASW operation is better at meeting overall war objectives if it focuses on reducing submarine effectiveness rather than killing submarines. After the occupation of France, the Kriegsmarine based U-boats on the French coast to be closer to their patrol areas. In response, the British mounted an offensive ASW campaign in the Bay starting in January 1942 to sink U-boats as they entered or left port, as depicted in Figure 13.

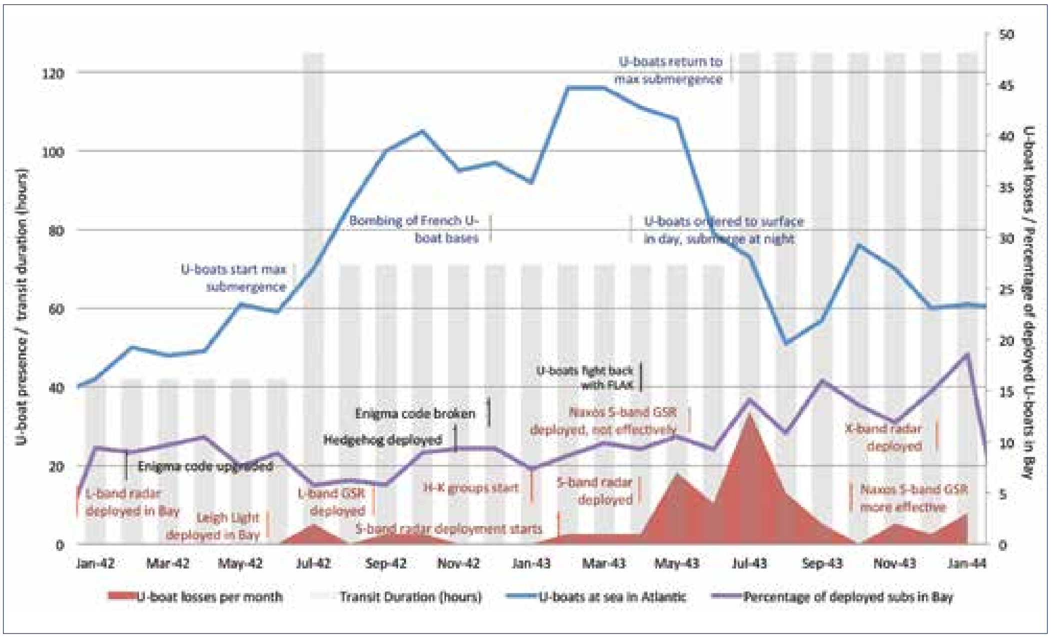
FIGURE 13. BAY OF BISCAY OPERATIONS



U-boat routes and patrol areas in red, allied search area in blue

The British effort did not yield any significant results for more than a year, based on the operational commanders' metric of U-boats sunk. At the beginning of the operation, Britain could spare no ships and only a dozen planes for the Bay of Biscay, and most did not have radar. They also lacked an effective weapon and tactic for attacking submarines. The British did not assemble all the pieces of an effective kill chain to sink submarines until they deployed long-range search sensors (radar), targeting sensors (spotlights, ASDIC), weapons (Hedgehog from ships, depth bombs from aircraft), and separate search and attack platforms (aircraft for search and initial attack, hunter-killer groups to prosecute submarine contacts). With these elements in place, German submarine losses in the Bay finally began to mount in early 1943, but never reached a point where they would significantly degrade Atlantic U-boat presence.

FIGURE 14. RESULTS OF BAY OF BISCAY OPERATIONS[28]



The British succeeded in pursuing the Allies' overall objective and metric of protecting shipping, although not in the way they intended. By hunting U-boats in the Bay of Biscay, the British compelled submarines to take steps to avoid them, which translated into their taking progressively more time transiting the Bay to reach Atlantic patrol areas (see Figure 14). This, in turn, increased the percentage of submarines in the Atlantic that were stuck in the Bay (purple line) as opposed to being on patrol (blue line). The British imposed three types of delays in the Bay of Biscay:

- *Submarines submerged for more of the transit.* Until the ASW campaign started, submarines crossed the Bay on the surface to maximize their speed. Once British aircraft began patrolling the Bay, submarines started submerging during the day and surfacing at night to avoid visual detection. The portion of the transit submarines spent submerged grew as the British fielded radar, leading to more ASW attacks, and as Germans deployed improved radar receivers, which alerted submarine commanders of potential radar detection. The time spent submerged further increased when submarine losses began in mid-1942, and increased in spring 1943.
- *Submarines stayed under Axis air cover.* When submarine losses in the Bay rose sharply in spring 1943, Doenitz ordered his commanders to both maximize their submerged time and hug the French and Spanish coast until they entered the Atlantic patrol areas, as indicated in Figure 13. The combined effect of the increased submergence and the longer

28 McCue, *U-Boats in the Bay of Biscay,* p. 54.

route is indicated by the gray bars in Figure 14, which show the planned duration of the Bay of Biscay transit.

- *Submarines lost time evading even ineffective attacks*. Consistently improving radar enabled British aircraft to find and pursue submarines more effectively day and night. Final targeting still had to be conducted visually, since radar was not precise enough for weapons placement. In mid-1942, a spotlight known as the "Leigh Light" gave planes a way to place weapons on U-boats at night. Even though few attacks were successful, U-boats that were attacked had to submerge and manuever off course to evade ASW forces. This delayed their overall transit.

German submarines stuck in the Bay of Biscay were not able to support the countershipping campaign in the Atlantic. They can be thought of as victims of virtual attrition, which rose throughout the British ASW operation. This effect became especially pronounced starting in mid-1943, when Bay of Biscay virtual attrition reached nearly 25 percent of underway submarines.

The Bay of Biscay operation highlights some counterintuitive ways an ASW force can most easily reduce the effectiveness of submarines. In particular, overt search methods were more effective in slowing submarines than covert methods because they compelled submarines to submerge, hug the coast, or evade. Figure 14 shows U-boats transited the Bay faster when they did not realize they were being detected (e.g., January–June 1942 and February–June 1943), reducing the percentage of them stuck in the Bay and increasing the number of them on patrol. When losses subsequently increased and U-boats realized they were being detected by seeing the Leigh Light or by using their new GSRs, they submerged and evaded. This reduced losses, but slowed their transits. Covert methods were more likely to result in sinking U-boats. Given the few losses when allies had this advantage, however, it is unlikely that these losses would have impacted overall U-boat patrol presence as much as slowing U-boat transits to their patrol areas. Figure 3 shows shipping losses peaking in November 1942 and lowering thereafter, whereas submarine losses did not rise, and U-boat presence fall, until mid-1943.

The Battle of the Atlantic shows that an ASW battle network focused on protecting shipping rather than sinking submarines will provide more independent paths to success. This kind of network offers the opportunity to create a "web" network as opposed to a "chain" that is more resilient in the face of adversary counter-ASW efforts. Within this web network the greatest cost versus benefit is derived from:

1. Convoys able to travel up to twice the quiet speed of the submarine;

2. Escorts with overt sensors;

3. Offensive ASW groups with convoys or along submarine transit routes designed to prevent submarines from getting into firing position; and

4. Weapons able to compel submarines to evade while not putting the launch platform at risk.

The Cold War

The Allies were "saved by the bell" at the end of World War II. Anglo-American and Soviet forces were advancing into Germany just as the Germans were fielding technologies to take submarines underwater and out of the EM domain. These technologies—the snorkel, burst communications, and permanently-mounted radar receivers—became the property of the victors at the end of the war. All the Allies benefited from this bounty since, while some had developed these technologies, none had fielded them.

U.S. leaders were concerned the Soviets would quickly apply German military technology to their own forces as the World War II Grand Alliance quickly evolved into the competition and later confrontation of the Cold War. In particular, the U.S. Navy worried that the Soviet submarine force, already the world's largest at the end of World War II, would create a large fleet of boats based on the Type XXI German submarine. The Type XXI incorporated all of the latest German technologies and would require an entirely different approach to ASW.

To conduct ASW against a Soviet version of the Type XXI, the U.S. Navy mounted a two-pronged approach to detect snorkeling submarines:

1. Planes and ships with radar, ELINT equipment, and active sonar to detect snorkels, periscopes, and radio communications while the submarine is snorkeling; and

2. Passive sonar-equipped ASW submarines, destroyers, and patrol aircraft to detect the sound of a snorkeling submarine.

This approach was fortuitous. The USSR was slow to build a large force of snorkel-equipped diesel submarines, but when their *Whiskey*-class submarines eventually did reach the fleet, the U.S. Navy found the EM and active sonar approaches of World War II were still effective. More importantly, when the Soviets deployed nuclear attack submarines (SSNs), the Navy had already begun to develop a passive sonar capability able to detect them.

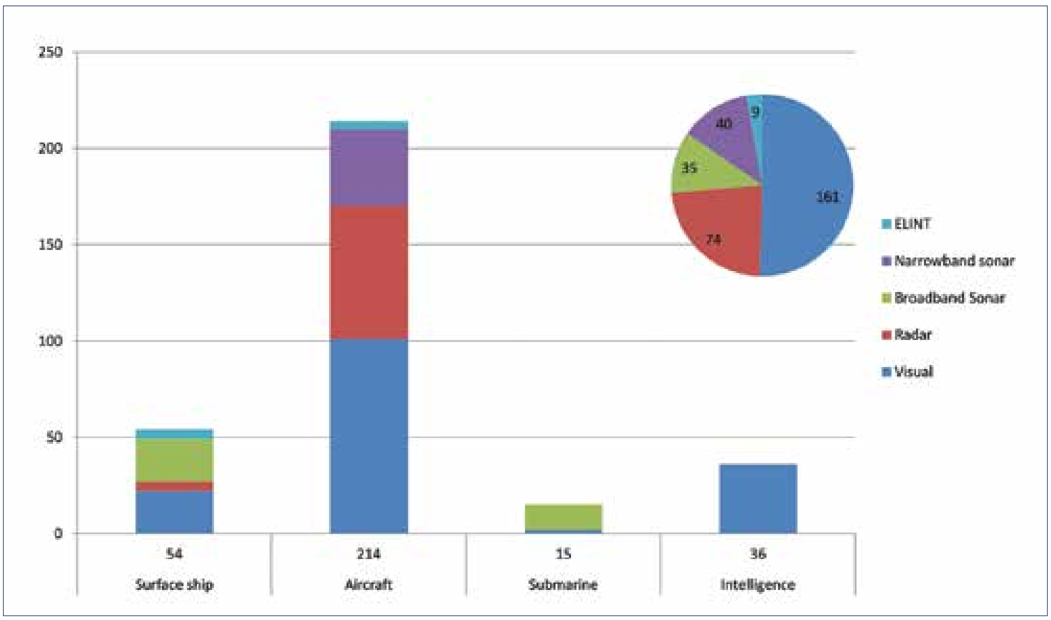
The Passive Sonar Competitive Regime

World War I and II were both fundamentally EM-based submarine-ASW competitions because submarines were actually "submersibles" rather than true submarines. They would operate on the surface most of the time and submerge only to covertly attack or evade. Before the Type XXI submarine, mass-produced military submarines could only run their diesel engines while surfaced. The diesel engines were needed to recharge the batteries and to provide faster speeds by being directly engaged with the submarine drivetrain. This made it easier to detect World War I and II-era submarines with EM sensors such as radar rather than with immature acoustic sensors such as sonar. A safe and effective snorkel system fundamentally changed that.

In the early Cold War, the Navy found passive sonar was not effective at tracking diesel submarines. When they were snorkeling, diesel submarines sounded like diesel-powered surface ships. When they were submerged, they were too quiet to hear at the relatively high frequencies possible with early shipboard sonar systems. Larger hull-mounted sonar arrays and towed arrays were introduced in the 1960s that enabled listening at lower frequencies. These improved the probability of detecting diesel submarines operating on battery power, but not at long enough range to support wide area searches for diesel submarines.

The techniques of World War II, however, were still effective against diesel submarines. The Navy deployed a series of airborne and shipboard S- and X-band radars that progressively improved their ability to detect periscopes and snorkels—an effort that continues today. The Navy also fielded active sonars on ships and air-dropped active sonobuoys designed to take advantage of the shallow sound channel in which snorkeling submarines operated near the surface of the ocean. Over the Cold War, the Navy improved active sonars by moving to lower frequencies that enabled longer detection ranges, due to lower reverberation losses, and using variable-depth transducers that could operate in deeper sound channels. ELINT such as HFDF, so critical in World War II, also progressed and expanded in the Cold War to include most communication and radar frequencies. By the 1960s, electronic sensors were also deployed on satellites, greatly expanding their coverage. The reliance on EM-based and active sonar techniques for tracking Cold War diesel submarines is demonstrated by recently declassified results for submarine detections during the 1967 Arab-Israeli War (see Figure 15).

FIGURE 15. DIESEL SUBMARINE DETECTIONS DURING THE 1967 ARAB-ISRAELI WAR[29]



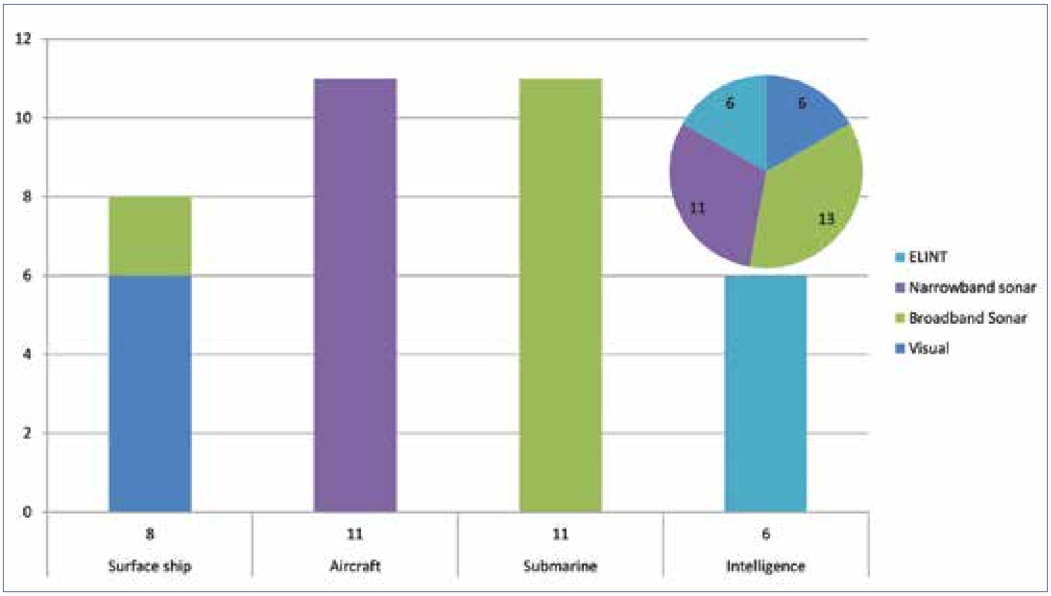
29 R. F. Cross Associates, *Sea-based Airborne Antisubmarine Warfare 1940–1977* (Alexandria, VA: R. F. Cross Associates, 1978), p. 95.

The greatest U.S. concern regarding Soviet submarines in the Cold War was their ability to carry nuclear cruise missiles close to the U.S. coast because the resulting time of flight would be too short to enable effective defensive measures. While such a salvo would not be large enough to significantly degrade U.S. military capability, submarine-launched cruise missiles could execute a "decapitating" attack against command structures or other high-value targets. In practice, however, the U.S. and Soviet navies both found diesel guided-missile submarines (SSGs) had great difficulty in making transoceanic transits without being detected because they still had to snorkel (and frequently broached while doing so), exposing them to visual and radar detection and often had to transmit to receive orders or resolve material problems, exposing them to ELINT measures.

The slow buildup of the Soviet diesel submarine fleet and the limited ability of diesel submarines to threaten attacks on the U.S. homeland reduced U.S. concern about the Soviets quickly leveraging German technology to gain an advantage in the early part of the Cold War. A far greater worry manifested itself, however, when the U.S. Navy practiced ASW against its first nuclear submarine, the *USS Nautilus*, in 1954. As a true submarine, *Nautilus* could transit long distances at high speed without surfacing or coming to snorkel depth. It could also maneuver as fast as its surface adversaries, enabling *Nautilus* to overcome the limited angle of approach of diesel submarines. *Nautilus* could thus position itself for an attack, evade, and reposition itself for subsequent attacks on the same surface group or convoy. A nuclear-powered submarine could also provide a hard-to-counter "first-strike" capability for nuclear attack on the U.S. homeland. Together these capabilities created urgency in the Navy leadership to develop a means of detecting and holding at risk Soviet nuclear submarines, since it was inevitable they would eventually be developed.

This is where the U.S. Navy's decade of experimentation with passive sonar finally paid off. Using Nautilus and other early nuclear submarines as practice targets, the Navy found the machinery associated with the submarine's nuclear power plant and support systems made noise over a range of frequencies, or "broadband" sound, and in some specific frequencies, or "narrowband" sound. The most detectable sounds turned out to be broadband flow noise from the submarine moving through the water at higher speeds, greater than 10–15 knots, and discrete narrowband tonals associated with rotating machinery, such as pumps in the nuclear power plant. When Soviet nuclear submarines entered their fleet in the late 1950s, U.S. ASW forces found them to be even noisier than the Nautilus in these same ways. Figure 16 shows how detection of nuclear submarines differed from that of diesel submarines during the 1967 Arab-Israeli War.

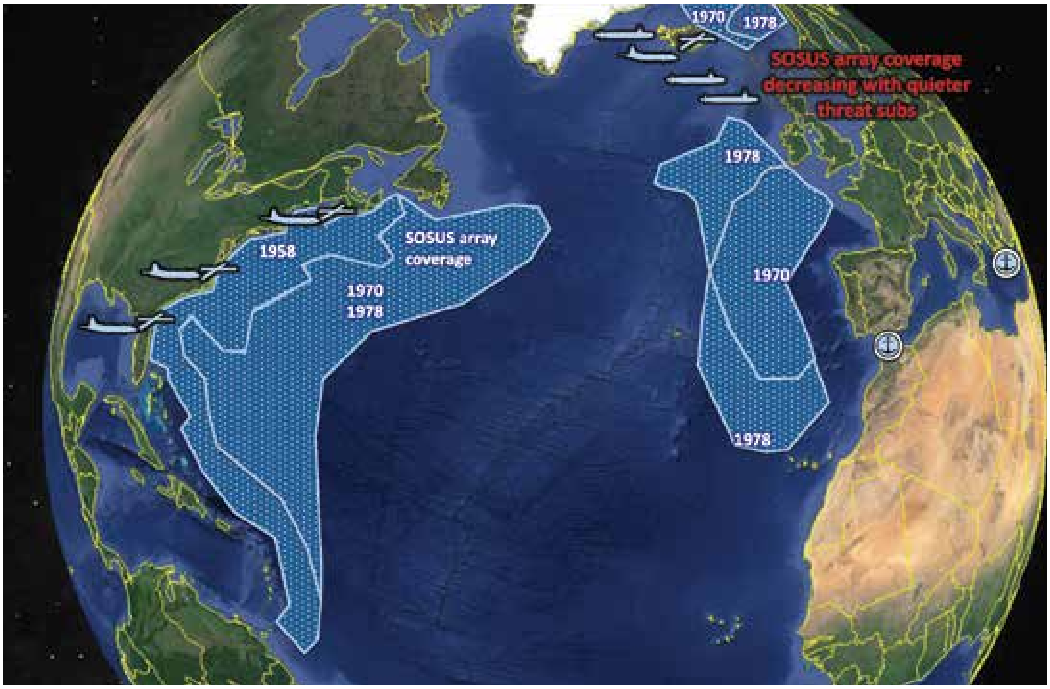
FIGURE 16. NUCLEAR SUBMARINE DETECTIONS DURING THE 1967 ARAB-ISRAELI WAR[30]



To take advantage of nuclear submarines' acoustic vulnerability, the U.S. Navy implemented an integrated passive sonar ASW battle network in the late 1950s consisting of fixed sonar arrays on the ocean floor, land-based patrol aircraft, and ASW submarines. The ocean floor arrays, known as the "sound surveillance system," or SOSUS, could be large and thus could detect very low frequency broadband and narrowband sound and achieve high gains; this enabled long detection ranges. These arrays were installed initially off the U.S. coast (for homeland defense) and then expanded to the European coast and chokepoints through which Soviet submarines had to travel to reach the open ocean from their bastions in the Arctic and Pacific littorals. By the mid-1970s, SOSUS array coverage had grown enough to enable trans-oceanic tracking of submarines (see Figure 17). The SOSUS arrays were monitored at nearby Navy Support Activities, which would pass submarine contact information to patrol aircraft such as the P-3 Orion. The P-3s would track the Soviet submarine using passive broadband and narrowband sonobuoys. They then passed the contact to a U.S. nuclear submarine that would persistently trail the Soviet submarine—often back into its own coastal waters.

30 Ibid, p. 93.

FIGURE 17. ATLANTIC SOSUS ARRAY COVERAGE, 1958–1978[31]



The effectiveness of this passive ASW battle network shaped the entire American approach to ASW until the late 1970s. While World War II ASW was inherently defensive, focusing on protection of convoys across the Atlantic, America could pursue a mostly offensive ASW approach in the Cold War where U.S. ASW forces would track almost every deployed Soviet submarine, prepared to attack them at the onset of conflict. But this approach failed to incorporate lessons of World War II, which showed an ASW battle network designed to prevent submarines from being effective would better support the ASW force's overall objectives and do so with less investment and effort. The Navy's Cold War ASW approach would have consumed an enormous fleet of U.S. patrol aircraft and submarines and required very effective weapons to succeed in actual combat. And even after all that effort, the fleet would still need to protect convoys, battle groups, and forces ashore from submarine torpedo or missile attack, since not all submarines would be destroyed right away.

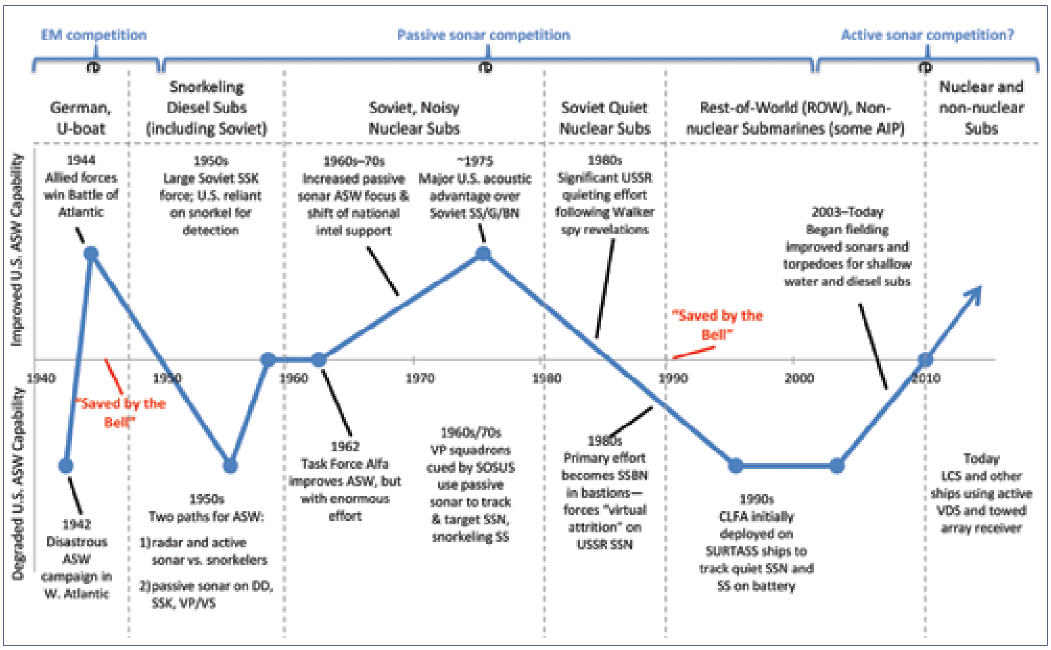
The Navy continued developing defensive ASW capabilities, starting with the World War II approach of radar and active sonar on escort destroyers and carrier-based ASW aircraft, but these systems were not very effective against nuclear submarines. By the late 1960s, the Navy abandoned dedicated ASW carriers and instead integrated ASW aircraft onto multipurpose carriers. Escort destroyers and frigates were retained, but increasingly relied on helicopters

31 Ibid., pp. 73, 155, 205.

with dipping sonar that could be lowered into the water layer in which nuclear and nonsnorkeling diesel submarines were most likely to operate.

The evolution of the U.S./USSR submarine-versus-ASW BNC is summarized graphically in Figure 18. The line qualitatively represents the capability of U.S. ASW versus USSR submarines, which was the most relevant aspect of the Cold War submarine-ASW competition. The Soviets put little effort into ASW and their submarines were focused on attacking U.S. surface battle groups and protecting Soviet ballistic missile submarines (SSBN). In contrast, U.S. submarines were focused on ASW. This diagram indicates two main phases in the Cold War submarine-ASW competition—one in which Western ASW forces were superior, and another during which Soviet submarines approached acoustic parity.

FIGURE 18. QUALITATIVE REPRESENTATION OF U.S. ASW CAPABILITIES VERSUS GERMAN AND SOVIET SUBMARINES[32]



Phase One: Western Superiority (1950s to 1970s)

The passive sonar network of SOSUS, P-3 *Orion* patrol aircraft, and attack submarines established a clear advantage for U.S. forces over Soviet nuclear submarines. During this time, the U.S. Navy was able to passively track virtually every deployed USSR SSN for most of its

32 Owen Cote, *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines* (Newport, RI: U.S. Naval War College, 2000), available at http://www.navy.mil/navydata/cno/n87/history/cold-war-asw.html; John Benedict, "The Unraveling and Revitalization of U.S. Navy Antisubmarine Warfare," *U.S. Naval War College Review*, 58, No. 2, Spring 2005, pp. 93–116.

deployment.[33] Soviet diesel submarines were increasingly the responsibility of Allies such as Britain, since they would normally operate in the littoral waters around Europe. This situation gave the Navy high confidence in its overall ASW capability, despite the fact that defensive ASW for individual carrier, amphibious, and battleship battle groups was still not very effective at finding nuclear submarines.

Navy leaders believed their offensive ASW efforts would be able to protect the fleet by attacking Soviet submarines before they were able to get close to battle groups. This approach, however, did not reflect the lessons of the world wars. Even if the Soviets' sixty-eight SSNs and SSGNs in 1975 were all being tracked, it is unlikely the U.S. Navy's fifty-five SSN and three hundred patrol aircraft would be able to prosecute all of them in short order, while also trying to keep track of Soviet SSBNs. Even it were possible, this was an exceptionally inefficient use of U.S. forces and would constitute a form of "virtual attrition" against the United States. While the USSR submarine force was a significant part of its military, it was still a much lower investment monetarily than the U.S. passive sonar network of SOSUS, P-3s, and SSNs. For this investment, the Soviets were able to tie up the U.S. submarine force, which would not be available to attack Soviet surface forces or launch cruise missile attacks against Warsaw Pact targets.

SOSUS also enabled the U.S. Navy to see the vulnerability of its own submarines to passive sonar. It therefore mounted a long-term deliberate effort to reduce the sound radiated from U.S. SSNs. This consisted of sound-absorbing mounts inside the boat to isolate machinery from the hull; shaping to reduce flow noise across the hull; and modifications to make the propeller less noisy and susceptible to cavitation. Through the late 1960s and 1970s, U.S. nuclear submarines established a significant acoustic advantage over their Soviet counterparts. This enabled them to consistently trail Soviet submarines while not themselves being susceptible to Soviet passive ASW efforts.

The Red Navy lacked the high-end passive sonar capabilities that would have detected U.S. submarines—or revealed the noisiness of their own submarines. Rather, it continued to emphasize the World War II approach to ASW of radar, ELINT, and active sonar. The Soviets also did not have some of the sophisticated manufacturing capability that would have enabled them to build quieter submarines even had they possessed this knowledge.

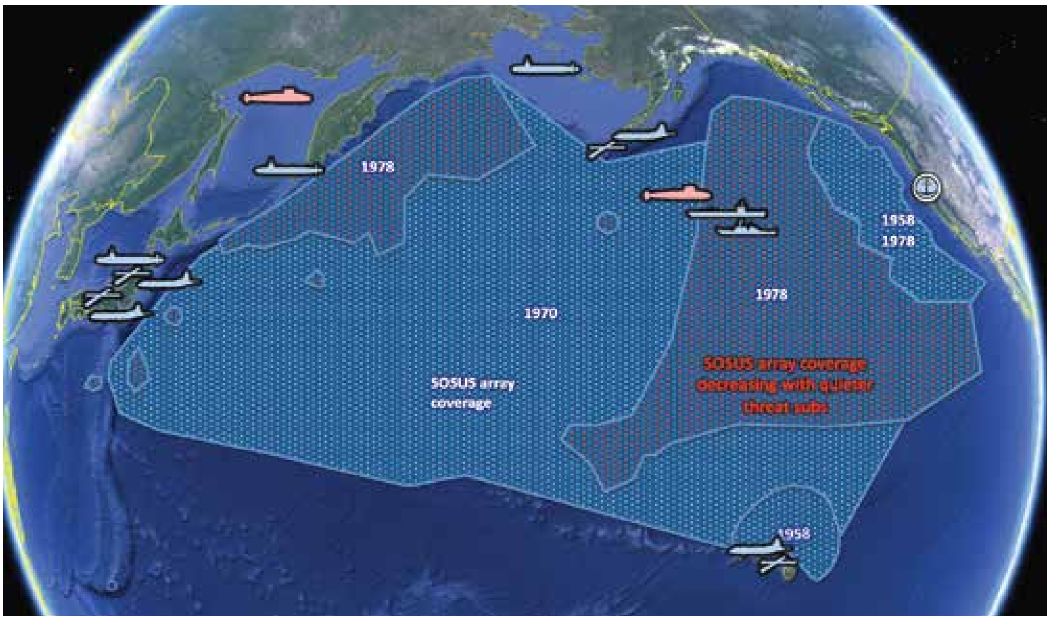
Phase Two: Looming Parity

In the late 1970s, the Soviets' operational experience and intelligence gathered from the John Walker spy ring revealed the need to reduce their submarines' sound signature. Industrial espionage provided some of the advanced manufacturing techniques needed to do so. The next generation, also known as the "third generation," of Soviet nuclear submarines began to incorporate the features that made U.S. SSNs so quiet, such as sound isolation mounts, "rafting"

33 Cote, *The Third Battle*, p. 27.

of machinery inside the hull, and new propeller technology.[34] As a result, the *Victor III* and *Akula* attack submarines and the *Oscar II* guided-missile submarines began to approach the radiated sound levels of the early U.S. *Los Angeles*-class attack submarines. This increased the probability that Soviet submarines would counterdetect U.S. submarines trailing them.[35] More importantly, however, quieter Soviet submarines eroded every element of the U.S. ASW battle network, particularly SOSUS. Figure 19 shows that by 1978, SOSUS coverage areas began to shrink dramatically. This trend continued through the end of the Cold War.

FIGURE 19. PACIFIC SOSUS ARRAY COVERAGE, 1958–1978[36]



Quieter Soviet submarines also increased the importance of defensive ASW. If U.S. patrol aircraft and submarines would not be able to reliably eliminate deployed Soviet submarines when conflict started, the destroyers, frigates, and helicopters protecting battle groups would have to defeat them. Hull-mounted active sonars had advanced somewhat by this time, improving ASW against diesel submarines, and the SQR-14 and SQR-15 passive towed arrays were fielded to provide surface ships the ability to detect SSNs. These systems were not able, however, to achieve the longer detection ranges needed to attack Soviet submarines before they were within ASCM range of the battle group.

34 "Rafting" is a silencing practice where an internal deck of a ship is mounted on flexible or sliding mounts. This isolates the deck from the hull and reduces the amount of sound transmitted from the deck (and deck-mounted equipment) to the hull.

35 Benedict, "U.S. Navy Antisubmarine Warfare"; Cote, *The Third Battle*.

36 R. F. Cross Associates, *Sea-based Airborne Antisubmarine Warfare,* pp. 73, 155, 205.

The ASCM, starting with the SS-N-3 deployed on the *Echo II* in 1962, gave Soviet submarines the ability to attack CVNs and other large ships from much longer ranges. The *Echo* had to surface to launch missiles, which made it easier to detect and counterattack, but the *Charlie I* (initial operation in 1967) and *Oscar* (initial operation in 1980) SSGNs could do so submerged. The third-generation *Oscar II* SSGN incorporated sound-silencing features, making passive detection almost impossible outside the 220-mile range of its SS-N-19 ASCM. Other third-generation attack submarines could also launch ASCMs with ranges of 100–150 nm from their torpedo tubes.[37] The most effective ASW sensors in the U.S. fleet in the late 1970s through late 1980s were submarine passive sonars and the active AQS-22 helicopter-borne dipping sonar, both of which could enable engagement of Soviet submarines before they approached within ASCM range of the CVBG if the submarine or helicopter were positioned ahead of the battle group. Surface ship passive sonar was also improving at this time, but they lacked a long-range weapon able to engage the submarine outside ASCM range, the U.S. ASW rocket (ASROC) being limited to about 10 miles. This would leave the ship vulnerable to ASCM attack before it could directly engage the Soviet submarine.

This situation suggested the need to rethink the U.S. Navy's ASW metric and battle network. Instead of focusing on sinking enemy submarines early in the conflict, U.S. forces instead began to emphasize driving them away from U.S. battle groups. Compared to the vast array of sensors, submarines, patrol aircraft, and weapons needed for the passive ASW approach, the defensive approach addressed the essential metric of protecting the fleet, at a fraction of the cost and effort involved in fielding a force to kill Soviet submarines. The U.S. Navy pursued two ways of keeping Soviet submarines away from the fleet:

1. Submarines were assigned to each battle group to "sanitize" the area in advance of the battle group, along with ship-based helicopters overtly using active sonar outside Soviet ASCM range from the battle group to find or drive away Soviet submarines; and

2. Attack submarines were sent to track Soviet SSBNs in their "bastions" to compel the USSR to shift its best attack submarines away from battle groups and toward SSBN defense.[38]

This approach applied the lessons of World War II. The defensive ASW battle network focused only on submarines that could influence the U.S. metric of protecting battle groups and concerned itself more with making Soviet submarines ineffective than with sinking them. For example, the surface ship and helicopter "kill chain" was not highly effective, but their active sonar was overt and able to drive submarines away from the defended area. At the same time, the counter-SSBN campaign in the bastions imposed "virtual attrition" on the Soviets by compelling them to take front-line submarines away from the pursuit of U.S. battle groups.

37 Norman Polmar and K. J. Moore, *Cold War Submarines: The Design and Construction of U.S. and Soviet Submarines, 1945–2001* (Washington, DC: Brassey's, Inc, 2004), p. 296.

38 Cote, *The Third Battle*, p. 77.

The specific systems implementing this new ASW approach, however, were not able to keep up with Soviet advancements. Through the 1980s, the Soviets continued to build quieter nuclear submarines, fielding the *Akula II, Sierra,* and *Oscar II*. They also returned to diesel submarine development. Through the 1970s Soviet diesel submarines focused on littoral defense and were exported to USSR client states. The *Kilo* submarine, fielded in 1980, gave the Soviets a blue-water SS able to launch the latest supersonic SS-N-27 ASCM. The USSR's other ASCMs also improved, extending their range, speed, and ability to penetrate U.S. air defenses such as the (then) new Aegis system.

These improvements meant the U.S. needed a longer-range detection method that could find quiet nuclear and diesel submarines before they could attack aircraft carrier battle groups (CVBGs). In the late 1980s, the Navy began work on lower-frequency active sonars (in the 100–300 Hz range) that would travel hundreds of miles and possibly detect submarines dozens of miles away.[39] Compact Low Frequency Active (CLFA) arrays consisting of a variable-depth transducer and a long towed array receiver offered great promise, but required extensive processing that was not possible in real time or on board a ship. More development was required before CLFA could be operationalized. Meanwhile, U.S. naval forces had to accept the risk of Soviet ASCM attacks.

"Saved by the Bell"

Luckily, as in World War II, U.S. forces would not have to face this threat for long. The USSR collapsed between 1989 and 1991 and with it, the Soviet Navy. Russian submarines returned to port and deployed infrequently. The falling of the Iron Curtain also revealed the poor material condition of the Soviet fleet, which had apparently been the case for several years before the collapse. The underlying capabilities of Russia's rusting and inoperable submarines, however, were still advanced and would have been effective if properly maintained.

Passive sonar had been the foundation of the Cold War submarine-ASW competitive regime. With both sides' improvements in submarine quieting, this was about to give way to an active sonar competitive regime—but America was again saved by the bell. The snapshot of ASW circa 1989 is important, however, because Russia is resurgent and its Cold War technology is being exported to a growing number of potential U.S. adversaries.

What Comes Next?

In the aftermath of the collapse of the Soviet Union, the U.S. Navy entered a period of nearly complete maritime dominance. No rival fleet offered anything comparable to the submarine-ASW competition it had encountered since the early days of World War II. No other potential adversary had capable submarines of their own, and the *Kilos* and other submarines the

39 Gordon Tyler, "The Emergence of Low Frequency Active Acoustics as a Critical Antisubmarine Warfare Technology," *Johns Hopkins APL Technical Digest*, 13, No. 1, 1992.

USSR had exported were not operated effectively or often by their buyers in China, Iran, and elsewhere. U.S. research on emerging low-frequency active sonar technology continued, and work began on nonacoustic techniques designed to detect a submarine visually using lasers or other light that can penetrate seawater. Without a compelling threat, these efforts proceeded slowly and for the most part U.S. ASW reverted to the early Cold War approach, when America had a significant acoustic advantage over Soviet submarines. U.S. SOSUS arrays, patrol aircraft, and SSNs tracked individual Chinese and Russian submarines during their infrequent deployments. Battle group ASW operations continued to rely on helicopter-borne active sonars and improving passive towed arrays on destroyers.

The culmination of the passive sonar competition was therefore suspended for about twenty years. Today, however, third-generation Russian submarines are again making regular overseas deployments, albeit at greatly reduced levels compared to the Cold War, and a new generation of even quieter and more capable submarines is on the way. China maintains a continuous presence of nuclear and diesel submarines in the Western Pacific, and will soon deploy an SSBN with missiles able to strike the United States and Europe. While Chinese submarines do not have the low radiated noise of Russian submarines, they are growing more numerous and Chinese sound-silencing efforts will undoubtedly accelerate. These trends will undermine U.S. efforts to rely primarily on passive sonar for ASW. The U.S. Navy is already deploying CLFA-equipped ships to the patrol areas of Chinese submarines to better understand their operational patterns.

The submarine-ASW competition will soon shift to a new competitive regime. Because the most capable submarines will grow quieter and carry longer-range weapons, techniques other than passive listening will be needed to detect them before they can threaten ships and facilities ashore. Passive sonar will retain its effectiveness against older submerged vessels, but the basis of the new competitive regime will likely be:

1. *Low-frequency active sonar:* The physics of this technology are well known, but operational use requires extensive supporting technology and engineering. For example, the sound should be transmitted by a variable-depth transducer that can be put into the appropriate sound layer, with the echo returns processed onboard a surface combatant or submarine in real time. The supporting processing and handling systems are now installed on dedicated ships and shore facilities. Eventually they could be miniaturized enough to be installed on operational warships that could also carry long-range weapons able to exploit the detection ranges possible with CLFA. If this regime takes hold, active decoys and countermeasures may prove effective to prevent detection and tracking, as jammers and decoys do in the RF spectrum today. Submarines may also become less effective as ASW platforms, due to the risk of counterdetection if they transmit active sonar.

2. *Background noise:* Scientific and commercial research is focused on this phenomenology because it can reveal locations and movement patterns of fish stocks and possible areas for oil and mineral exploration. This is made possible by miniaturized, large-scale

computer processing, or "big data," which enables analysis and modeling of the water column to classify and precisely locate noise sources and reflections.[40]

3. *Nonacoustic methods:* As with low-frequency active sonar, the physics of these techniques are well known, but limited by computer processing power. That is changing as large-scale processing is increasingly possible in real time and on operational platforms such as ships and aircraft.

Imperatives for Future Submarine and ASW Battle Networks

Examination of a century of submarine-ASW competition reveals a clear set of consistent imperatives that are similar to those of the aircraft-air defense competition and are directly applicable to developing battle networks for use in future submarine-ASW competitive regimes:

- Establish the right metrics: Selecting the right metrics for the submarine force and the ASW force is essential to creating an effective and sustainable battle network. For ASW forces, the inclination to try and sink submarines usually must be curtailed in favor of a metric focused on protecting and continuing the mission enemy submarines are attempting to prevent. For submarines, metrics should focus on defeating important enemy missions. An example of this is seen in the U.S. Navy's approach to late Cold War ASW, where U.S. SSNs imposed "virtual attrition" on Soviet SSNs by threatening the Soviet SSBN force in its littoral bastions.

- Know the current competitive regime: Competitors in each conflict were slow to identify the current regime: the EM spectrum in World War II, passive acoustics in the Cold War, and perhaps active acoustics today. Identifying the current regime enables the competitor to predict the moves and countermoves that are likely to ensue and where the competitive regime is likely to culminate. Identifying and working on improvements within the current competitive regime may be the best place for military laboratories and research organizations to focus.

- Identify possible future competitive regimes: Even more important than identifying the current regime is assessing where the competition will "jump" next. In both World War II and the Cold War, the United States and its allies were "saved by the bell" when the adversary collapsed before being able to culminate the current competitive regime and jump to a new one.

40 A. Frey and J. Gagnon, "Detection of a Silent Submarine from Ambient Noise Field Fluctuations," *UMAP Journal*, September 1996; Frederick Wang, Garrett Mitchener, and Gretta Bartels, Team #525 in the Mathematical Contest in Modeling, *Using Ambient Noise Fields for Submarine Location* (Durham, NC: Duke University, 1996), available at http://mitchenerg.people.cofc.edu/mcm96paper.pdf.

- ◇ In World War II, the Allies were not prepared for the acoustic competition that was about to ensue. In particular, the United States was fortunate to have begun research on passive acoustics when nuclear submarines became operational. In both active sonar against diesel submarines and passive sonar against nuclear submarines, the United States and its NATO allies benefited from the slow Soviet development of both types of submarines.
- ◇ Identifying and working on innovations that establish a new competitive regime may be the best place for disruptive technology organizations such as DARPA and academia.

- Build the appropriate battle network: The best ASW and submarine battle networks historically were those that had the best alignment between actions, metrics, and overall objectives; in particular:
  - ◇ Focus actions on the metric and focus metrics on the main objective. The Allies' convoy approach directly addressed the metric of protecting shipping, which directly supported the operational objective of keeping the Allies in the fight and eventually invading the continent. Conversely, in the early Cold War, the metric of tracking each deployed Soviet nuclear submarine missed the main objective of protecting battle groups from ASCM attack. While possible in peacetime, this was not an efficient approach and may have been ineffective in wartime.
  - ◇ Look for ways in which fundamentals of the submarine could be changed. As stated previously, submarines are slow, have limited situational awareness, and lack self-defense. New countertorpedo systems, long-range sensors, or combat systems able to calculate probability of being hit, as done by Aegis today, would alter those fundamentals and possibly enable submarines to more effectively "stand and fight" once detected.
  - ◇ Understand how operational tempo relates to communications. The submarine-ASW competition is relatively slow, so exploiting communications is more useful than denying them. This was exemplified by the Allies' use of convoys, which were routed based on ELINT and protected by escorts using EM sensors to avoid and threaten Axis submarines.
  - ◇ Exploit "virtual attrition" wherever possible. The Bay of Biscay operation caused significant virtual attrition against German submarines. This could have been more efficiently done if slowing, rather than killing, submarines had been established as the metric for the operation, in line with the overall metric of protecting convoy shipping. In the Cold War, the United States imposed "virtual attrition" on front-line Soviet SSNs by holding SSBNs at risk in the bastions and compelling Soviet SSNs to come to protect them.
  - ◇ Remember "virtual attrition" requires the threat of actual attrition. Long-range ASW weapons or fast ASW "pouncer" aircraft will be required to drive away submarines before they come within ASCM range of the defended unit. While these may not have a high probability of killing the attacking submarine, they must represent a credible enough threat for the submarine to have to evade.

Air Attack Versus Integrated Air Defense Systems

This section explores a second long-running BNC that has been crucial to many conflicts since World War II and is at the heart of many current and future concepts for U.S. military power projection: the competition between air attacks and the IADS designed to counter them. This section will explore two eras of sustained, intense air attack versus IADS competition through detailed examination of the best available quantitative data on combat outcomes from World War II and the late 1960s. It then traces trends in the competition to the present and suggests likely future developments based on these trends.

Enduring Aspects of the Competition

One immediate question is, "How much can we really learn about the current and future shape of the air attack versus IADS competition from studying decades-old cases?" If the focus is on specific tactics and techniques used to defeat long-obsolete systems, then the answer is probably, "Not very much." If the focus, however, is on how the opposing sides strategically approach and adapt to challenges posed by capable, competent opponents in deciding which new technologies to develop and field, then the answer is, "Quite a lot."

One reason for the durability of insights gained from past air attack versus IADS competitions is that, just like submarines, aircraft have certain fixed, fundamental attributes that have continually shaped the competition over the past seven-plus decades. The first of these is access. The fact that about 70 percent of the Earth's surface is covered by water is often discussed. The more obvious fact, however, that 100 percent of the Earth's surface is covered by air often goes unremarked, perhaps because it is so obvious. Therefore, in theory, aircraft can reach any point on Earth and, if properly equipped, attack and destroy all manner of targets—from military targets to transportation infrastructure, industrial facilities, or even cities—even without first defeating an opposing military force in battle. A second important attribute of air attack systems is their speed. Because they move much faster than ground or naval forces, air attack systems can appear suddenly and be massed at widely separated points in relatively quick succession. A third attribute favoring the air attacker is the small size of even the largest aircraft relative to the vastness of the sky. This makes visual detection and tracking of aircraft at ranges sufficient to allow a coordinated and effective defense difficult and resource intensive. This is the factual basis for British politician Stanley Baldwin's famous 1932 statement "I think it is well also for the man in the street to realise [sic] that there is no power on earth that can protect him from being bombed. Whatever people may tell him, the bomber will always get through." The development of radar in the late-1930s changed this by allowing defenders to detect and accurately track attacking aircraft at sufficient range to enable effective interception.

There are three additional attributes of aircraft that, in combination, confer considerable advantages to the defender. First, compared to land vehicles and ships, aircraft are inherently fragile. The desire to maximize their combat potential makes minimizing structural weight an important consideration in aircraft design. This leaves relatively little margin for redundant structural strength, making combat aircraft relatively vulnerable to structural damage. Since designers look to pack as much fuel, electronics, and weapons into an aircraft as possible, this leaves relatively few "unimportant" areas on most aircraft. Second, compared to ships and even ground vehicles, most aircraft have relatively small payload weight and volume capacity.[41] The final enduring attribute favorable to the defender is the relatively low combat persistence of individual aircraft. Limited fuel, weapons, and crew endurance mean aircraft generally deliver an attack with one or more weapons and then return to base to be refueled and rearmed for another mission.[42] Relatively low payloads and combat persistence typically make it necessary for combat aircraft to fly many missions in order to achieve campaign objectives. Table 4 illustrates this point.

The necessity to fly many combat sorties with relatively scarce and expensive combat aircraft makes air forces extremely sensitive to even seemingly small loss, or attrition, rates. For example, a 1 percent per sortie attrition rate during Operation Desert Storm would have resulted in the loss of 518 of the approximately 2,200 coalition combat aircraft available at the start of the conflict (roughly 23 percent). Actual coalition combat losses were just 38 (0.07 percent per sortie). This highlights clearly why air forces have historically been

41 Ships can carry thousands of tons of cargo. A standard 53-foot semitrailer has weight and volume capacities of 46,100 pounds and 3,715 cubic feet respectively. Adding an additional 28.5-foot trailer is legal in the United States and brings total payload to about 70,000 pounds and total volume to about 5,700 cubic feet. See Schneider International, "Loading Guidelines," available at http://www.schneiderfreightpayment.com/cm1/groups/public/@marketing-public/documents/webcontent/equipment_specs.pdf, accessed May 19, 2014. For comparison, even large aircraft like the venerable Boeing B-52 heavy bomber have limited payload capacity. The B-52's internal bomb bay has a volume of 1,043 cubic feet and is capable of carrying various combinations of weapons, including eight AGM-86 air-launched cruise missiles (ALCM) with a combined weight of approximately 25,000 pounds. The B-52 can carry an additional twelve ALCMs on external wing pylons for a total payload of about 63,000 pounds. The latter is possible only by taking off with approximately 75 percent of maximum fuel (based on data from U.S. Air Force Fact Sheets for B-52 and AGM-86, available at http://www.af.mil/AboutUs/FactSheets, accessed May 19, 2014).

42 Recent operations in Iraq and Afghanistan put a premium on "on-call" close air support (CAS) and thus on the ability of aircraft to loiter for long periods. They were also conducted in the absence of an opposing IADS and are therefore beyond the scope of the current discussion.

extremely sensitive to combat loss rates and why they are willing to devote significant effort and resources to minimizing them.

Night Bombing in World War II: Active Electromagnetic Competition

The first air attack versus IADS competition we will examine is the competition between bombers attacking at night and defensive measures designed to counter them. Before focusing on the night bombing competitions, it is important to briefly discuss why first the British Royal Air Force (RAF) and then the German Luftwaffe abandoned the much more accurate daylight bombing methods their forces were primarily trained and equipped to carry out prior to the war.

TABLE 4. COMBAT SORTIES PER MONTH IN VARIOUS CONFLICTS, 1944–1999[43]

Combat Sorties per Month	
USAAF vs. Germany—March 1944	26,411
Rolling Thunder—1965–1986	9,468
IAF During Yom Kippur War—1973	18,131
Operation Desert Storm—1991	51,840
Operation Allied Force—1999	10,231

Why Night Bombing?

By the late 1930s the major air forces destined to be involved in World War II had developed optical analog computing bombsights that combined inputs such as airspeed, altitude, wind drift, bomb type, etc., and allowed proficient operators to place bombs accurately enough to enable attacks against typical industrial targets. The best known of these is the Norden bombsight developed in the United States, although the RAF and Luftwaffe had comparable systems in service. These systems were able to place bombs within a circular error probable (CEP) of about 1,200 feet under combat conditions from altitudes of about 20,000 feet.

43 Sortie totals drawn from: Army Air Forces, Office of Statistical Control, *Army Air Forces Statistical Digest* (Washington, DC: Department of Defense [DoD], 1946), Table 119; Thomas C. Thayer, ed., *A Systems Analysis View of the Vietnam War: 1965–1967,* Vol. 5, *The Air War* (Washington, DC: DoD, 1975); Alfred Price, *History of US Electronic Warfare,* Vol. 3, *Rolling Thunder Through Allied Force,* 1964 to 2000 (Alexandria, VA: Association of Old Crows, 2000); U.S. Air Force, *Gulf War Air Power Survey,* Vol. 5, *A Statistical Compendium and Chronology* (Washington, DC: U.S. GPO, 1993); William S. Cohen and Henry H. Shelton, *Kosovo/Operation Allied Force After-Action Report,* Report to Congress (Washington, DC: DoD, 2000), pp. 68–69.

FIGURE 20. DAYLIGHT BOMBING ACCURACY DURING WORLD WAR II

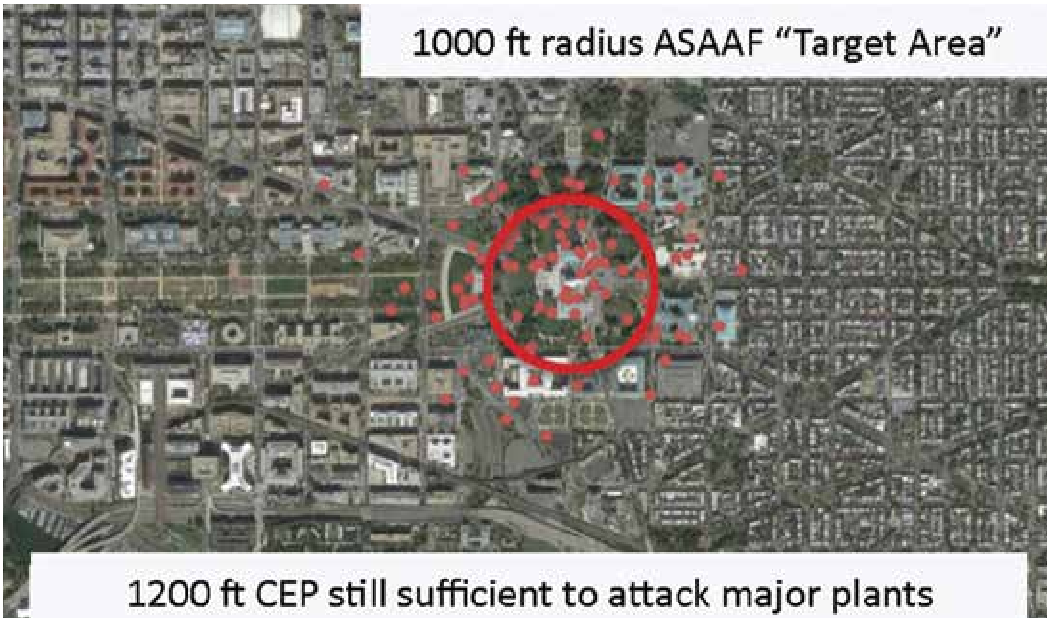


Figure 20 illustrates a typical bombing pattern for a hundred bombers attacking an industrial facility about the size of the U.S. Capitol building. It also shows the 1,000-foot radius circle the USAAF defined as the "target area." With each bomber dropping a payload of two to four tons, it is clear that such an attack would do considerable damage to an industrial facility of this size. In many cases, however, damage was quickly repaired and production resumed, so follow-up attacks were necessary. For example, it required twenty-two separate daylight attacks on the Leuna synthetic oil plant in Germany between May and December 1944 by 6,552 bomber sorties dropping 18,328 tons of bombs to restrict average output to 9 percent of capacity.[44]

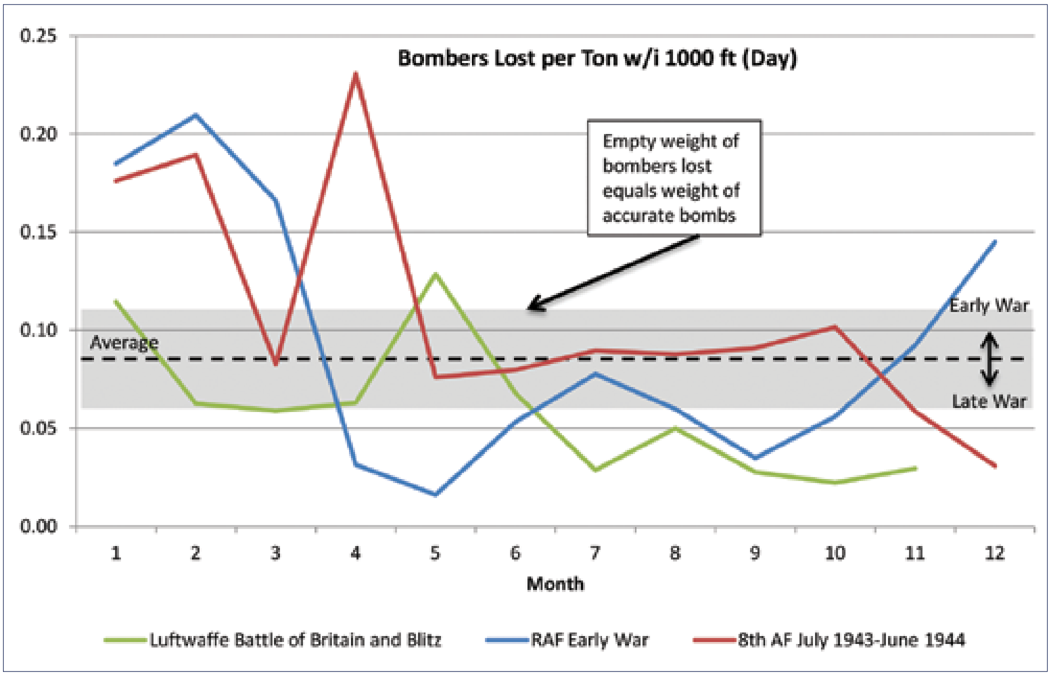
The need to fly thousands of bomber sorties to disrupt industrial production over extended periods provided defenders the opportunity to defeat the long-term objective, severe disruption of war production, of the air attacks by inflicting unacceptable levels of attrition on attacking bomber forces. Figure 21 illustrates how the introduction of radar in the late 1930s transformed the effectiveness of daylight fighter defenses by providing ample warning of approaching raids and accurate tracking of bomber formations. This allowed defenders to hold interceptors on the ground until an approaching attack was detected and mass them against the raid instead of mounting inefficient dispersed standing combat air patrols (CAPs).

Both the Luftwaffe and the RAF abandoned daylight bombing in reaction to the unsustainable losses suffered. The USAAF suspended daylight raids deep into Germany in October 1943

44 United States Strategic Bombing Survey (USSBS), *Summary Report, (European War)* (Washington, DC: U.S. GPO, 1945), pp. 22–23.

and did not resume them until sufficient long-range fighters were available to escort bombers throughout their entire missions. For both the Luftwaffe and the RAF, the switch to night bombing operations solved the bomber survivability problem, but they were confronted with navigation and bomb-aiming challenges that most of their crews were not trained or equipped to handle.

FIGURE 21. BOMBERS LOST PER TON OF BOMBS WITHIN 1,000 FEET OF AIM POINT[45]



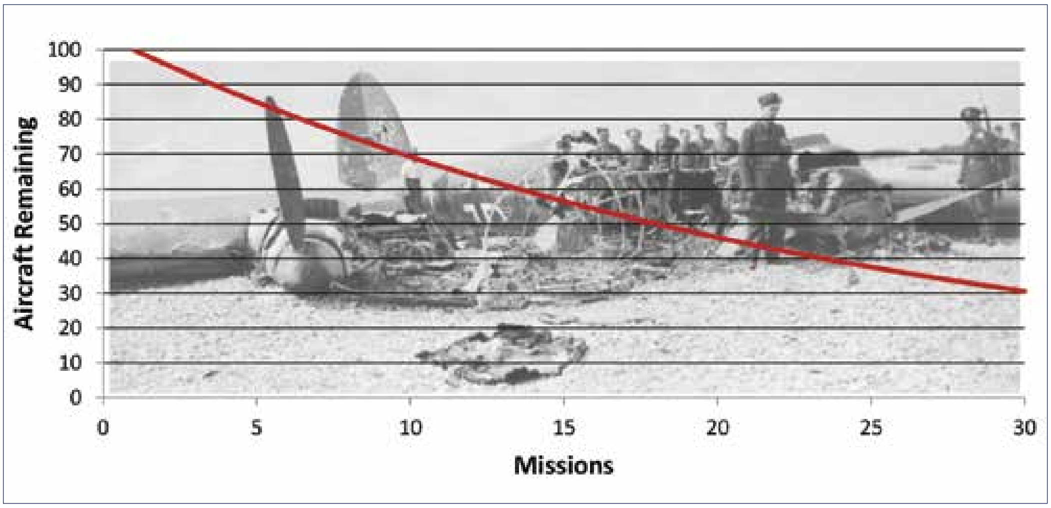
Analysis of bomber sortie and loss data indicates that in the first twelve months of sustained operations in Europe, the RAF, Luftwaffe, and USAAF all suffered average bomber losses of about 4 percent per sortie.[46] Figure 22 illustrates how this seemingly small attrition rate

45 This chart assumes bombs dropped in daylight had the typical 1,200-foot CEP discussed above. On this basis, the bombers lost per ton of "accurate bombs" can be calculated. It averaged about 0.085 bombers lost per ton of bombs dropped in the "target area." So, in early daylight operations the air forces could expect to lose about one bomber for every 11.7 tons of bombs dropped in the target area. For perspective, the empty weight of the German He 111H bomber was just over 9.5 tons and a B-17G just over 18 tons. On many occasions the empty weight of bombers lost exceeded the weight of bombs accurately delivered!

46 The bomber sortie and loss data presented in this section are derived from a number of sources including: Army Air Forces, *Army Air Forces Statistical Digest*; Williamson Murray, *Strategy for Defeat: The Luftwaffe, 1933–1945* (Washington, DC: U.S. GPO, 1983); Derek Wood and Derek Dempster, *The Narrow Margin: The Dramatic Story of the Battle of Britain and the Rise of Airpower: 1930–1940* (New York: Paperback Library, 1969); Max Hastings, *Bomber Command: Churchill's Epic Campaign* (New York: Touchstone, 1989); Stephen Bungay, *The Most Dangerous Enemy: A History of the Battle of Britain* (London, UK: Arum Press, 2000).

resulted in the loss of 70 percent of aircraft (or aircrews) over the course of just thirty combat missions—a typical RAF Bomber Command operational tour.

FIGURE 22. EFFECT OF 4 PERCENT ATTRITION RATE ON A FORCE OF 100 AIRCRAFT



The “Blitz” and the German Beams[47]

The first large-scale night bombing raids of World War II were launched against London beginning on August 28, 1940. This attack was the first of fifty-eight night attacks flown against targets in London through early November that came be known as the “Blitz.” German bomber crews were about ten times more likely to survive a night bombing mission over England in late 1940 than a day mission.[48] Just as the RAF fighter pilots could not find and attack the bombers effectively in the dark, the German bombers could not rely on visual navigation and optical bombsights to hit their targets.

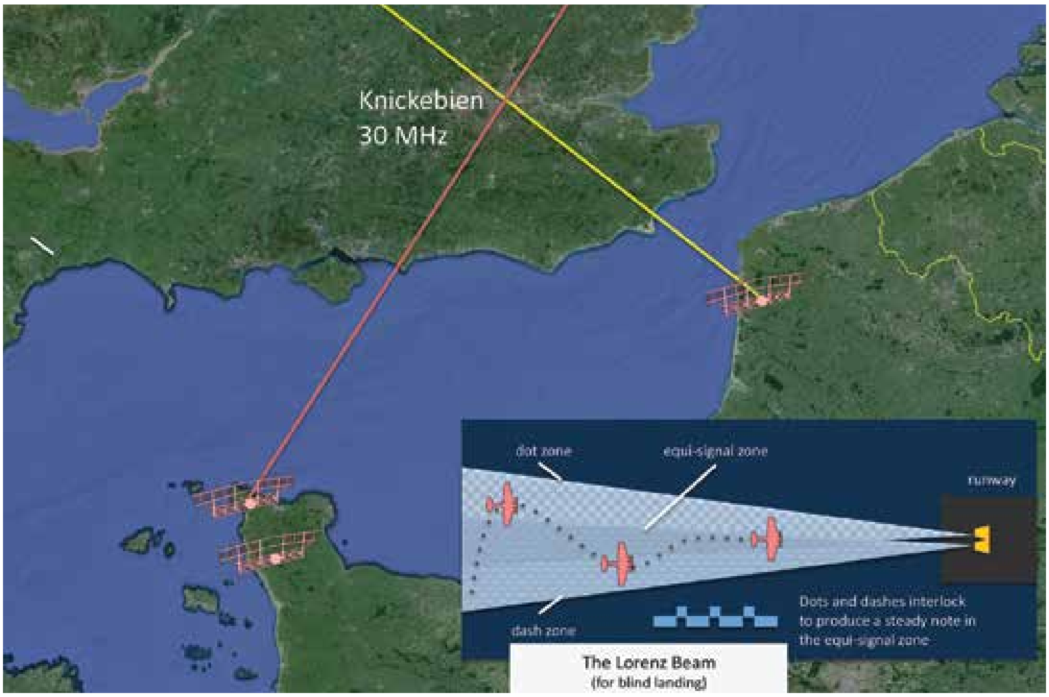
Alone among the major air forces, the Luftwaffe had anticipated the navigation and targeting challenges associated with night bombing prior to the start of the war and had invested in developing sophisticated electronic aids to navigation and targeting. The first to reach operational service was the Knickebein (bent leg) system. This was derived from the widely used Lorenz instrument landing system. The Lorenz system transmitted two radio beams on the same frequency along the runway with a small angle of divergence. The left-hand beam, as seen from the approaching aircraft, transmitted Morse code “dots” while the right-hand beam transmitted synchronized “dashes.” If a pilot was left of course he heard dots, if right of course

47 The narrative of the World War II air attack vs. IADS competition presented here is a condensed version of the comprehensive story presented by Alfred Price in *Instruments of Darkness: The History of Electronic Warfare* (New York: Charles Scribner’s Sons, 1978), Chapters 1–10.

48 For example, in October 1940 the Luftwaffe lost 79 bombers on an estimated 2,300 daytime bombing sorties over England (3.4 percent), but lost just 23 bombers while flying 5,900 night missions (0.38 percent).

he heard dashes, and if on centerline, where the beams overlapped, he heard a steady tone. Knickebein used much larger and more powerful transmitters combined with more sensitive Lorenz receivers on board the bombers to guide them to their targets at ranges up to 175 nm for aircraft flying at 20,000 feet.[49] Figure 23 illustrates how the system worked. Two widely separated radio beam transmitters were aligned on the target so that they crossed at a significant angle. Aircraft flew down the center of one beam (the "approach" beam) in the same way they would for a Lorenz approach. As the aircraft approached the target they tuned a second receiver to the second "cross" beam frequency and dropped their bombs when they heard the steady central tone. System accuracy decreased with range, but was comparable to daylight bombing at about 150 nm from the transmitters. The system had the advantages of requiring little additional training for the bomber crews, and the aircraft only required minor modifications to their existing Lorenz receivers.

FIGURE 23. GERMAN KNICKEBEIN RADIO BEAM NAVIGATION SYSTEM



Knickebein should have allowed Luftwaffe bomber crews to bomb British targets at night nearly as accurately as during the day with much lower losses. The system, however, was transitioning from development to production just as the war began in September 1939. The Luftwaffe decided to equip a small number of aircraft with the more sensitive Lorenz receivers and conduct operational trials against targets in England late in 1939. One of these aircraft

49 Price, *Instruments of Darkness*.

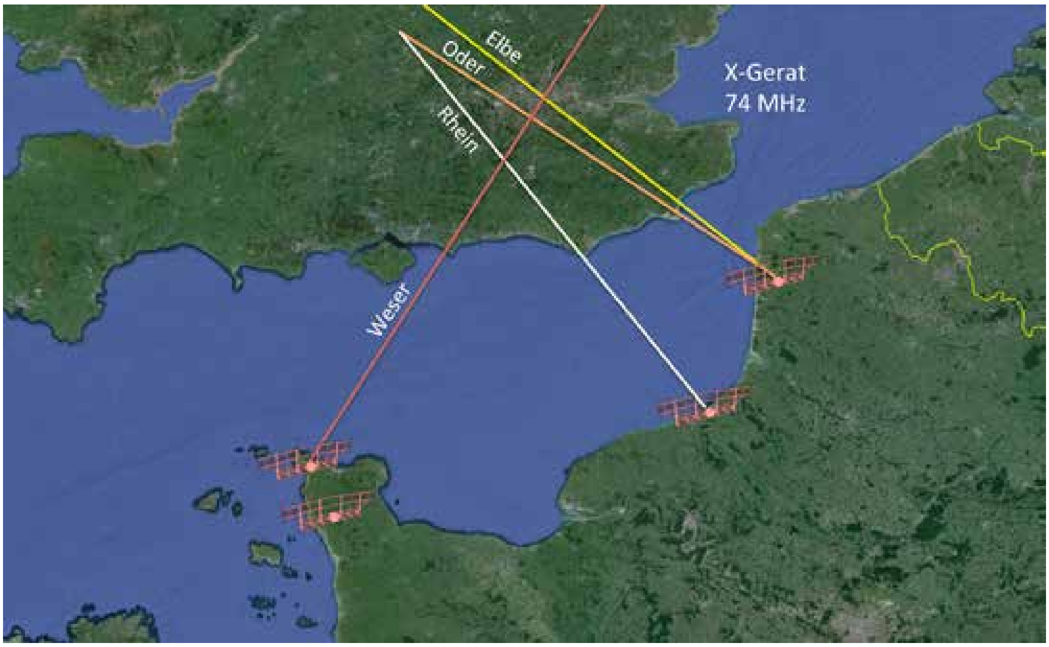
was shot down over Scotland in October 1939 and carefully examined by British scientific intelligence. The unusually sensitive Lorenz receivers raised concerns that they represented a new form of navigation aid. This was later confirmed by prisoner interrogations. The British gave the system the codename "Headache."

British scientific intelligence worked with the RAF to detect the radio transmissions associated with Knickebein throughout the spring of 1940. Eventually signals were detected and their characteristics recorded. By late June, with the fall of France, it was clear that Britain would soon face the concentrated attention of the entire German air effort, and a team was formed at Prime Minister Churchill's direction to counter Headache. The team fielded its first improvised broad band noise jammers on August 20, just fifty-nine days after it was formed. These were modified electrodiathermy sets hospitals used to cauterize wounds. These early jammers had only limited range and were too few to prevent German crews from using Knickebein effectively over a large area. They were fielded, however, *eight days before* the first mass use of Knickebein by the Luftwaffe on August 28. By September 7, the countermeasures team began deploying purpose-built high-power jammers specifically tuned to Knickebein frequencies. These jammers, code named "Aspirin," made Knickebein, aka Headache, effectively useless over the British Isles by mid-November.

Overall, Knickebein had a useful operational life of just eighty days. The Germans' "premature" introduction of small numbers for operational trials gave the British access to both the Knickebein receivers and personnel familiar with its use and capabilities almost a year before it was first employed in large numbers. This provided the British with a valuable head start in developing countermeasures. This is an important element of the aerial BNC that tends to make the move-countermove cycle much shorter than the submarine-ASW competition. The attacker must always bear in mind that since aircraft are likely to be lost over enemy territory, the defender is almost certain to gain physical access to any new system introduced, as well as the aircrews that are aware of its capabilities and limitations. This makes it likely that the period of maximum operational effectiveness will be relatively short, in which case it becomes important that systems be introduced in large enough quantities to achieve substantial operational and strategic impact during this relatively brief period. Introducing systems in small quantities for "combat trials" is likely to lead to early compromise and significantly shorter operational utility.

Just as Knickebein effectiveness faded, the Germans introduced their second radio navigation/bombing aid. Known as X-Gerat (X-Device) to the Germans and as "Ruffian" to the British, this system was more accurate than Knickebein and operated in the 74-MHz frequency range (versus the 30-MHz range of Knickebein and Lorenz). Therefore, it required special electronic equipment and additional aircrew training. As a result, the Luftwaffe fitted about fifty X-Gerat receivers to the aircraft of Kampf Gruppe 100 (KG 100). The crews of KG 100 flew down an approach beam, known as Weser, in much the same way as crews using Knickebein. Instead of a single cross beam as in Knickebein, X-Gerat employed three. The first cross beam, Rhein, alerted the crew that they were approaching the target area and should fly as close as possible to the approach beam centerline. When the aircraft crossed the second beam, Oder, the navigator started a stopwatch integrated into the X-Gerat console. When the aircraft crossed the third beam, Elbe, he depressed the stopwatch button a second time. This stopped movement of the first watch hand and simultaneously started movement of another hand geared to move twice as fast as the first. The Oder and Elbe beams were set to cross Weser so that the distance between them was exactly twice the distance between Elbe and the target. Therefore, the time required to travel from Elbe to the target should be just half that required from Oder to Elbe. When the two second hands met, an electrical contact was closed that automatically dropped the bombs. Figure 24 illustrates how X-Gerat worked.

FIGURE 24. X-GERAT RADIO BEAM NAVIGATION SYSTEM



In mid-November 1940, the Luftwaffe began employing KG 100 as a "pathfinder" force. KG 100 aircraft would be the first to attack a target and carried primarily incendiary bombs to start large fires. The main bomber force units would then follow up by bombing the fires with a mix of high-explosive and incendiary bombs. This method was highly effective in the famous attack on Coventry on November 14, 1940. Unfortunately for the Germans, British scientific intelligence was already working on a counter to the X-Gerat. They had been tipped off to its existence by a combination of unusual equipment taken from downed KG 100 aircraft, prisoner interrogation, and its early use in "combat trials." The first of these to come to the attention of British scientific intelligence was a night raid on a Spitfire factory carried out in early August by KG 100 aircraft. In this raid, a large fraction of bombs dropped actually hit the target, indicating that some new form of electronic navigation aid with greater accuracy than Knickebein was likely in use.

FIGURE 25. RELATIVE ACCURACY OF KNICKEBEIN AND X-GERAT

Figure 25 illustrates the relative accuracy of Knickebein (large box) and X-Gerat using the Tower of London as a notional target. The British promptly found and analyzed the transmissions associated with the Spitfire factory raid and began working on a jamming system. They discovered that the standard British Army mobile air defense radar set worked in a similar frequency range, and a number of these were modified to jam X-Gerat signals. Their first success was on November 19, 1940, just five days after the Coventry raid, when they foiled a similar attack launched against Birmingham. X-Gerat rapidly lost its effectiveness as more jammers were fielded, and by mid-January 1941, all of southern England had effective jamming coverage.

FIGURE 26. QUANTITATIVE DEPICTION OF LUFTWAFFE BOMBING OF BRITAIN

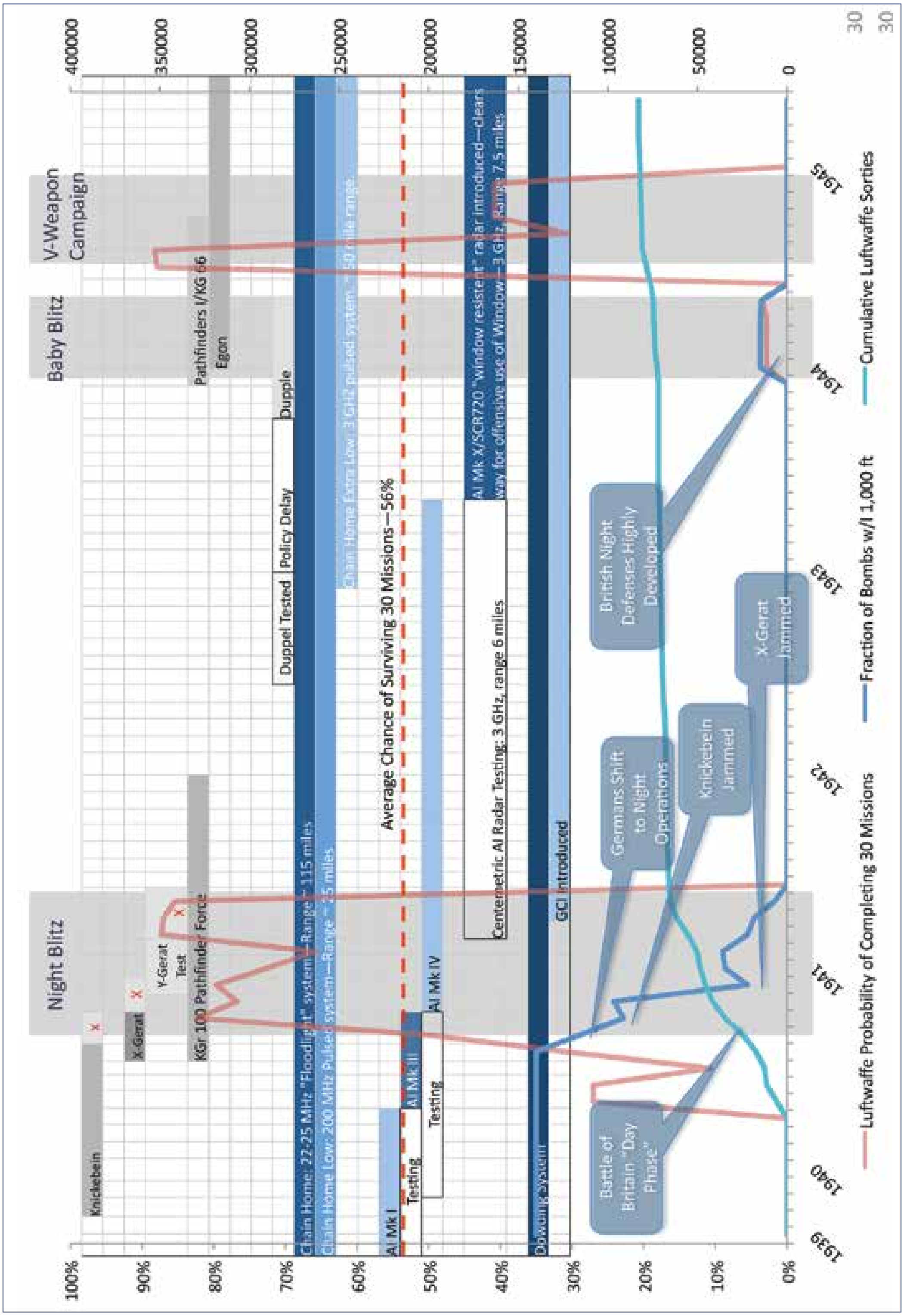


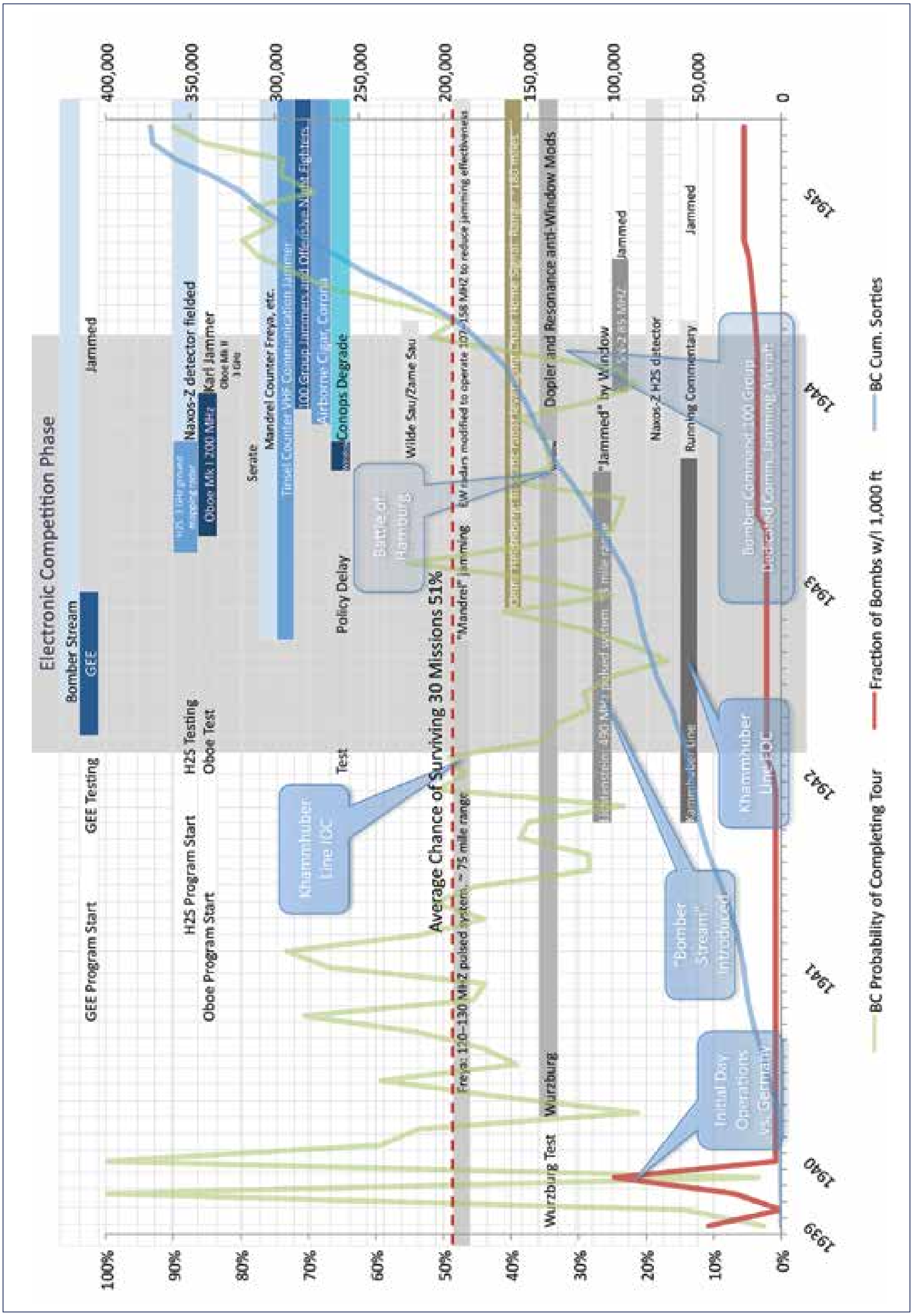
Figure 26 shows the cumulative number of Luftwaffe bombing sorties flown against Britain, the probability Luftwaffe bomber crews would complete thirty missions, and an estimate of the fraction of bombs dropped falling within 1,000 feet of their designated target. It also shows the introduction of various measures and countermeasures in this BNC and how they altered both the probability of bomber crew survival and their accuracy. The significant developments in 1940 and early 1941 have largely been described, but there are several additional important aspects of this competition to note. First, Hitler's decision to invade the Soviet Union consumed virtually all Luftwaffe bomber capacity from mid-1941 through late 1943 when the Luftwaffe concentrated much of its remaining bomber strength in France to launch operation Steinbock, known as the "Baby Blitz" in Britain, in retaliation for the rapidly increasing RAF Bomber Command area bombing campaign against German industrial cities. Another is that the German shift to night bombing spurred British development of airborne intercept (AI) radar technology. This became an important factor in the British decision, discussed below, to employ Window, or "chaff," against German radar defenses in 1943. Britain used Window once they had fielded AI radar sets operating in the S and X bands that were largely immune to Window and thus less concerned if Germany were to reverse-engineer Window. When the Germans used it in return during the Baby Blitz it had little effect. Finally, while British night defenses were highly effective against German bombers during the Baby Blitz, once the Luftwaffe deployed air-launched V-1 cruise missiles from mid-1944, bomber survivability, but not accuracy, dramatically improved.[50]

RAF Bomber Command versus German Night Defenses, 1942–1944

Bomber Command's campaign against Germany is in some ways a mirror image of the Luftwaffe campaign against Britain. While the Germans started out with significant resources and sophisticated electronic navigation aids largely developed before the war began, Bomber Command began the war with a relatively small number of obsolescent bombers and had devoted no resources to electronic navigation and targeting aids. As the war progressed, the Luftwaffe bombing offensive against Britain virtually stopped for over two years upon Germany's invasion of the Soviet Union, and when it resumed it was on a much smaller scale with no effective electronic aids. In contrast, from early-1942 onwards Bomber Command fielded ever-larger numbers of better bombers supported by a steady stream of electronic aids that ultimately overwhelmed the German night defenses. Figure 27 depicts significant quantitative elements of the Bomber Command versus German night defenses BNC as well as the development and introduction of important electronic and tactical innovations.

50 Of roughly 10,000 V-1s launched against Britain, almost 1,200 were air-launched by He 111 bombers flying over the North Sea. This "standoff weapon" capability allowed the bombers to avoid most defenses, but decreased the already poor accuracy of the V-1s. Warbirds Resource Center, "Fi-103/V-1 'Buzz Bomb'," available at http://www.warbirdsresourcegroup.org/LRG/v1.html, accessed June 4, 2014.

FIGURE 27. BOMBER COMMAND VERSUS GERMAN NIGHT DEFENSES, 1939–1945



Prior to early 1942, Bomber Command's efforts were largely ineffective and posed little threat to German industry or the German war effort. Early in the war, Bomber Command leadership believed that British crews were better trained than their German counterparts and were capable of using deduced reckoning (also "dead reckoning" or DR) navigation, supplemented by celestial fixes, to successfully navigate to their targets and did not need electronic navigation aids like the Germans.[51] Bomber Command targets were selected by headquarters, but it was left to individual crews to plan their own routes and arrival times. This resulted in a number of aircraft flying diverse routes and arriving over the target area over a period of up to seven hours. About this time, questions were raised about the effectiveness of Bomber Command operations. By late 1941, German forces were at the gates of Moscow and the only means Britain had of striking at the Germans in support of her new ally was via Bomber Command. Churchill's scientific adviser, Professor Frederick Lindemann, directed his assistant D. M. Butt to conduct a systematic study of Bomber Command accuracy. After examining over six hundred bombing photographs taken in June and July 1941, the "Butt Report," as it came to be known, concluded that only about 10 percent of bombs dropped on German industry in the Ruhr region fell within 5 statute miles of the target.[52] Figure 28 illustrates where a hundred bombers with similar accuracy would drop their payloads in a hypothetical attack on the U.S. Capitol building. With bombs dispersed across a wide area between Baltimore, Maryland and Fredericksburg, Virginia, it is easy to see why the Germans often had difficulty determining what the objective of an attack had been once it was completed, as well as why postwar studies confirmed that about half of the bombs dropped by Bomber Command up to this time landed in open country.[53]

51 DR aerial navigation begins from a known point and then estimates the aircraft's position by observing speed over a known time to determine distance flown and heading over time to determine direction. This works extremely well if there is no wind, but this is almost never the case at the altitudes bombers operated at during World War II (15,000 feet or more). Applying forecast winds to correct the "no wind" position might improve accuracy, but forecast winds were often wrong—sometimes so far wrong that applying them actually decreased the accuracy of the basic DR position. Using a sextant, air navigators could take measurements of stars and the moon to update, or "fix," their position and then begin the DR process from an updated start. However, even the most skilled celestial navigators could not consistently achieve fixes less than 3 nm from the aircraft's actual position.

52 Richard G. Davis, *Bombing the European Axis Powers: A Historical Digest of the Combined Bomber Offensive, 1939–1945* (Maxwell AFB, AL: Air University Press, 2006), pp. 29, 30.

53 Ibid., p. 30.

FIGURE 28. TYPICAL RAF BOMBER COMMAND ACCURACY, PRE-1942

By itself this news was bad enough for Bomber Command, but at about the same time the Germans began to devote significant attention to fielding defenses specifically tailored to Bomber Command's operational style. Known to the British as the Kammhuber Line after the energetic German General responsible for its creation, and as the Himmelbett (four-poster bed) system to the Germans, this consisted of a line of "boxes" about 10 nm wide and 17 nm deep eventually stretching from Denmark through the Netherlands, Belgium, and France to the Swiss border.

Each Himmelbett box contained a radio beacon and a German night fighter, which orbited while awaiting instructions from a ground control station. This station was linked to a long-range Freya early-warning radar capable of detecting and tracking British bombers up to 100 miles away. While the Freya had excellent range performance, it lacked the ability to accurately determine the bomber's altitude, so as the bomber closed to about 30 miles, the Freya "handed off" the contact to the shorter range, but much more accurate, Wurzburg target tracking radar. This radar accurately measured the range, bearing, and altitude of the bomber from the control station. Simultaneously, a second Wurzburg radar tracked the German night fighter, and the position of the bomber and fighter were projected onto a frosted glass table from below and updated in near real time by projector operators linked to the Wurzburg by phone lines. The night fighter controller then quickly computed an intercept vector for the fighter and updated this until the fighter was close enough, within about three miles, that its onboard AI radar could detect the bomber. After this, the fighter completed the intercept on its own. Each box could complete a maximum of about six intercepts per hour. Given the nature of Bomber Command operations, highly dispersed in space and time, this was usually more than adequate. Figure 29 and Figure 30 illustrate the dispersed nature of Bomber Command operations and the tightly controlled, linear Himmelbett systems developed by the Germans in response.

FIGURE 29. KAMMHUBER LINE/HIMMELBETT SYSTEM VERSUS BOMBER COMMAND, EARLY 1942

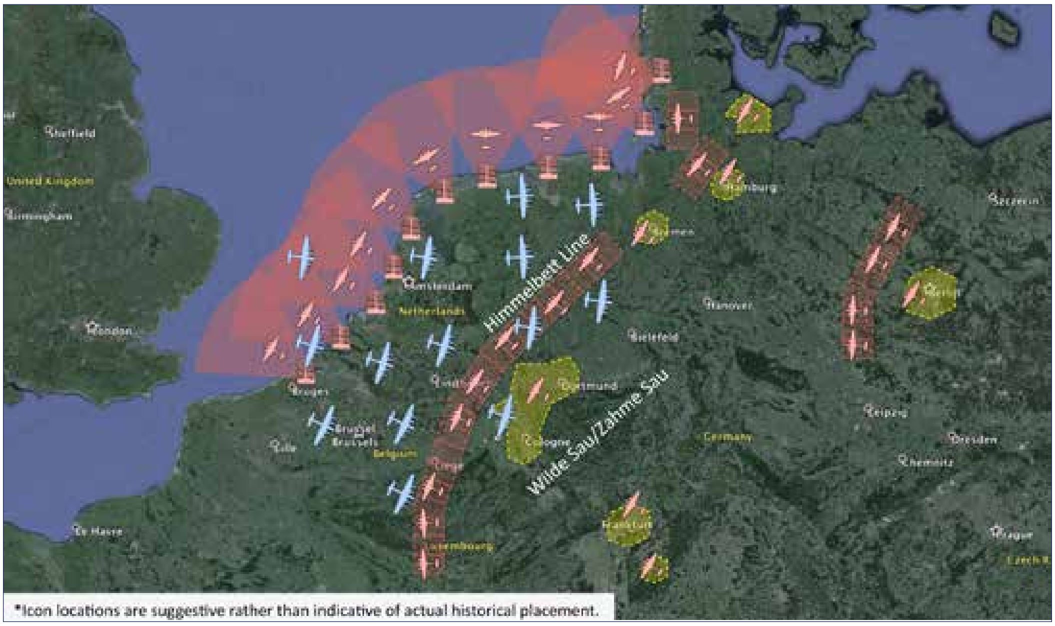


FIGURE 30. HIMMELBETT BOX INTERCEPTION CONCEPT

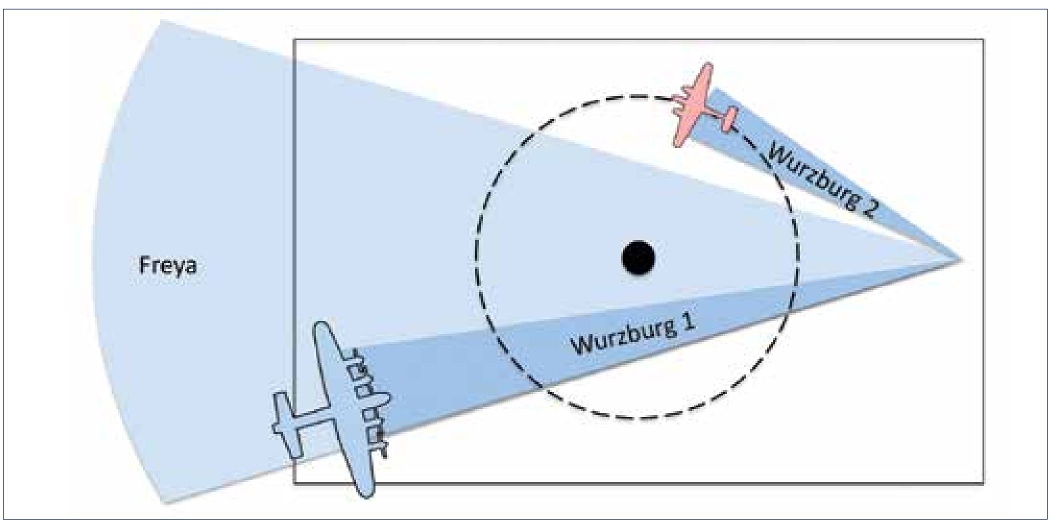
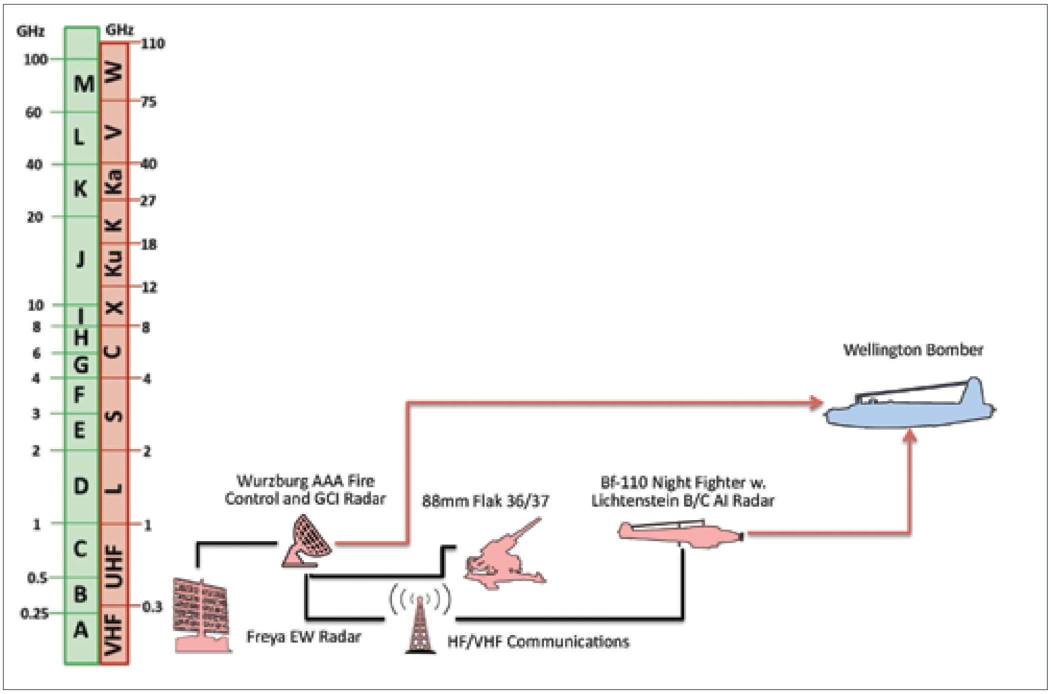


FIGURE 31. ELEMENTS OF THE NIGHT BOMBING BNC, EARLY 1942



Bomber Command's loss rate per sortie more than doubled from about 2 percent to over 4 percent between late 1941 and early 1942 as the Kamhuber Line defenses came on line and the Germans refined their interception techniques. Figure 31 depicts the elements of the BNC in early 1942. Bomber Command was approaching a crisis. Overall loss rates at night against well-defended targets in Germany were approaching the unsustainable levels experienced early in the war in daylight operations, but were much less effective. What was needed was some way to improve navigation accuracy while reducing losses to more sustainable levels. Fortunately, the RAF had been investing in a system known as GEE since mid-1940.

GEE was the first "hyperbolic radio navigation system" and worked on principles similar to the later U.S. long-range navigation LORAN system as described below:

> A receiver in an aircraft received signals from three transmitters, situated on the ground at known locations and as far apart as practicable. One acted as a master station that triggered the other two to transmit on alternate pulses from the master. These became known as slave stations. The transmission pulses were displayed on a cathode ray tube with a double timebase. The distance of the aircraft from each slave station could be measured on a scale and superimposed on the timebase. These distances could then be transferred to a grid of hyperbolic lines on the navigators' maps and the location determined by the point of interception of these lines.[54]

54 George K. Grande et al., *Canadians on Radar: Royal Canadian Air Force 1940–1945* (Canadian Radar History Project, 2000), p. XV1–5.

GEE was accurate to about 2 percent of range (e.g., about 5 statute miles at its maximum reliable range of 250 statute miles). This was sufficient to greatly improve bomber command navigational accuracy. At the same time, it gave Bomber Command mission planners the ability to concentrate bombers reliably into a "stream" by having them fly the same standard route to and from the target, while assigning "time over target" to individual units to concentrate them in time. This had the effect of "flooding a zone" along the Kammhuber line, since no matter how many bombers passed through a given box in an hour the Himmelbett system could only intercept about six per hour. By presenting many targets to just a small portion of the German night defenses over a relatively short time, defenses were saturated and bomber losses reduced. Figure 32 illustrates the significant improvement in navigation, and with it bombing, accuracy that the introduction of GEE had on Bomber Command operations.

FIGURE 32. EFFECT OF GEE ON BOMBER COMMAND NAVIGATION AND BOMBING ACCURACY

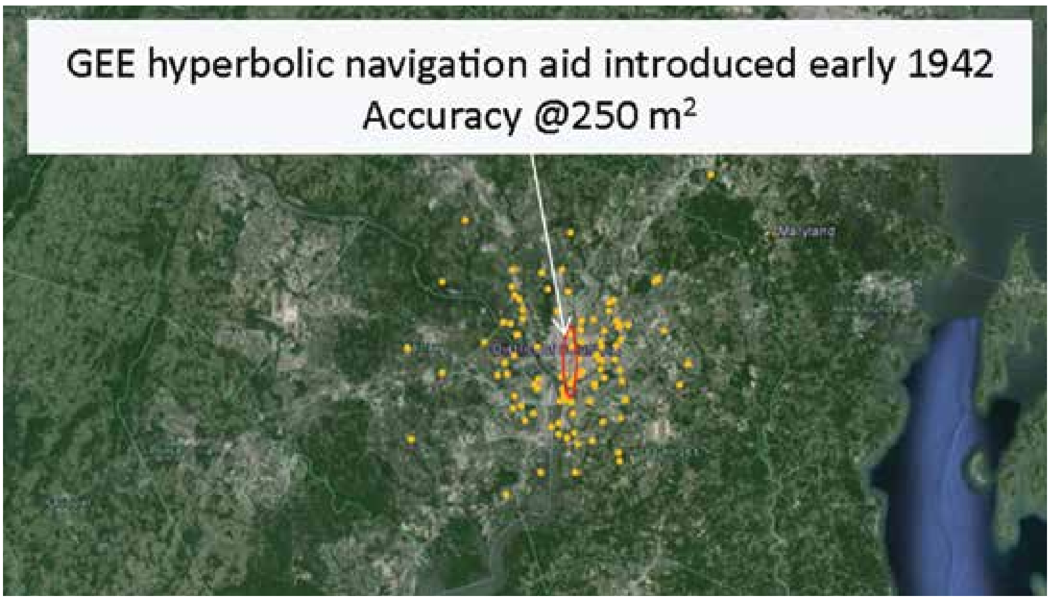


FIGURE 33. ELEMENTS OF THE NIGHT BOMBING BNC, MARCH 1942–JANUARY 1943

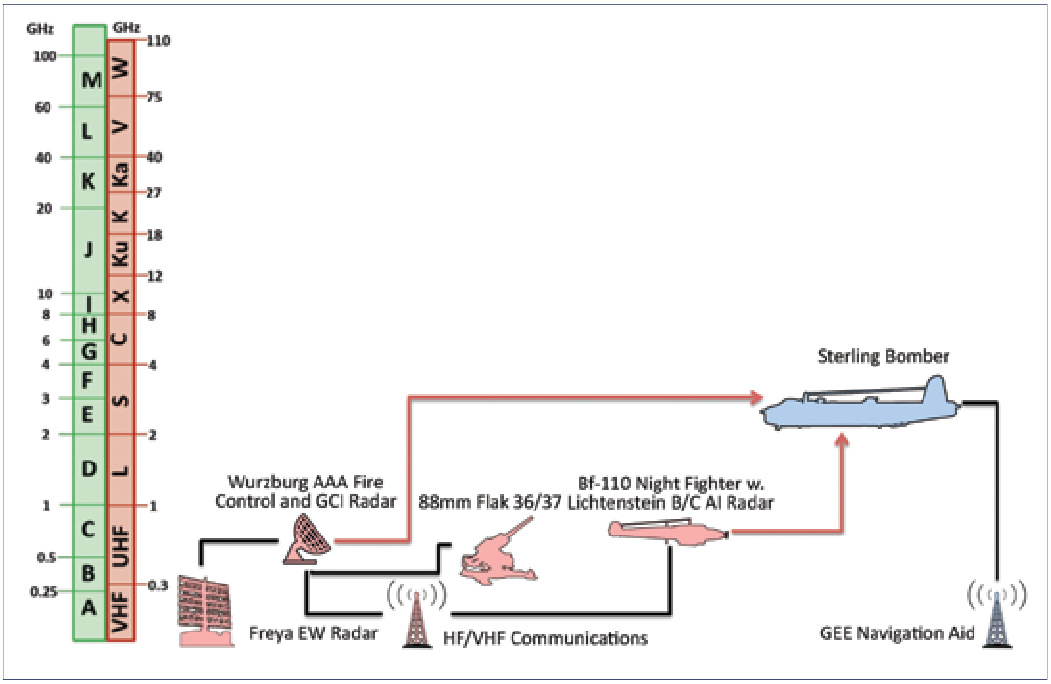


Figure 33 depicts the elements of the BNC between the introduction of GEE in March 1942 and January 1943.

Bomber Command's ability to introduce GEE in early 1942 rested on the providential decision made in June 1940 to begin developing the system. It helped substantially, but faced three challenges. The first challenge, limited range, has already been discussed. Second, it was designed as an aid to navigation rather than as an aid to "blind bombing." As Figure 32 shows, it was not really capable of supporting accurate night attacks on targets smaller than large cities. Finally, there was the certainty that once the Germans realized GEE was in use, it was only a matter of time before they began to jam it, just as the British had jammed the German radio navigation systems in 1940. The first large-scale use of GEE occurred on March 8, 1942, and by month's end the Germans had recovered an intact GEE receiver, despite the fitting of demolition charges to all GEE receivers to be activated as the radio operator abandoned a stricken aircraft. By late May 1942, the Germans understood the purpose of the receiver and had identified the ground transmissions associated with it. On August 4, 149 days after its first combat use, GEE was jammed for the first time and, by December 1, 1942, the proliferation of powerful jammers rendered GEE useless over Germany. In this case, a system that required twenty-one months to develop and deploy operationally had a total useful life of less than 270 days, or about nine months.

In July 1941, preproduction GEE sets were fitted to a few RAF Wellington bombers for operational trials. Reports from the crews from initial noncombat missions over the North Sea were encouraging, but on August 11 a GEE-equipped aircraft was lost on a mission over Germany.

This was only the fourth mission over Germany by a GEE-equipped aircraft, but it suddenly brought home to senior RAF leadership that they now found themselves in the same situation the Germans had been in with respect to the early compromise of Knickebein and X-Gerat the year before. As a result, further operational trials were stopped and it was decided to install the necessary wiring for GEE in all aircraft, but not the actual receivers until enough had been produced to equip a sufficiently large portion of the bomber fleet to achieve significant operational results during the unknown, but likely brief, useful life of the system. By March 1942, sufficient GEE receivers were on hand to equip about 30 percent of the bomber fleet and GEE-enabled operations began.[55]

At the time of the Butt Report, development of an additional electronic aid to navigation and targeting was initiated. This was the H2S radar system. It was an S-band radar using cavity magnetron technology invented in Britain in 1940, but unknown to the Germans. The cavity magnetron enabled the Allies to build high-power radio frequency devices operating initially in the S-band (3 GHz) range.[56] While the Germans could build receivers in this frequency range, they lacked the technology to build high-power transmitters for frequencies much above 500 MHz. Figure 34 shows the H2S antenna installation on a Bomber Command aircraft.

The H2S allowed specially trained crews of Bomber Command's newly formed Pathfinder Force to accurately find and mark targets for "Main Force" units. Special training in radar navigation techniques was required and even then there were limits to the types of targets that could be attacked. For example, the best candidate targets for attack using radar techniques were those that allowed the radar operators to take advantage of the fact that large bodies of water tend to reflect radar energy away from the transmitting aircraft, resulting in a "dark area" on the radar display, while cities and towns with lots of vertical surfaces and metal to reflect radar energy back to the transmitting aircraft show up as "bright areas." Forests and fields give returns of moderate intensity. Figure 35 shows a satellite image of the Zuider Zee on the left and the same image with a wartime image of an H2S radar display fit to scale on the right. The advantages of landmarks and targets with good land-water contrast are clear.

55 The GEE compromise scare resulted in an elaborate deception operation that included deliberate mislabeling of the cables installed in the bombers, slight alteration of the GEE waveform to make it resemble ordinary radar pulses, and decoy transmission of signals for a wholly fabricated system disclosed to the Germans "accidentally, on purpose" known as "JAY." See Price, *Instruments of Darkness*, pp. 99–103, for details.

56 At the center of a cavity magnetron is a cathode heated by direct current to produce a stream of electrons. The cathode is situated in a carefully shaped cavity within a block of copper, which is itself inside the magnetic field of a powerful permanent magnet. When properly calibrated and correctly sized, interaction of the electrical field within the cavity and the magnetic field of the permanent magnets results in the output of powerful radio frequency energy in the S-band or higher frequency range.

FIGURE 34. H2S S-BAND NAVIGATION AND TARGETING RADAR MOUNTED ON A HANDLEY PAGE HALIFAX BOMBER

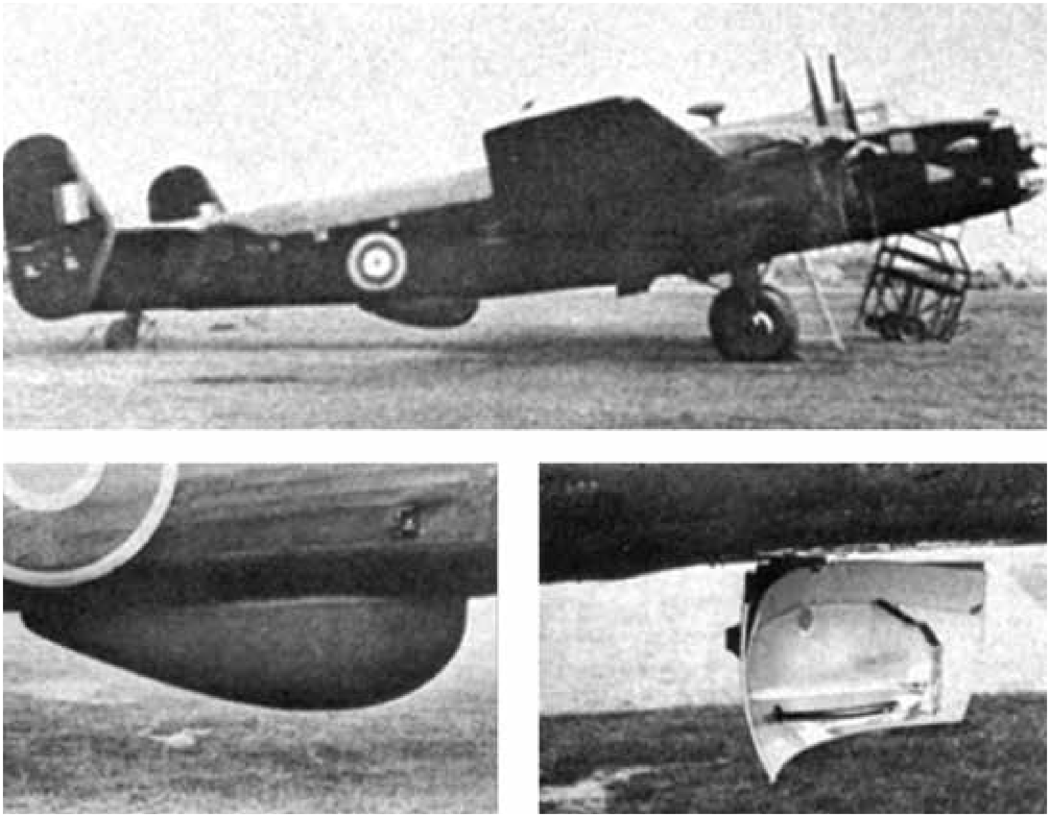


FIGURE 35. RADAR NAVIGATION WITH H2S

Despite some limitations, H2S had three important advantages over GEE. Against appropriate targets, H2S bombing was about twice as accurate as GEE. Furthermore, H2S accuracy was independent of the range from ground stations. Finally, because the Germans lacked the ability to generate high powers at S-band frequencies, they lacked the ability to jam H2S.

H2S made its operational debut on January 30, 1943, once about twenty-five bombers of the Pathfinder Force had been equipped. From Bomber Command's perspective, Murphy's Law was definitely in effect three days later when on its second combat use, one of the H2S-equipped aircraft was shot down by a German night fighter. A routine search of the wreckage immediately discovered the H2S equipment and its unique nature was obvious to Luftwaffe technicians. Just twenty days later, the head of the Luftwaffe signals service, General Wolfgang Martini, assembled a team of the best German radar experts from industry and academic institutions to assess the new equipment and begin to devise countermeasures. There was a delay when the salvaged H2S set was destroyed in a bombing raid on March 1, but additional sets were soon salvaged from other aircraft, and by late March the Germans had pieced together a working H2S and learned from prisoner interrogations that its purpose was navigation and bomb aiming.[57] British engineers estimated that, assuming they were not already working on a cavity magnetron of their own, it would require about two years for their German counterparts to replicate the device and begin fielding S-band radars of their own. This estimate turned out to be very accurate, as the Germans finally fielded an S-band radar twenty-five months after capturing the first H2S sets in April 1945. For the moment, the best the Luftwaffe could do was field airborne and ground-based receivers to detect H2S emissions to guide night fighters to the Pathfinders. These receivers began to reach combat units in September 1943, and proved quite effective.

In the meantime, debate smoldered in both Britain and Germany concerning the employment of an inexpensive and highly effective radar countermeasure. Known as "Window" to the British, "Duppel" to the Germans, and now referred to as chaff, it consisted of strips of aluminized paper about an inch wide cut to the appropriate length to act as dipole reflectors

57 Price, *Instruments of Darkness*, p. 136.

to opposing radars. Both sides had experimented with this technique in early 1942 and found that dropping strips from aircraft created numerous false returns that rapidly filled the operator's displays, effectively "jamming" them. Neither side dared deploy it because they both feared that the combination of effectiveness and simplicity would result in the rapid adoption of similar measures by the enemy. The debate finally came to an end in Britain in April 1943 when, with a new generation of AI and ground radars based on cavity magnetron technology and less susceptible to the effects of Window reaching service, Window was released for use against German radars effective May 1, 1943.[58] It took several months for the stock of Window to be built up to a level that significant operational impact could be achieved after its introduction, so it was not until July 24, 1943, that it was first used in combat by Bomber Command.[59] Window played a large role in reducing Bomber Command losses during "Operation Gomorrah," later known as the Battle of Hamburg.

For this operation, Bomber Command planned on a "maximum effort" and succeeded in putting over 740 bombers across the target areas of central Hamburg in forty-eight minutes. Each bomber crew began dropping one-pound packets of Window about 100 nm from the target and continued to drop them at one-minute intervals until about 100 nm clear of the target. Crews were briefed to maintain a tight "bomber stream" to maximize the mutual protection provided by the packets of foil. Each Window packet returned a signal to the German radars similar to a heavy bomber for about fifteen minutes before dispersing, resulting in approximately 11,000 false radar returns in addition to the 740 real ones. German radar operators noticed that most of the returns were stationary, or only moved slowly, but their sheer number made it extremely difficult to track the fast-moving returns. This threw the methodical Himmelbett fighter interception system into chaos. Few night fighters were directed toward targets, and those that were found their own Lichtenstein AI radars—operating on a similar wavelength to the Wurzburg ground control radars—also picked up the false returns. Bomber Command losses were reduced 75 percent from previous attacks on Hamburg with only 1.5 percent (twelve aircraft) failing to return.[60] Bomber Command launched two additional 700-plus bomber attacks against Hamburg over the next four days. The bombing in the second attack was unusually concentrated with over 1,500 tons of bombs falling in a two-square-mile area of the city. Combined with hot, dry, windy conditions, this created a firestorm with winds reaching 120 miles per hour and temperatures reaching 1,500 degrees Fahrenheit. Fires consumed eight square miles of the city and caused over 30,000 deaths.[61] Figure 36 illustrates the state of the night bombing BNC at the time of the Battle of Hamburg.

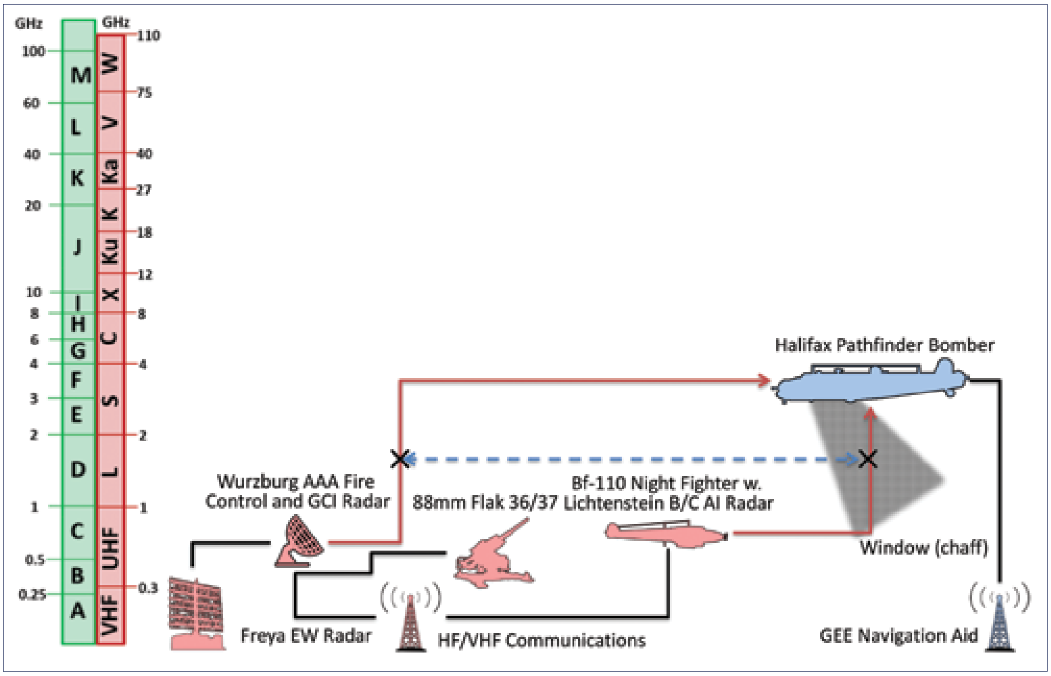
58 Ibid., p. 140.

59 Price points out that the Japanese had independently discovered the same technique and were the first to employ it against the Americans in the Solomon Islands in May 1943. Ibid., p. 142.

60 Ibid., pp. 151–58.

61 Hans Brunswig, *Feuersturm über Hamburg* (Stuttgart: Mortorbuch-Verlag, 1978), p. 195.

FIGURE 36. ELEMENTS OF THE NIGHT BOMBING BNC, JULY 1943–JANUARY 1944



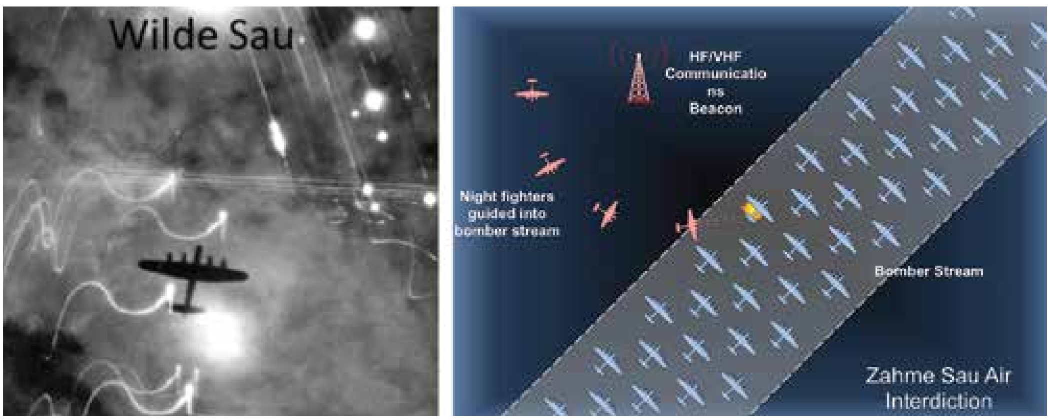
The scale of the devastation in Hamburg was by far the largest of any air attack up to that time.[62] Combined with the negation of the most effective elements of their defenses by Window, the attacks set off a crisis within the German political and military leadership. Some way of restoring the effectiveness of the night defenses was urgently needed. The response took two main forms. The first, known as *Wilde Sau* (Wild Boar) tactics, was the brainchild of a former Luftwaffe bomber pilot named Hajo Herrmann. For some time Herrmann, a major, had been concerned that the Himmelbett system was too rigid to cope with improved Bomber Command tactics such as the introduction of the bomber stream. He had worked out a system that would allow single-seat day fighters to contribute to the night battle. Searchlight crews would indicate the course and direction of the bomber stream by shining their lights horizontally along the bomber's path. Anti-aircraft gun crews in the city under attack would fire bright-colored flares to guide the day fighters to the target area. Once there the pilots would climb to high altitude and look for bombers silhouetted against the fires below, then dive to attack. The method did not require German ground radars to track individual bombers, only the location of the mass of bombers constituting the main bomber stream. The use of Window by Bomber Command actually made this task easier by making the location of the bomber stream obvious. Herrmann had been allowed to create a small experimental unit in mid-1943

62 For perspective, total civilian deaths in Britain due to air and missile attack during the entire war were just over 67,000. See Dan Alex, "World War 2 Statistics," Second World War History, available at http://www.secondworldwarhistory.com/world-war-2-statistics.asp, accessed May 27, 2014.

and this was rushed into action in time to achieve some success in the final raid in the Battle of Hamburg. Its success led to the rapid expansion of his unit.

The second response was known as *Zahme Sau* (Tame Boar) tactics. Under this scheme Luftwaffe ground controllers provided a "running commentary" on the location and track of the bomber stream, and directed night fighters into it via conventional ground-based radio beacons. Once in the stream, the night fighters could more easily sort the true returns from Window by ignoring "rapidly closing" returns (likely to be Window) and focusing on "slowly closing" returns (likely to be bombers). Furthermore, the concentration in space and time that aided the bomber stream against the Himmelbett system of defense worked against the bomber stream when confronted by Zahme Sau tactics because the high concentration of bombers greatly increased the probability a night fighter crew could acquire them visually. Figure 37 illustrates how each of the Sau tactics worked.

FIGURE 37. GERMAN TACTICAL ADAPATAION TO BOMBER COMMAND WINDOW USE[63]



These innovations restored the effectiveness of the night defenses in a remarkably short time. On August 23, 1943, less than a month after Window was introduced, German night defenses claimed 56 of 727 bombers launched to attack Berlin (7.7 percent). Of the 56 bombers lost, at least 33 were lost to fighters. Of the 33 lost to fighters, 20 or more were lost to Wilde Sau fighters over Berlin itself.

Bomber Command quickly realized that "blinding" the German night defenses with Window alone was not sufficient to defeat them. They concluded that, in addition to Window, it would be necessary to disrupt the "running commentary" of the German ground controllers. Powerful HF commercial radio transmitters in Britain were quickly modified to transmit

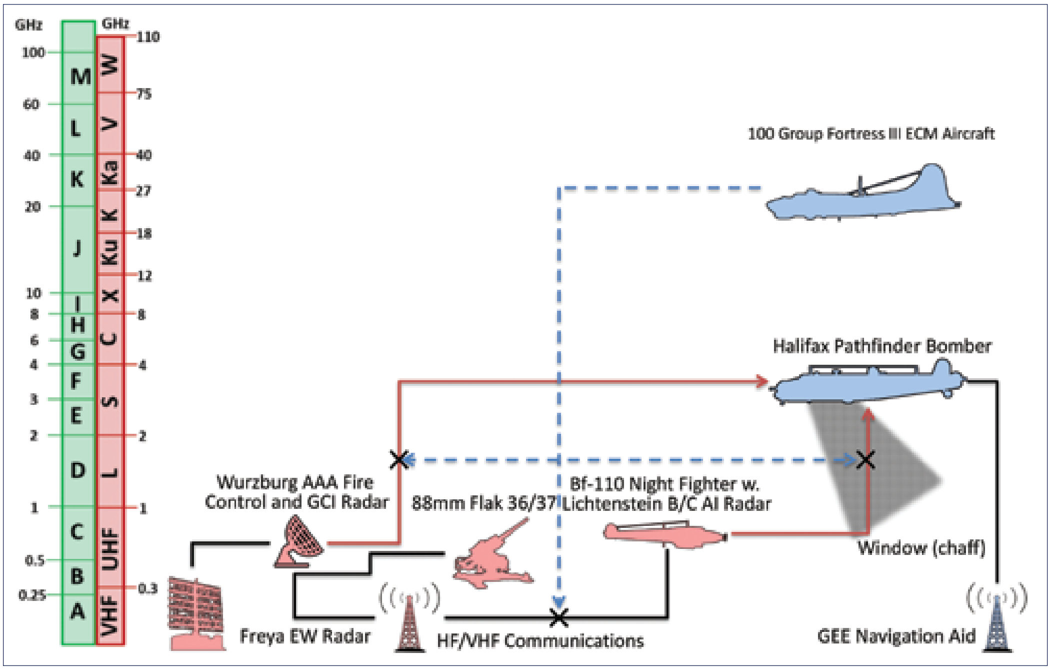
63 Zahme Sau Air Interdiction diagram based on designs in Lee Brimmicombe-Wood, *Nightfighter,* published by GMT Games, available at http://www.gmtgames.com/t-NightfightingPart5-2.aspx; Wilde Sau image is a public-domain image published by the British government.

false instructions to the German night fighters, and by late October 1943 there were occasions where the real German controllers and the "decoy" controllers in Britain exchanged insults amid their contradictory instructions to the increasingly confused and annoyed German night fighter crews.[64] In the late fall of 1943, the Germans countered this long-range communications interference by installing more, and more powerful, transmitters. This, together with the introduction of new German electronic systems, such as the Naxos-Z that allowed night fighters to home in on H2S transmissions, did much to restore the effectiveness of the night fighter force. This prompted Bomber Command to concentrate its electronic warfare activities into a single organization known as 100 Group. Formed in November 1943, by early-1944, 100 Group controlled about 250 aircraft flying missions in support of about 1,000 night bombers. All of these aircraft were modified bombers and could have taken part in the night bombing campaign in that role if they were not needed to protect the bomber force.

100 Group defeated the German night fighter defenses through the introduction of a significant numbers of "Jostle" jammers in 1944. Jostle was a 650-pound 2.5 kilowatt communications jammer targeted at the night fighter frequencies. Up to four could be accommodated in the bomb bay of the specially modified American-made B-17 bombers assigned to carry them. The B-17s flew several thousand feet above the more heavily laden aircraft in the bomber stream and were highly effective in jamming the running commentary so necessary for the "Sau" tactics. With their main sensors compromised by Window and their "low-tech" workaround jammed by Jostle, the German night fighters were rendered much less effective and Bomber Command loss rates fell rapidly. This success was achieved at considerable cost. The diversion of potential strike aircraft to enhance the survivability of others is an example of "virtual attrition." From the perspective of the German defenders, while their efforts were often frustrated by the activities of 100 Group, the existence of the German defenses created the ongoing need for the British to divert about 20 percent of their total bomber fleet from dropping bombs to providing electronic support and thus reduced the potential weight of bombs dropped by Bomber Command by about the same percentage. Figure 38 illustrates the final state of the night bomber BNC in mid-1944.

64 Price, *Instruments of Darkness,* pp. 183–84.

FIGURE 38. ELEMENTS OF THE NIGHT BOMBING BNC, 1944



Early in World War II, intensive British efforts to field countermeasures to German night navigation and bombing systems dramatically shortened their useful lives and greatly decreased the effectiveness of German night bombing attacks during late 1940 and early 1941. The German invasion of the Soviet Union in June 1941 required nearly the full resources of the Luftwaffe and brought an end to large-scale bombing of Britain for almost eighteen months. With no other effective way to strike directly at Germany, Britain devoted substantial resources to Bomber Command from early in the war. About 125,000 men served as aircrew in Bomber Command during World War II. British Air Ministry records indicate 47,268 (38 percent) were killed in action, over 9,800 (8 percent) were captured, and 4,200 (3.5 percent) were wounded in action, but returned to duty. Almost 8,200 were killed in flying accidents and an additional 4,200 wounded in accidents. Overall, almost 74,000 (59 percent) of Bomber Command aircrew were killed, injured, or captured during the course of the war.[65] Most of the losses occurred during the period of intense EM BNC from early 1942 to early 1944 explored in this section. Figure 39 shows the dramatic increase in the probability of completing a standard Bomber Command tour of thirty missions from late 1943 to mid-1944. Over a six-month period, the chances of surviving a tour increased from about 20 percent to about 80 percent, largely due to the defeat of German radar and communication systems through the introduction of various navigation aids, electronic countermeasures (ECM), and dedicated electronic warfare units by Bomber Command.

65 Martin Middlebrook and Chris Everitt, *The Bomber Command War Diaries: An Operational Reference Book, 1939–1945* (Leicester, UK: Midland Publishing, 1998), p. 708.

FIGURE 39. NIGHT BOMBING BNC DISCOVERY TO FIRST COUNTERMEASURE

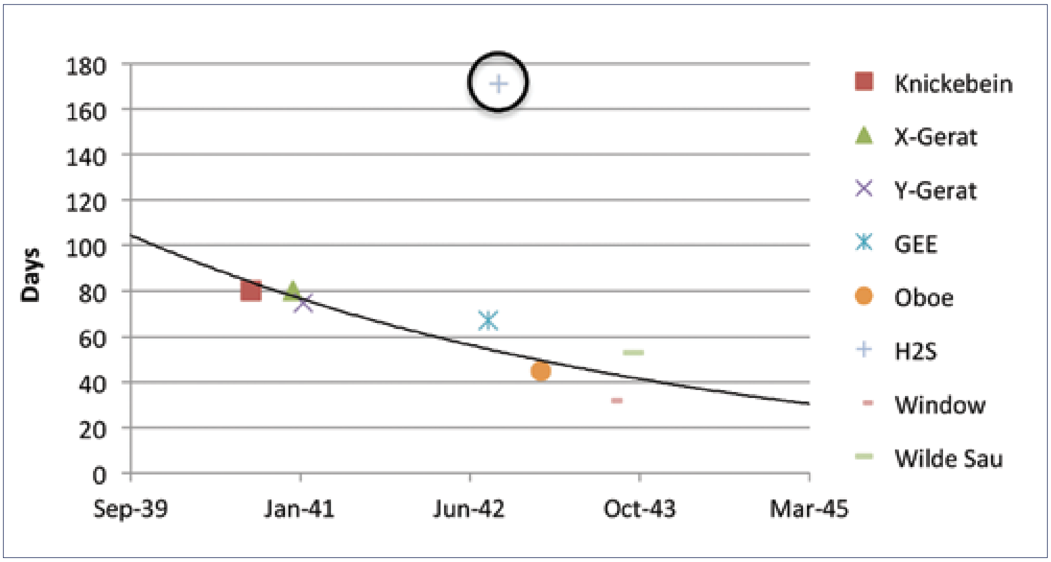


Figure 39 shows how the time from discovery of a system by the opponent to the fielding of the first countermeasure generally declined as the war progressed. On average, the time from the introduction of a new electronic system to the debut of a countermeasure decreased from almost three months early in the war to about forty-five days by the beginning of 1944. The exception to this trend was the British introduction of cavity magnetron radar technology. From the German perspective, S-band radars represented an "out of band" innovation that took considerable time and resources to counter. The next section of this chapter will turn to an examination of the Cold War air attack versus IADS BNC with special attention paid to the long-running battle between U.S. Air Force (USAF) and U.S. Navy (USN) aircraft and Vietnamese air defenses during Operation Rolling Thunder from 1965 through 1968.

The Cold War: The Active Electromagnetic Competition Culminates

The electronic warfare systems fielded under intense pressure and at great cost during World War II fell into neglect almost immediately once the war was over. There seemed little need for them in the U.S. military until the Soviet air threat became apparent in the late 1940s, and even then Soviet radar technology was fairly rudimentary compared to late-war German systems.[66] The unexpected war in Korea provided a brief resurgence of interest in electronic warfare as USAF B-29 bombers repeated the pattern of British and German air forces of a decade earlier by initially abandoning daylight operations in the face of MiG-15 interceptors operating from "sanctuary" in China. At first, the move to night operations was effective in cutting losses, but eventually the North Koreans and their Chinese allies fielded a growing collection of World War II-era radars, searchlights, heavy anti-aircraft guns, and an increasingly effective night

66 Price, *Instruments of Darkness*, p. 251.

interceptor force. This led, by mid-1952, to the refurbishment and use of World War II-era ECM equipment by USAF B-29s. Against the "leftover" World War II radars, these measures were adequate and limited losses to acceptable levels. The next large, sustained air war did not take place for twelve years.

Vietnam: Operation Rolling Thunder, 1965–1968

Operation Rolling Thunder was a sustained bombing campaign against targets in North Vietnam conducted primarily by the USAF and USN. It was initially intended to gradually put pressure on the North Vietnamese regime to stop its support for communist insurgents in South Vietnam, cease infiltrating North Vietnamese Army forces into South Vietnam, and raise the morale of South Vietnamese forces. Over time these objectives were joined by others, including those focused on disrupting North Vietnamese transportation systems, industrial production, and air defense networks, as well as interdicting the flow of supplies and reinforcements into South Vietnam.[67]

CSBA assembled a database of Operation Rolling Thunder sorties, losses, and significant BNC innovations from a wide range of sources. Many of these are government documents declassified over the past decade, while others are drawn from academic works or analytic studies.[68] From these sources, we calculate that the USAF, USN, and U.S. Marine Corps (USMC) flew approximately 464,000 sorties over North Vietnam between the beginning of Operation Rolling Thunder in March 1965 and its end on November 1, 1968. About 295,000 (63 percent) of these sorties were strike sorties intended to drop bombs on targets in North Vietnam. The remaining sorties were reconnaissance, fighter escort/fighter CAP, Suppression of Enemy Air Defenses (SEAD), electronic warfare, or other sorties intended to reduce strike aircraft attrition by degrading or destroying the North Vietnamese IADS. Figure 40 presents significant aspects of the Rolling Thunder BNC.

67 Chris Hobson, *Vietnam Air Losses: United States Air Force, Navy, and Marine Corps Fixed-Wing Aircraft Losses in Southeast Asia 1961–1973*, (North Branch, MN: Specialty Press, 2001), p. 15.

68 To our knowledge, no single source for Operation Rolling Thunder statistics and data exists. The two most useful data sources were Thayer, *A Systems Analysis View of the Vietnam War*; OASD, Southeast Asia Programs Division, *Southeast Asia Analysis Report* (Washington, DC: DoD, 1967); and a series of reports on Operation Rolling Thunder published by Headquarters, Pacific Air Forces, Directorate for Tactical Evaluation under the umbrella of Project Contemporary Historical Evaluation of Combat Operations (CHECO). All of these documents and other "Project CHECO" reports, particularly the series on USAF Tactics Against Air and Ground Defenses in Southeast Asia, were used to compile the database for this section and are available for download from the Defense Technical Information Center (DTIC) website at http://www.dtic.mil/dtic/, accessed May 28, 2014.

FIGURE 40. QUANTITATIVE DEPICTION OF THE OPERATION ROLLING THUNDER BNC

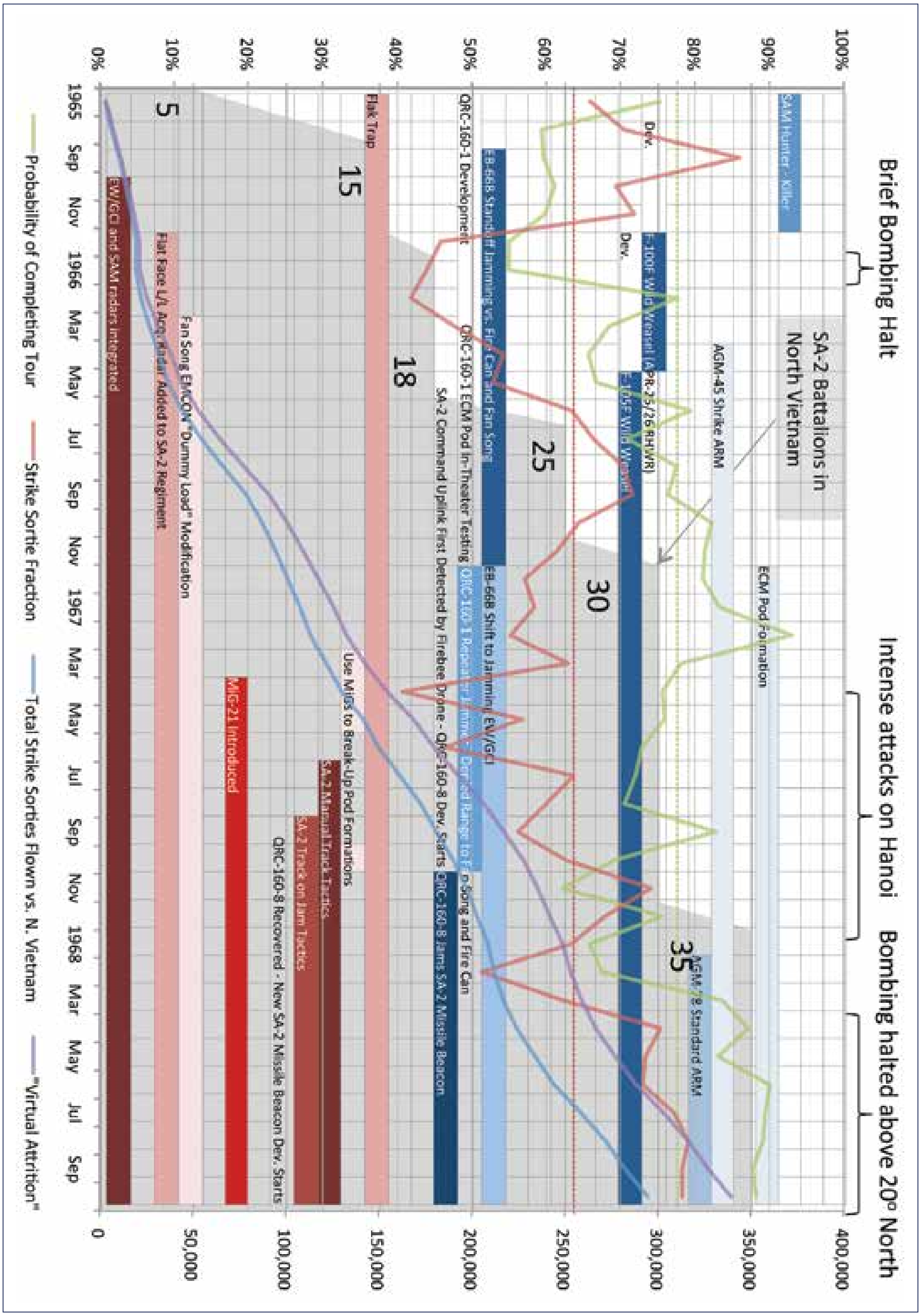


Figure 40 is similar to the quantitative overviews presented earlier in this section, but has a few unique elements. First, the addition of several notations near the top of the figure show several intervals where President Lyndon Johnson ordered bombing halts or imposed severe restrictions on bombing operations over North Vietnam. Second, the basis for the "probability of completing tour" line reflects a typical USAF combat tour of a hundred missions over North Vietnam. Third, the "strike sortie fraction" line that tracks changes in the level of support sorties required to maintain strike aircraft losses at reasonable levels. The purple "virtual attrition" line tracks the cumulative number of strike sorties that fighter-bombers performing support missions could have flown if their efforts were not required to reduce strike aircraft attrition. This is similar to the "tax" Bomber Command paid late in World War II by fielding 100 Group as a dedicated electronic warfare formation rather than as bombers. Finally, the gray "stair-step" in the chart background tracks U.S. estimates of the number of Soviet-made SA-2 Guideline surface-to-air missile (SAM) firing units in use in North Vietnam.

The influence of the SA-2 on Rolling Thunder air operations is difficult to overstate. While the SA-2 was not the cause of most U.S. aircraft losses—anti-aircraft artillery, or AAA, was—the presence of the SA-2 indirectly contributed to many AAA losses. This occurred because U.S. aircraft operating in areas with known SA-2 locations often took advantage of the SA-2's inability to engage targets at low altitudes to defeat it. Unfortunately, this tactic put the U.S. aircraft in the very heart of the AAA engagement envelope and led to many more losses to AAA than otherwise would have been the case. Table 5 summarizes U.S. aircraft losses during Rolling Thunder by cause.

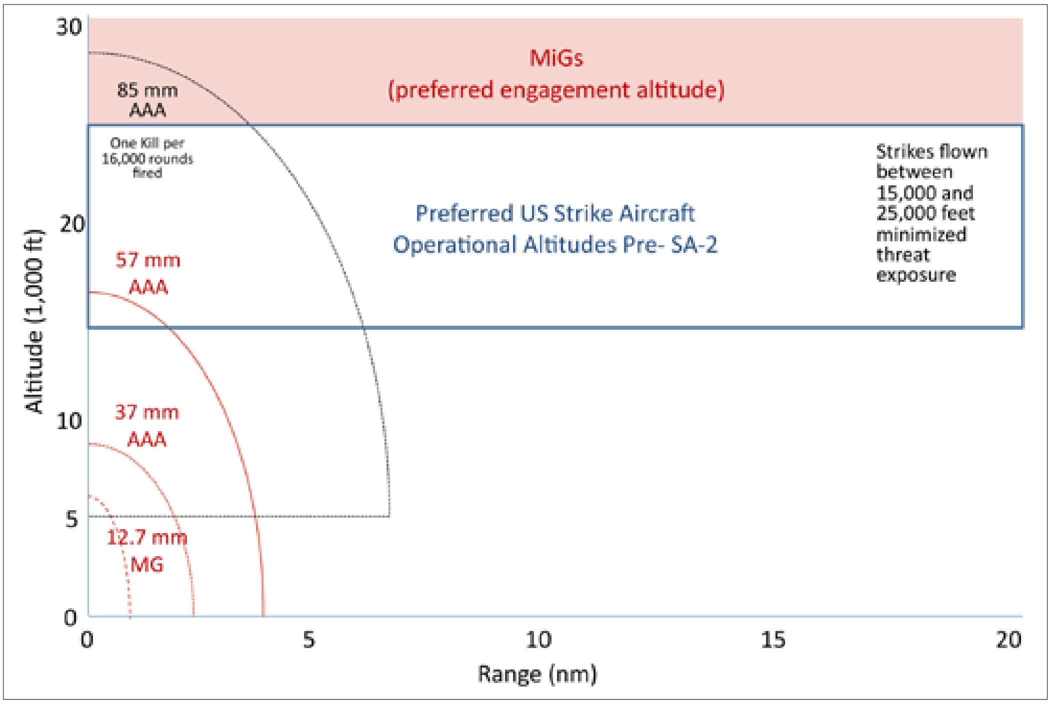
TABLE 5. U.S. FIXED-WING AIRCRAFT LOSSES DURING OPERATION ROLLING THUNDER

Cause	Number	Percentage
SAM	109	14%
AAA	457	57%
AI	48	6%
Unknown	169	21%
Other	22	2%
Total	805	100%

To understand why this happened, it is necessary to describe in some detail why the SA-2 represented such a radical shift in the competition. Use of the SA-2 in North Vietnam was the first instance of sustained, large-scale employment of a precision-guided air defense weapon system. Ground-based air defenses are as old as air warfare, and aircrew expected to be engaged by them. Experience in World War II and Korea, however, indicated that defenses had to fire about 16,000 large-caliber anti-aircraft gun rounds to bring down an attacking aircraft. This surprisingly large number is the result of the delay between the time a gun fires at an aircraft and the time the shell arrives. For example, if a gun fired a shell with an average velocity of 3,000 feet per second at an aircraft flying directly overhead at 18,000 feet, it would require six seconds for the shell to arrive. A World War II-era bomber cruising at 160 knots traveled about 1,600 feet during the six second time of flight of the shell, so the gunner had to aim about 1,600 feet in front of the bomber in order to achieve a hit. Even if the gunner had an analog computer receiving information on the aircraft's current course, speed, and altitude, the best he could do was place a shell where the aircraft would be *if it did not change course, speed, or altitude during the time of flight*. Aircrews knew this as well as the gunners. Therefore, when within AAA range, they varied course, speed, and altitude continuously, except for the relatively brief period during bomb delivery. U.S. strike aircraft of the Vietnam era cruised at about 480 knots, requiring gunners to lead them by almost a mile to achieve a hit when flying at 18,000 feet. The higher the aircraft flew, the longer the shell's time of flight, the farther the aircraft could be from the predicted point of aim, and the harder the gunner's task became. Conversely, the lower the aircraft flew, the shorter the time of flight and the easier the gunner's task.

The best available estimates are that the North Vietnamese IADS launched over 5,200 SA-2s during Rolling Thunder to bring down 109 U.S. aircraft. This produced an overall single-shot probability of kill (Pk) of just 2.1 percent. This equated to forty-eight SAMs launched for each aircraft brought down. While this does not sound very impressive, understand that each SA-2 launched was over 300 times more likely to bring down an aircraft than an AAA shell. Early in the Rolling Thunder BNC, before the U.S. fielded effective countermeasures, the SA-2's Pk was about 10 percent, with an average of one aircraft lost for every ten SAMs fired. This is a huge improvement over the 16,000 AAA shells required per aircraft shot down. Hence, at the time it was introduced into the campaign, one SA-2 was as likely to bring down a U.S. aircraft as about 1,600 AAA shells. Furthermore, because it was guided and had a much longer range than even the largest AAA weapons, modest weaving by the targeted aircraft was insufficient to prevent a hit. Worse still, flying higher did not decrease the accuracy of the SAM as it did AAA. Overall, the SA-2 confronted U.S. aircrew with a ground-based defensive system with longer range and higher ceiling that proved over a thousand times more effective per shot than traditional AAA systems.

FIGURE 41. VIETNAM IADS BNC BEFORE INTRODUCTION OF SA-2 IN JULY 1965



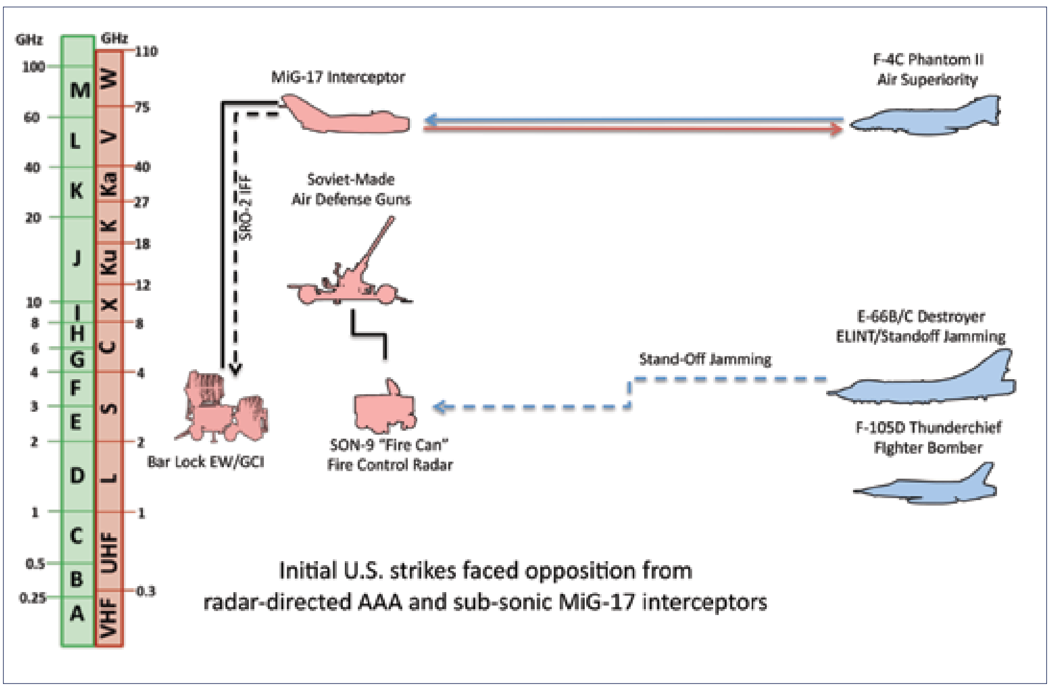


Figure 41 illustrates the initial characteristics of the Vietnam competition. The diagram on the left shows the effective engagement envelope of various AAA systems in use in North Vietnam at the time as well as the "higher-altitude" band where North Vietnamese MiG fighters preferred to engage U.S. strike aircraft.[69] The initial U.S. approach to dealing with the North Vietnamese IADS was to have "strike packages" fly at medium altitude to avoid the worst of the AAA threat. These would be escorted by F-4 Phantom II air superiority fighters to counter any MiGs that might try to intervene. The strike package was supported by EB-66 "standoff jamming" aircraft operating beyond the effective reach of the IADS. They were assigned to jam AAA fire-control radars in the designated target area. Strike aircraft had to enter the effective engagement envelope of AAA systems assigned to protect their targets, but the combination of short exposure times (generally about one minute or less) and EB-66 jamming was sufficient to keep losses to tolerable levels. The diagram on the right provides an illustration of this early state of the competition.

The SA-2 had some significant limitations. Like all "first-generation" SAMs and air-to-air missiles, the SA-2 was designed in the mid-1950s with the objective of destroying large, nuclear-armed strategic bombers at high altitude (30,000 feet or more) as far from their targets as possible. With this "design mission," it is not surprising that the V-750, code named Guideline by NATO, missile of the SA-2 was optimized to operate at high speed over long ranges and carry a large, 300-pound or more, warhead. Only modest missile maneuverability was required, making it possible for more agile fighters to outmaneuver the missile if they could see it in time. This was usually effective, but if U.S. aircraft were flying above overcast skies or inside clouds, or were attacked by multiple missiles from different directions, the Guideline could still be deadly.[70]

In addition to poor Guideline maneuverability, another weakness of the SA-2 system was that its engagement radar, code named Fan Song by NATO, was unable to detect and track targets operating less than about 3,000 feet above ground level (AGL). This opened another possible tactic to defeat the system: low-altitude ingress and attack. After the first U.S. aircraft was lost to an SA-2 on July 24, 1965, both the USAF and USN initially attempted to deal with the SA-2 menace by aggressively seeking out and destroying the limited number of Fan Song radars and their associated missile launchers. On July 28, the USAF launched a low-altitude, 50–100-foot AGL, fifty-four-aircraft strike against two of the eighteen known SA-2 sites suspected of shooting down the USAF F-4C lost on July 24th. Neither of the sites attacked housed an active SA-2 battery. Instead, they were decoy sites heavily protected by AAA intended to lure U.S. aircraft into just such an attack. Six of the fifty-four attacking aircraft (11 percent) were shot down by AAA. Two days after losing its first aircraft to an SA-2 on August 12, the USN launched a

69 In general, the heavier and faster U.S. fighters had advantages over the smaller and lighter MiGs at higher speeds and lower altitudes, while the lighter, tight-turning MiGs had advantages at lower speeds and higher altitudes. The MiGs could attack at any altitude, but operating at higher altitude made the most of the relative advantages of their aircraft. For more on the relative merits of U.S. and North Vietnamese fighter aircraft, see Marshal L. Michel III, *Clashes: Air Combat Over North Vietnam 1965–1972* (Annapolis, MD: Naval Institute Press, 1997), Chapter One.

70 Price, *History of US Electronic Warfare,* pp. 54–56.

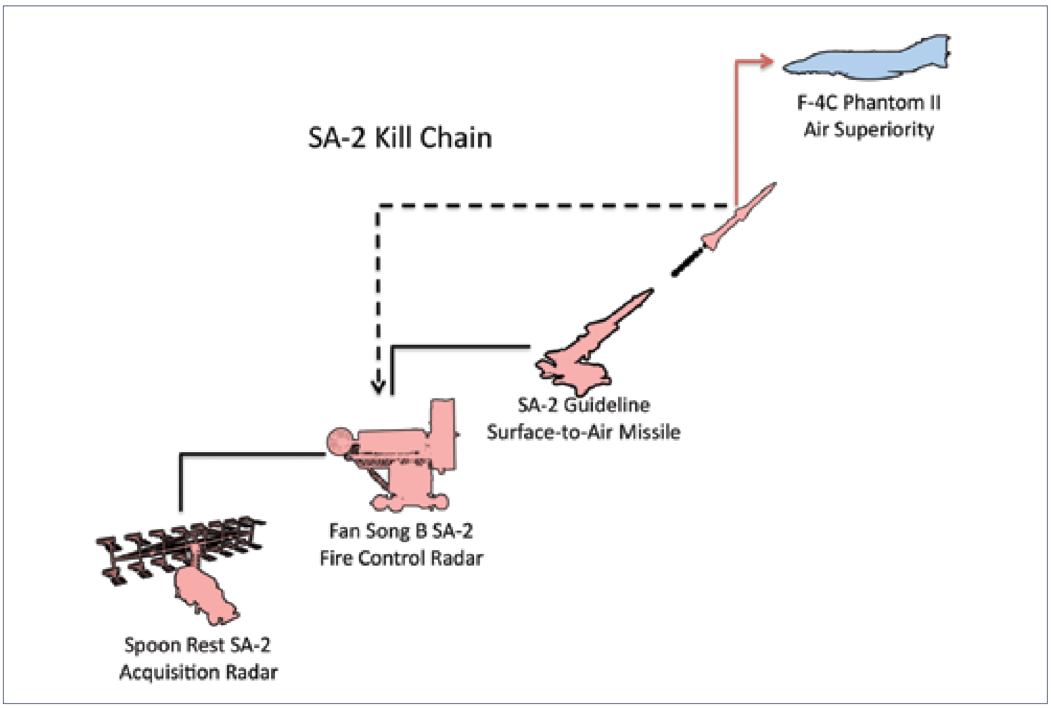
similar effort to find and destroy the SA-2 site and sustained heavy losses without damaging the SAM.

Offensive efforts to destroy SA-2 sites were problematic because the system was designed to be transportable. While not truly mobile in the sense that it could fire a missile and be on the move within minutes to another site, the SA-2 could be packed up and moved within a matter of several hours. Generally the SA-2 was positioned in a distinctive “Star of David” arrangement with the Fan Song radar in the center of the site and the six missile launchers positioned in the “points” of the star, as shown in Figure 42.

FIGURE 42. TYPICAL SA-2 SITE CONFIGURATION

The North Vietnamese constructed several alternative sites for each operational SA-2 battery. When unoccupied by real units, these were often filled with decoy missiles and radars and guarded by AAA in hopes of attracting U.S. attacks. This tactic, known to U.S. aircrews as a “Flak Trap,” was used from the outset of SA-2 employment. The USAF and USN needed to devise more effective countermeasures to the SA-2. This required analysis of how the system worked to identify potential vulnerabilities. An SA-2 battery was a miniature battle network or “kill chain.” Targets were initially detected and tracked by long-range early-warning radars such as the P-12, code named Spoon Rest by NATO, very high frequency (VHF) system. The Spoon Rest had a range of about 135 nm, but could not accurately determine target altitude and lacked the resolution to provide accurate guidance to the Guideline missiles. Instead, it passed target information to the Fan Song engagement radar. The Fan Song was both the eyes and brain of the SA-2. It transmitted two fan-shaped beams. One beam scanned vertically and the other horizontally. Together they could continuously scan a 10-degree-by-10-degree portion of the sky and track any target within that area. The sky from the horizon to zenith contains hundreds of 10-by-10-degree sectors, so the Fan Song crew needed an accurate cue from the Spoon Rest or some other source to help them know where to point the Fan Song to acquire a target. Once a target was acquired, the Fan Song tracked it for a short time to determine an accurate track and allow the integrated analog fire-control computer to calculate an intercept point. If the intercept point was within the maximum range of the Guideline, a missile, usually two, could be launched. At the time the SA-2 was designed, computing power was heavy, bulky, and expensive. Therefore, all calculations to complete the SAM intercept occurred on the ground. Updating the intercept calculations required an accurate track of both the target and the missile. The Fan Song tracked the target, but the missile was tracked via a beacon system that responded to pulses from the Fan Song with coded replies. As the aircraft and missile maneuvered, the computer continuously updated the intercept point and transmitted guidance commands to a receiver on the missile whose autopilot then executed the instructions.[71] Figure 43 illustrates the usual SA-2 kill chain.

FIGURE 43. SA-2 "KILL CHAIN"



71 Ibid., pp. 33–35.

There were several points in this chain that could be attacked effectively in various ways by the right systems. Initially, the United States shifted EB-66 jamming priority from AAA radars to the Fan Song. This was relatively ineffective because the vulnerable EB-66s were obliged to remain well outside the reach of the IADS and had only limited jamming power available. Jamming the Spoon Rest was possible in theory, but the SA-2 batteries were fully integrated into the North Vietnamese IADS network by October 1965. This allowed Fan Song operators to use target track data from any of the dozens of early-warning radars in North Vietnam rather than their own Spoon Rests alone.

By early 1966, the USAF had a small force of F-100F Super Sabre fighter bombers modified with a Radar Homing and Warning Receiver (RHWR) and equipped to fire AGM-45 Shrike Anti-Radiation Missiles. The F-100Fs, code named Wild Weasels, were dedicated to seeking out and destroying SA-2 sites. The RHWR system allowed them to find and localize active SA-2 sites if their Fan Song radars were transmitting. They would then close on the SA-2 site at low altitude to avoid detection and launch a Shrike. The Shrike automatically homed on the Fan Song transmissions, and, if all went as advertised, struck the Fan Song and damaged or destroyed it with its 147-pound blast-fragmentation warhead.[72] Unfortunately, things often did not go as advertised. Shrike launch parameters were restrictive. Its seeker had only a 4-degree field of view, so it had to be launched on a heading within plus or minus 2 degrees of the actual target bearing or it would not "see" the Fan Song and would fail to guide. In addition, Shrike's maximum range was significantly less than the SA-2, so Wild Weasel crews had to close on the site at low altitude where they were highly vulnerable to the ever-present AAA guarding the SAM sites. One Shrike weakness that cut both ways was that the Shrike needed a continuous target signal to guide on. If the Fan Song crew turned their radar off after detecting the Shrike, the Shrike would "go stupid" and miss the target. This allowed the Fan Song crew to avoid damage or destruction, but it also prevented them from engaging U.S. strike aircraft while their radar was off. This was a significant limitation because the vacuum tube electronics of the Fan Song required about a minute to "warm up" before they reached their operating temperature. Therefore, even if a Shrike shot did not hit a Fan Song, it could suppress the SA-2 site long enough for a strike package to attack its target and egress the area.

SA-2 crews rapidly improvised a partial solution to the RHWR and Shrike challenge by modifying maintenance equipment to allow them to keep their Fan Songs fully powered, but not radiating by diverting transmissions into a "dummy load" until just prior to acquiring a target and firing missiles. This greatly reduced the amount of time available for Wild Weasel crews to locate a site and fire a Shrike. Both sides in the competition built up capacity throughout much of 1966 with the number of SA-2 batteries active in North Vietnam growing from fifteen at the end of 1965 to thirty by the end of 1966. On the U.S. side, the USAF introduced larger numbers of Wild Weasels by equipping a number of F-105F two-seat trainers with RHWR and

72 "AGM-45 'Shrike' Anti-Radiation Missile Fact Sheet," U.S. Air Force, available at http://www.hill.af.mil/library/factsheets/factsheet.asp?id=5797, accessed May 29, 2014.

Shrike capability. These could better keep up with the F-105 strike packages compared to the older and slower F-100s.

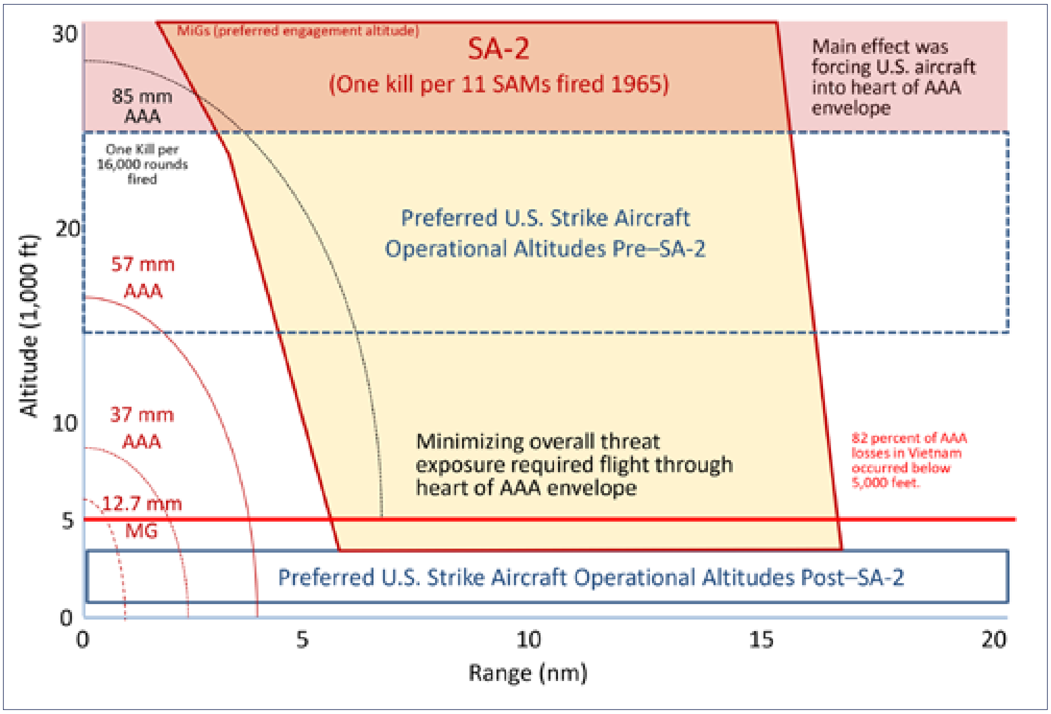
In late 1966, the USAF introduced the QRC-160-1 ECM pod for use by its F-105 strike aircraft. By the early 1960s, advances in miniaturizing electronics allowed engineers to contemplate adding ECM to fighter bombers for the first time. Previously, only bombers had sufficient space, payload, and power to accommodate ECM systems. One of the first of these was the QRC-160. Each pod weighed several hundred pounds and contained four 100-Watt S-band jammers. When first introduced the pods radiated amplitude-modulated noise on Fan Song frequencies to deny the radar range information. With each jammer transmitting only 100 Watts, about 400 Watts per pod, effectiveness was marginal against the 600 kilowatt Fan Song, but if operated by four or more aircraft in a carefully spaced "pod" formation, the effect was dramatic.

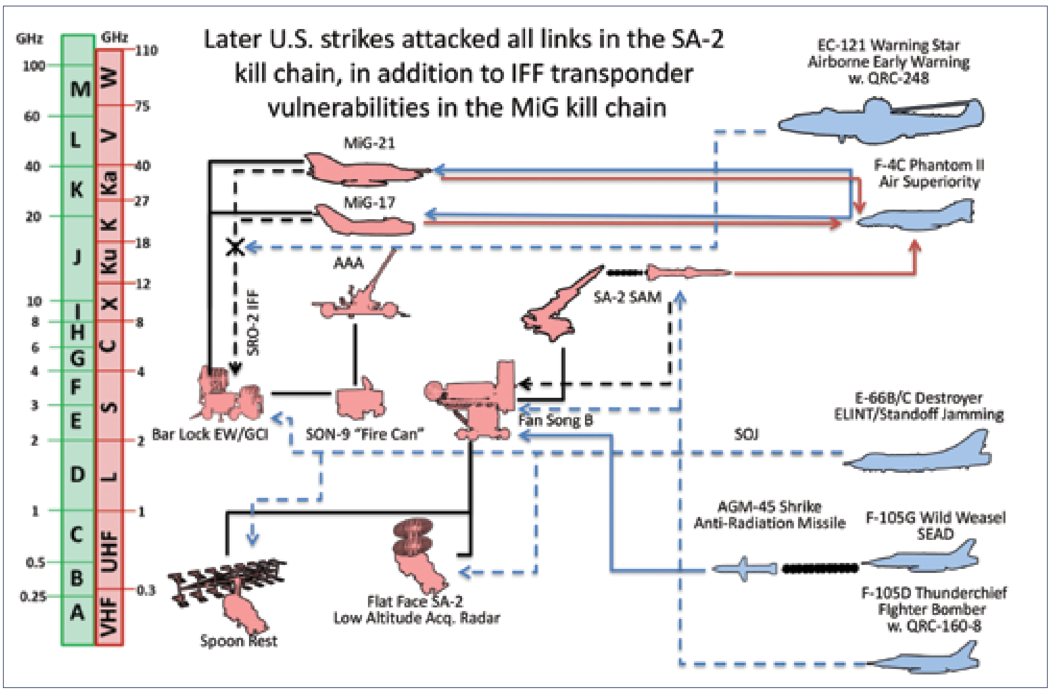
Figure 40 shows a rapid increase in the probability of completing a tour in early 1967 coinciding with the widespread introduction of the QRC-160-1. Aircraft flying in the relatively ridged "pod formation" were much less vulnerable to SAMs and it was again possible to fly most missions at medium altitude, greatly reducing AAA effectiveness. This greatly eased navigation challenges compared to low-altitude ingress against heavily defended targets and increased bombing accuracy by giving pilots more time to identify and line up on the target compared to rapidly executed "pop-up" maneuvers used to attack from low level.[73] The pod formation, however, made the strike aircraft vulnerable to MiG attack. The North Vietnamese rapidly recognized this and responded to the QRC-160-1 with a sustained series of intense fighter operations. These initially inflicted increased losses on U.S. strike aircraft, with a record nine U.S. aircraft lost to North Vietnamese fighters in April 1967. The North Vietnamese fighter force, however, suffered heavily as well and by June was unable to sustain high-tempo operations due to excessive losses to U.S. fighter escorts.

Meanwhile, SA-2 crews were developing new tactics to overcome the QRC-160-1. These included reliance on highly trained operators to manually track targets rather than employing automatic tracking, beginning in July 1967, and introducing a new "home on jam" mode. U.S. losses to SAMs increased from just two in June to eleven in November 1967. Fortunately for U.S. aircrews, a new version of the QRC-160 pod, the Dash 8 ("-8"), was entering service. Rather than targeting the Fan Song target tracking radar, the -8 jammed the missile beacon. This was made possible when, after years of searching, the United States finally succeeded in identifying the beacon frequency in early 1966. Jamming the missile beacon was a "knockout blow" to the SA-2. Without accurate information on missile position, the Fan Song transmitted faulty guidance commands to the missile. This not only caused the missiles to miss their targets, but it usually resulted in missiles crashing within seconds of the start of command guidance. Losses to SAMs fell immediately to just two in December 1967 and four each

73 John C. Pratt, *Project CHECO Southeast Asia Report: Air Tactics Against NVN Air/Ground Defenses, December 1966–November 1969* (Hickam AFB, HI: Pacific Air Forces, 1967), p. 50.

FIGURE 44. VIETNAM IADS BNC, EARLY 1968





in January and February 1968. In March 1968, President Johnson ordered a halt to bombing of most of North Vietnam including the most heavily defended areas near Hanoi. This put an end to the intensive Rolling Thunder BNC, and it was almost four years before intensive air operations against North Vietnam were resumed. Figure 44 shows the dramatic changes in the Rolling Thunder competition that occurred between 1965 and 1968. It also illustrates the significant investment the United States made in specialized support systems—most of them directed at disrupting one or more parts of the SA-2 kill chain.

Before moving on, it is important to reconsider the overall results of the Rolling Thunder BNC. The USAF, USN, and USMC delivered over 700,000 tons of bombs to targets inside North Vietnam. This caused considerable disruption to North Vietnamese industry, transportation systems, and other damage, but did not stop their ability to provide sufficient support to prevent the defeat of Viet Cong and North Vietnamese Army forces waging war against South Vietnam and its allies. North Vietnamese air defenses shot down over 800 U.S. aircraft. By forcing the U.S. to devote ever-larger portions of its air effort to support versus strike sorties, the defenses diverted an estimated 44,700 fighter-bomber sorties away from bomb delivery and into supporting tasks such as fighter escort and SEAD.[74] Over the course of Rolling Thunder, the average strike sortie delivered about 2.8 tons of bombs, so the "virtual attrition" prevented the delivery of an estimated 126,000 tons of additional bombs against targets in the North. Taking into account reduced bombing accuracy due to efforts to evade defenses, it is reasonable to believe that the North Vietnamese air defenses reduced the overall effectiveness of Rolling Thunder by 25 percent or more.

The 1972–73 Experience: Linebacker II, the Yom Kippur War, and the Search for a New Approach

The trend toward higher support-to-strike aircraft ratios that began in World War II continued when U.S. bombing of heavily defended areas of North Vietnam resumed in 1972. These operations culminated in an eleven-day intensive bombing campaign against targets in the Hanoi region during December 1972. Known as Operation Linebacker II, the goal of the operation was to bring about agreement between North Vietnam, South Vietnam, and the United States on terms of a ceasefire agreement that would allow the eventual end of U.S. involvement in the Vietnam War. The bombing was designed to put pressure on Hanoi to accept the offered terms and reassure the South Vietnamese that the United States would come to their aid if Hanoi did not abide by the agreement. For the first time, the United States employed B-52 heavy bombers in attacks against heavily defended North Vietnamese targets. Over the course of eleven days (from December 18–29, 1972, with a one-day pause on Christmas day), an initial force of 206 B-52s flew almost 750 missions and dropped 15,000 tons of bombs on

74 This calculation assumes a "baseline level" of fighter escort and SEAD support similar to levels used during the "bombing pauses" would have been provided had the defenses been less effective as a matter of "standard operating procedure." The 44,000 "lost" sorties represent those over and above the level provided during the "bombing pause" phases of the campaign.

targets in the Hanoi area. They were protected by a combined total of 770 SEAD, EW, and fighter escort sorties. The North Vietnamese fired over 1,200 SA-2s at the high-flying B-52 and succeeded in shooting down fifteen and heavily damaging five more. Despite the heavy support, the B-52s suffered a 2 percent loss rate per sortie, over seven times higher than the average rate for strike aircraft during Rolling Thunder. The operation eventually succeeded when, with their SA-2 stocks almost exhausted and facing the prospect of continued heavy bombing attacks, the North Vietnamese agreed to resume negotiations. The B-52 losses, however, were at the limit of what could be accepted in a protracted campaign. All of the lost B-52s and 75 percent of all USAF aircraft losses in Linebacker II were to SA-2s.[75] The implications for aircraft survivability against adversaries with more advanced air defenses than North Vietnam were quite discouraging.

Just ten months later, the experience of the Israeli Air Force (IAF) in the Yom Kippur war confirmed this finding. An assessment of the best available sources shows the IAF lost between 102 and 106 aircraft during the course of the twenty days of intense fighting out of an initial inventory of about 406 combat aircraft.[76] Losses were heaviest early in the war. The most credible estimates suggest the IAF flew about 2,600 combat sorties during the first four days, while losing about fifty aircraft.[77] This indicates a loss rate early in the conflict of about 2 percent per sortie, about the same as that experienced in Linebacker II. The loss rate declined to about 1.7 percent per sortie during days 5–7, and then fell dramatically for the remainder of the conflict to about 0.3 percent per sortie once the Syrians and Egyptians had expended most of their SAMs and IAF SEAD efforts further reduced the threat. The IAF commander indicated that the biggest threat was the SA-6. This was a "second-generation" SAM specifically designed to engage tactical aircraft at low and medium altitudes in support of mobile ground forces. The Yom Kippur war was the West's first combat encounter with the SA-6 and it proved highly effective. The best available data indicates that SAMs accounted for about 40 percent of IAF losses.[78] In contrast, SAMs accounted for just 14 percent of U.S. losses in Rolling Thunder. SAMs were rapidly increasing in capability relative to aircraft, and the overall effectiveness of IADS was growing with them. With support sortie ratios already high and strike aircraft carrying their own active ECM, it was clear some new approach to aircraft survivability was needed.

DARPA played a critical role in first identifying a technical path to the new approach and then moving it forward from concept, to technical demonstration, to development, and finally to

75 One reason for this was that in 1968 QRC-160-8 pod-carrying aircraft were lost and the pods exploited by Soviet engineers. They rapidly designed and fielded a new missile beacon system working on different frequencies rendering missile beacon jamming ineffective by 1972.

76 Itai Brun, "Israeli Air Power," in John Andreas Olsen, ed., *Global Air Power* (Washington, DC: Potomac Books, 2011), pp. 155–156; Martin Musella, *Air Operations During the 1973 Arab-Israeli War and the Implications for Marine Aviation* (Quantico, VA: Marine Corps Command and Staff College, 1985), available at "http://www.globalsecurity.org/military/library/report/1985/MML.htm, accessed May 30, 2014.

77 Price, *History of US Electronic Warfare,* p. 254.

78 William Norton, *Air War on the Edge: A History of the Israeli Air Force and Its Aircraft Since 1947* (Leicester, UK: Midland Publishing, 2002), p. 40.

fielded capability. The new aircraft survivability concept centered on defeating IADS by defeating their sensors through passive rather than active means. As opposed to attempting to jam or deceive IADS radars, the new concept called for fielding aircraft carefully shaped and coated with radar absorbent materials (RAM) to minimize the amount of radar energy reflected from the aircraft and returned to the radar receiver. This approach, later dubbed "stealth," proved highly effective during the opening days of Operation Desert Storm when the eventual product of the effort, the F-117A Nighthawk, attacked high-priority targets deep inside Iraq defended by an IADS significantly more sophisticated than those encountered by the IAF in 1973, with no losses. This shift of the air attack versus IADS competition from an active ECM versus active radar to a passive ECM versus active radar competitive regime has fundamentally changed the design criteria for combat aircraft. Figure 45 highlights how the incorporation of stealth design criteria changed the overall shape of U.S. tactical aircraft. The Vietnam-era F-4 Phantom, upper right, lacked any stealth features and was optimized for high speed. The F-117 Nighthawk, center, design was dominated by stealth considerations. Moreover, unlike the F-4, the F-117 lacks a radar, as well as the ability to carry external stores and supersonic top speed. The F-22A Raptor, lower left, incorporates advanced stealth features, an advanced radar, is capable of supersonic cruise, and can carry external stores.

FIGURE 45. THREE GENERATIONS OF U.S. COMBAT AIRCRAFT FROM VIETNAM TO THE PRESENT

"Saved by the Bell"

For the first three days of Operation Desert Storm, coalition aircrews used low-altitude tactics developed and practiced over the previous two decades to maximize the probability NATO aircraft could successfully engage in offensive missions against the increasingly sophisticated Soviet IADS facing them across the "Central Front" in Germany. These tactics were specifically designed to minimize the engagement time available to Soviet and Warsaw Pact SAM operators. The tradeoff, as in Vietnam, was that it put aircraft in the heart of the AAA engagement envelope. Analysis of sortie and aircraft loss data from these first three days of Operation

Desert Storm indicates that radar-guided SAMs, in this case primarily the same SA-6 first used against the IAF eighteen years earlier, were the primary threat, accounting for seven of the seventeen Coalition aircraft losses (about 40 percent). Overall losses to Coalition aircraft entering Iraq during the first three days of the operation were about 0.5 percent per sortie. This is over one and a half times the average rate experienced by strike aircraft during Rolling Thunder.[79]

Considering the more modern and much denser threat environment presented by the Warsaw Pact forces along NATOs Central Front, it is likely NATO air forces would have experienced loss rates at least as high as those experienced by the IAF early in the 1973 conflict. The small number of F-117s procured, a total of just fifty-nine, represented only a tiny fraction of the thousands of combat aircraft NATO would have deployed had the Cold War "gone hot" in the late 1980s.[80] Even now, stealthy aircraft account for only a small fraction of operational U.S. air combat aircraft. The USAF currently fields almost 2,200 fighter, attack, and bomber aircraft. Of these, only 20 B-2As and 187 F-22As are stealthy. The USN and USMC have no stealthy aircraft currently assigned to combat units. This will soon change as the F-35 Joint Strike Fighter begins to reach operational units, currently planned to occur between 2015 and 2019 depending on the Service and variant.[81]

What Comes Next?

The United States is not the only nation developing stealthy aircraft. Over the next decade, what has been a unique U.S. capability will proliferate to many other nations. Russia and India are jointly developing a stealthy fighter centered on the Sukhoi T-50 prototypes first flown in 2010.[82] China has two stealthy aircraft known to be in development: the large J-20 and the moderate-size J-31. All of these programs are likely to bear fruit by the early 2020s. In addition to these efforts, there are about a dozen countries planning to procure F-35s. With export sales of the Russo-Indian and Chinese fighters added, it is likely that well over a thousand stealthy fighters will be in service with upwards of twenty nations within a decade.

The proliferation of stealth technology will make many existing radar-centric air defense systems far less effective. In response, we are likely to see the continued improvement and proliferation of advanced Infra-Red Search and Track Systems (IRSTS) for combat aircraft and the

79 During the first three days of Operation Desert Storm, Coalition forces flew 3,632 interdiction, CAS, defensive counter air, offensive counter air, and reconnaissance sorties while losing seventeen aircraft. This equates to an overall per sortie loss rate of 0.47 percent. Overall strike aircraft losses in Rolling Thunder were 805 aircraft on 294,539 sorties for an average per sortie loss rate of 0.27 percent.

80 "Lockheed F-117A Nighthawk," U.S. Air Force, available at http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=410, accessed May 30, 2014.

81 "DOD Announces Services' F-35 IOC Dates," Lockheed Martin, press release, May 13, 2013, available at https://www.f35.com/news/detail/department-of-defense-announces-f-35-ioc-dates-for-all-services/, accessed May 30, 2014.

82 Gushran Luthra, "IAF decides on 144 Fifth Generation Fighters," *India Strategic,* October 2012, available at http://www.indiastrategic.in/topstories1766_IAF_decides_144_fifth_generation_fighters.htm, accessed May 30, 2014.

fielding of advanced mobile ground radar systems, such as the Almaz-Antey VHF-band Nebo-SVU, whose makers claim have "counter-stealth" capabilities.[83] Many Russian, Chinese, and European fighters are equipped with fully integrated IRSTS and the United States is working to retrofit this capability to all of its existing "Teen-Series"[84] fighters via external pods.[85]

One of the best ways to counter an airborne IRSTS is to have a more capable IRSTS that allows longer-range detection, engagement, and avoidance of the opposing aircraft. This is likely to lead to an eventual "arms race" in IRSTS technology. Countering "counter-stealth" radars is likely to require a combination of improved stealth technology plus the fielding of advanced ECM systems to degrade their performance.

Significant Insights

Some of the more unique and important insights from the enduring air attack-versus-IADS BNC are:

- Unlike submarines, aircraft are often lost over enemy territory providing adversary engineers physical access to innovative systems. This, plus the ability to interrogate captured aircrew on the purpose and operation of the systems, often greatly aids the rapid fielding of countermeasures.
- It is generally better to wait until innovative airborne systems can be fielded in sufficient numbers to achieve significant operational results during their relatively short "unopposed" operational lives than to introduce them piecemeal and risk early compromise.
- Air forces are extremely sensitive to "actual attrition" due to several immutable attributes of aircraft such as their relatively limited payloads, persistence, and fragility.
- The goal of IADS is to minimize damage to important assets, not (necessarily) to shoot down aircraft.
- IADS can impose significant "virtual attrition" on attacking air forces by forcing them to operate less effectively (e.g., at night during World War II) or efficiently (e.g., increasing support sortie ratios during Rolling Thunder). Virtual attrition can decrease the effectiveness of an attacking force by up to 25 percent as long as a threat exists, even if very few aircraft are actually shot down.

For attackers, these observations suggest that it may be worthwhile to equip innovative electronic systems with demolition charges or other self-destruction mechanisms to make it more

83 "'Nevo-SVU' (1L119) Radar System," Almez-Antey, available at http://www.almaz-antey.ru/en/catalogue/millitary_catalogue/1219/1241/1340, accessed May 30, 2014.

84 These include the F-15C/D/E Eagle, F-16C/D Fighting Falcon, and the F/A-18C/D Hornet and F/A-18E/F Super Hornet.

85 "Heat Vision: US Teen Series Fighters Getting IRST," *Defense Industry Daily,* available at http://www.defenseindustrydaily.com/f-18-super-hornets-to-get-irst-03429/, accessed May 30, 2014.

difficult, or impossible, for opposing engineers to examine important system hardware when it is inevitably lost. They also suggest that an underappreciated advantage of unmanned aircraft could be that they eliminate an important past intelligence vulnerability concerning innovative system operation—captured aircrew interrogations. Finally, the ability to rapidly design and produce significant numbers of innovative electronic systems in response to adversary innovations is critical to success against a sophisticated IADS.

The IADS commander must assess whether it is possible to impose such heavy losses on an attacker that the attacks are curtailed through an “all-out” effort, or whether it is better to operate at a lower tempo, but pose a “threat in being” that induces the attacker to devote significant resources to support rather than strike missions. The choice to engage in all-out battle may result in either the depletion of the available SAM inventory or such heavy damage to the IADS network that the “threat in being” is not credible.

Conclusions

This concluding section highlights some of the most important common elements of BNCs we discovered during the analysis of our two quantitative historical case studies. Furthermore, it outlines how these observations can be used as an analytic framework to analyze virtually any existing or proposed battle network.

Competitions Are Driven by Fundamental Attributes of Their Central Systems. Our first major conclusion is that BNCs tend to be defined by the fundamental attributes of the systems at the center of the competition. In the cases we explored, these are the submarine and the bomber or attack aircraft. Attributes like the low "situational awareness" of submarines or the "fragility" of aircraft are, like most attributes, relative. For example, modern submarines have much better sensors than a World War II U-boat, and modern combat aircraft can absorb much more punishment than the wood and fabric biplanes of World War I. Relative to the systems, however, that are hunting or shooting at them, modern submarines remain disadvantaged in situational awareness and aircraft remain fragile.

Metrics Drive Network Structure and Operation. We also found that the goals and metrics chosen for a battle network have a significant impact on its cost, complexity, organization, and effectiveness. For example, the sophistication, organization, and cost of a network designed to find and destroy all opposing submarines would be quite different from one designed primarily to allow convoys of merchant ships to avoid enemy submarines. Similarly, a network designed to impose virtual attrition by holding aircraft at risk of destruction might emphasize different attributes than one designed to destroy as many aircraft as possible as quickly as possible. The former might place great importance on the survivability of its systems, whereas the latter might place more value on high volume of fires. Depending on one's strategic goals, a network whose main purpose is avoiding or driving off submarines and imposing virtual attrition on air attacks might be "good enough" while also likely to prove both less costly and more technically feasible than a network with more ambitious goals, such as destroying enemy forces.

Engagement Tempo Impacts Whether Disruption or Exploitation of Enemy Communications Is Preferred. We found that the pace and tempo of operations and tactical engagements greatly influences whether it is preferable to exploit an adversary's network communications, or attempt to disrupt them. For example, submarine operations unfold over days or weeks while air operations tend to be completed in a matter of minutes, or at most, hours. This makes communications exploitation more useful in submarine and ASW operations, whereas communications interruption is more useful in air operations.

Battle Network Competitions Accelerate, Culminate, Then Jump to a New Competitive Regime. Perhaps one of our most interesting and important findings is that as conflicts persist, the pace of the move-countermove cycle accelerates and eventually reaches a pace so rapid that one side is either unable to keep up or takes measures to force the competition into a new "competitive regime," which neutralizes much of the opposing battle network by rendering ineffective or eliminating the physical phenomena used to detect and localize the most important systems. For example, the German Navy was on the verge of moving the ASW BNC from the EM realm to the passive acoustic realm at the end of World War II. Another example is the U.S. development of stealth aircraft technology in the closing years of the Cold War. This technology greatly reduced the ability of radars to detect and track aircraft, effectively "blinding" IADS and rendering them much less effective. This move was the result of an accurate assessment by DARPA and senior DoD leadership that the active ECM-versus-active radar competition had reached a culminating point, and that the United States must either move to a new competitive regime or lose its ability to project power with manned aircraft at a reasonable cost.

A corollary to this finding is that components of the new competitive regime should not be introduced in small numbers. To take advantage of the new innovation, the side making the move to a new competitive regime must do so with sufficient numbers to actually shift the competition. If the force retains a significant foot in both the old and new competitive regime, the other competitor may still be successful with its existing battle network.

One Side May Be "Saved by the Bell" When a Conflict or Competition Ends. Had World War II lasted longer, the Allies would have confronted significant numbers of advanced German submarines able to remain underwater for extended periods and avoid exploitation of their communications via burst transmissions. The Allies were completely unprepared for this as it would have rendered their radar and HFDF sensors useless. Similarly, NATO air forces were unprepared to meet the threat of a wide array of advanced Soviet ground-based air defenses fielded in the closing years of the Cold War. The technology to address this problem, stealth aircraft, existed, but stealth aircraft were procured in such small numbers that their introduction could have been seen as breaking the rule against introducing innovative technologies piecemeal.

A Framework for Analysis of Battle Networks

Taken together, these five main observations can be used to structure analysis of existing and proposed battle networks or the competition between networks. In the case of some existing battle networks, analysis could be quite precise and quantitative, but for proposed or less well understood adversary systems it may be less precise or more qualitative.

Metrics and Goals

Assessing what the network is designed to do and how this will be measured is of prime importance. This is different from assessing what various systems composing the network are designed to do. For example, an IADS may contain elements such as SAM batteries or fighter aircraft that were designed to have the maximum possible chance of destroying an opposing aircraft within the constraints of size, weight, volume, technology, and time given the design team. The goal of the IADS as a battle network, however, may be to pose a long-term threat to an opposing air force and maximize virtual attrition rather than actual attrition. This is important because it determines how often and under what conditions the IADS network will attempt to engage attacking aircraft. This, in turn, influences how much data must be exchanged within the network, as well as how fast and how often.

Attributes of "Central" Systems

Assessing the attributes of the central systems of the competition is equally important. In the examples presented in this report, the central systems were aircraft and submarines. Their attributes determined the physical phenomena that could be leveraged to detect and avoid or attack opposing systems. They also determined how the opposing network is likely to respond to setbacks and success, as well as how vulnerable individual elements may be to different modes of attack or exploitation. Often, a change in one of the attributes of a central system will indicate when a competitive regime change is either likely or required. For example, the fielding of "true submarines" with the introduction of nuclear power largely negated the effectiveness of EM sensors in ASW. Similarly, the introduction of stealth technology allowed aircraft, formerly "high-contrast" EM targets, to become "low-contrast" EM targets and indicated a shift in the competitive regime. Another way to view these central attributes is that they represent foundational assumptions about how a network will function. For example, "We will find U-boats using their radio transmissions to generalize their location and radar to localize them because they spend most of their time on the surface" might characterize the foundational assumptions of the Allied ASW network during World War II. If U-boats made many fewer or shorter transmissions, or if they spent most of their time under water, the Allied ASW battle network would have been fundamentally undermined. This element of the analysis should also examine whether it is more desirable to disrupt or exploit an adversary's battle network, or if a mix is preferable.

Identify Culmination and Possible Follow-On Competitive Regimes

This task is probably best done by assessing how the failure of various foundational assumptions about the central attribute of the central systems in the competition would impact the effectiveness of the opposing networks. Stealth aircraft technology was born when someone observed that IADS effectiveness was tightly linked to radar as both a broad-area and target-engagement sensor. This led DARPA to investigate the possibility of building an aircraft "invisible to radar" to undermine this foundational element of all existing IADS. Another sign that a competition may be ripe for competitive regime change is when the move-countermove cycle reaches the point where one side or the other is no longer able to compete and must look for a "nontraditional" solution to its challenges. An example of this is the German Navy's decision to stake everything on development of "true submarines" following the defeat of its traditional U-boat submersibles in May 1943. DoD could undertake a systematic analysis of a wide range of current U.S. battle networks to determine the vulnerability of their foundational assumptions to adversary innovations and identify promising paths toward alternative competitive regimes to prioritize technology investments.

LIST OF ACRONYMS

-8	Dash 8
AAA	anti-aircraft artillery
AGL	above ground level
AI	airborne intercept
ALCM	air-launched cruise missiles
ASCM	anti-ship cruise missile
ASDIC	Allied Submarine Detection Investigation Committee
ASROC	anti-submarine rocket
ASW	anti-submarine warfare
BNC	battle network competition
C2	command and control
CAP	combat air patrol
CAS	close air support
CEP	circular error probable
CHECO	Contemporary Historical Evaluation of Combat Operations
CLFA	Compact Low Frequency Active
CSBA	Center for Strategic and Budgetary Assessments
CVBG	aircraft carrier battle group
DARPA-STO	Defense Advanced Research Projects Agency-Strategic Technology Office
DR	deduced reckoning or dead reckoning
DTIC	Defense Technical Information Center
ECM	electronic countermeasures
ELINT	electronic intelligence
EM	electromagnetic
GSR	German Search Receiver
HF	high-frequency
HFDF	high-frequency direction-finding
IADS	integrated air defense system
IAF	Israeli Air Force
IRSTS	Infra-Red Search and Track Systems
ISR	intelligence, surveillance, and reconnaissance
KG 100	Kampf Gruppe 100
NATO	North Atlantic Treaty Organization
NHHC	Navy History and Heritage Command

LIST OF ACRONYMS

nm	nautical miles
Pk	probability of kill
RAF	British Royal Air Force
RAM	radar absorbent materials
RHWR	Radar Homing and Warning Receiver
SAM	surface-to-air missile
SEAD	Suppression of Enemy Air Defenses
Sonar	sound navigation and ranging
SOSUS	sound surveillance system
SSBN	ballistic missile submarine
SSG	guided-missile submarine
SSGN	nuclear guided-missile submarine
SSN	nuclear attack submarine
USAF	U.S. Air Force
USMC	U.S. Marine Corps
USN	U.S. Navy
VHF	very high frequency
GEE	RAF radio navigation system used in WWII
LORAN	Long Range Navigation
H2S	RAF airborne ground scanning radar system

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