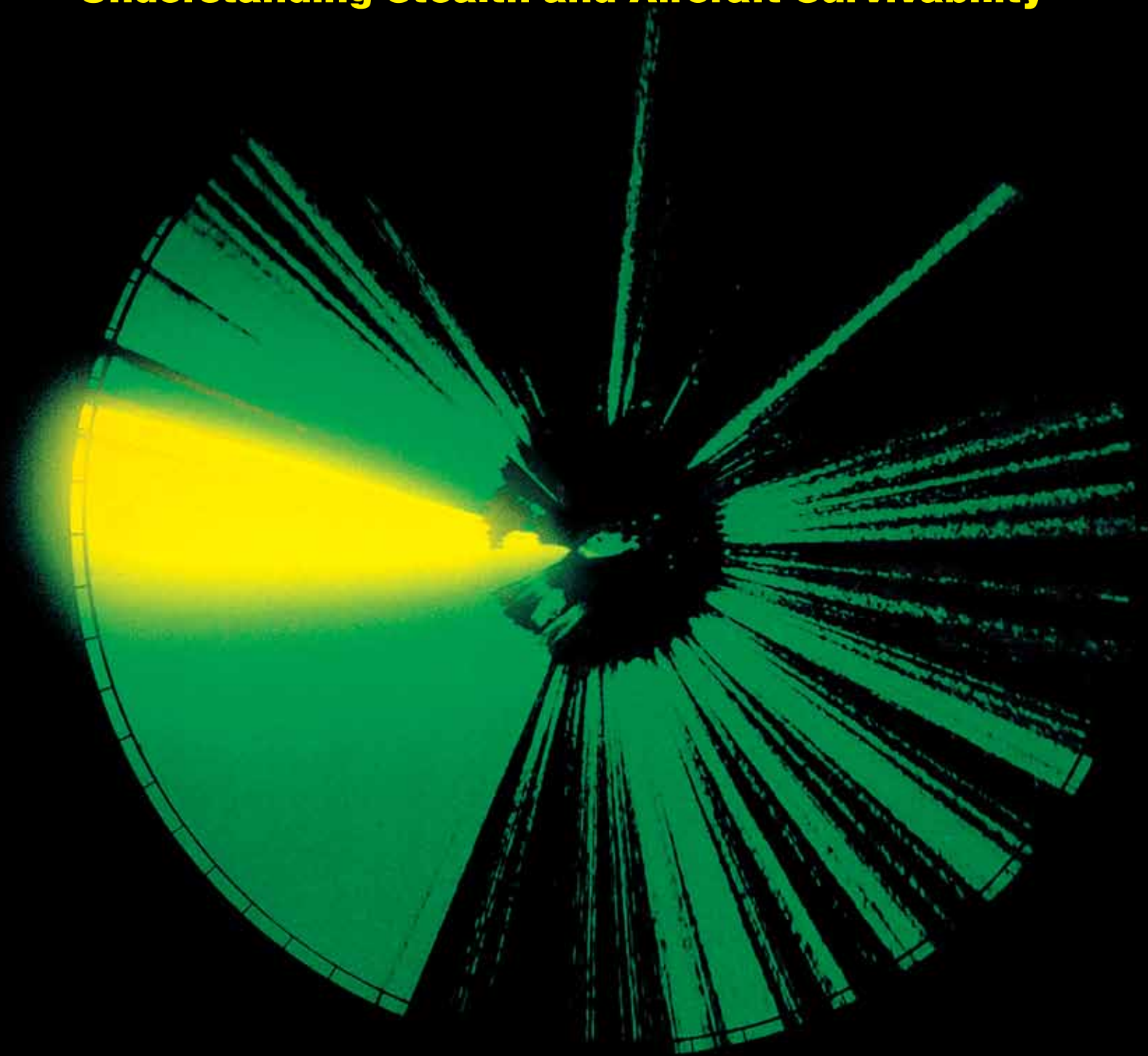


# — THE RADAR GAME —

**Understanding Stealth and Aircraft Survivability**



**By Rebecca Grant**  
**SEPTEMBER 2010**  
**A MITCHELL INSTITUTE STUDY**



## Brig. Gen. Billy Mitchell

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On September 12, 1918 at St. Mihiel in France, Col. William Mitchell became the first person ever to command a major force of allied aircraft in a combined-arms operation. This battle was the debut of the US Army fighting under a single American commander on European soil. Under Mitchell's control, more than 1,100 allied aircraft worked in unison with ground forces in a broad offensive—one encompassing not only the advance of ground troops but also direct air attacks on enemy strategic targets, aircraft, communications, logistics, and forces beyond the front lines.



Mitchell was promoted to Brigadier General by order of Gen. John J. Pershing, commander of the American Expeditionary Force, in recognition of his command accomplishments during the St. Mihiel offensive and the subsequent Meuse-Argonne offensive.

After World War I, General Mitchell served in Washington and then became Commander, First Provisional Air Brigade, in 1921. That summer, he led joint Army and Navy demonstration attacks as bombs delivered from aircraft sank several captured German vessels, including the SS *Ostfriesland*.

His determination to speak the truth about airpower and its importance to America led to a court-martial trial in 1925. Mitchell was convicted, and resigned from the service in February 1926.

Mitchell, through personal example and through his writing, inspired and encouraged a cadre of younger airmen. These included future General of the Air Force Henry H. Arnold, who led the two million-man Army Air Forces in World War II; Gen. Ira Eaker, who commanded the first bomber forces in Europe in 1942; and Gen. Carl Spaatz, who became the first Chief of Staff of the United States Air Force upon its charter of independence in 1947.

Mitchell died in 1936. One of the pallbearers at his funeral in Wisconsin was George Catlett Marshall, who was the chief ground-force planner for the St. Mihiel offensive.

**ABOUT THE MITCHELL INSTITUTE FOR AIRPOWER STUDIES:** The Mitchell Institute for Airpower Studies, founded by the Air Force Association, seeks to honor the leadership of Brig. Gen. William Mitchell through timely and high-quality research and writing on airpower and its role in the security of this nation.

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## Foreword

Radio aids to detection and ranging ... radar—as it's commonly called—transformed air warfare in 1940. It has held a grip on would-be attackers and defenders ever since.

This special report from the Mitchell Institute for Airpower Studies is a republication of a long essay I wrote in 1998 to get at why stealth was such an important breakthrough for airpower. Then, as now, there were questions about the future of stealth.

Consider the times. The dazzling combat success of the F-117 in the Gulf War of 1991 had been followed by the cancellation of the B-2 stealth bomber program in 1992. Cuts to the F-22 stealth fighter program had already been made. Experienced airmen were strongly in favor of stealth. Some officials, like former Secretary of Defense William Perry and then-Undersecretary of Defense for Acquisition Paul Kaminski, were thoroughly steeped in the workings of stealth and its benefits. But for many, intricate stealth programs seemed a questionable investment given the declining defense budgets of the late 1990s. Stealth was wrapped up in the value of airpower as a whole and in the re-evaluation of American security policies.

Still, a dozen years ago there was a strong commitment to stealth. The Air Force, Navy, and Marine Corps along with Britain had committed to the Joint Strike Fighter. Teams led by Lockheed Martin and Boeing were working on designs. Perhaps most important, the long-range Air Force budget had a plan to field an all-stealth fighter force of more than 2,200 fighters. The future of stealth seemed assured.

Combat experience quickly revalidated its importance during the 1999 NATO air war with Serbia. B-2s flew missions into heavily defended airspace and did everything from taking out the Novi Sad bridge to attacking and destroying an SA-3 surface-to-air missile battery. F-117s flew crucial missions. (One F-117 was shot down.) The intensive air war with Iraq in early 2003 again saw the use of both F-117s and B-2s against a variety of targets in and around Baghdad.

Since then, stealth has come under assault. The reasons have much to do with strategy, politics, and budgets, and little to do with the capability assessments that drove the decisions to develop and buy stealth aircraft in the first place.

The radar game itself is just as critical as it was a dozen years ago. Radar remains the leader in technologies for detecting aircraft and missile attack. As the study notes: "Why were aircraft so vulnerable to radar detection? In short, for all the reasons that increased their aerodynamic qualities and performance. Metal skins, large vertical control surfaces, big powerful engines" and so on.

The study details how the first rounds of the radar game were all about electronic countermeasures. RAF Bomber Command famously held back the first use of chaff for over a year, fearing that the Germans would implement countermeasures, too. During the Cold War, electronic countermeasures and electronic counter-countermeasures became one of the blackest arts of airpower and one of its most important. Stealth was in part a way to break the tug-of-war.

That was why stealth was so attractive. Attackers must undo the adversary's advantage either by low-level ingress, high-altitude operations, speed, electronic countermeasures, or stealth. Of these, the ability to diminish the effects of radar return is one of the most challenging and one of the most rewarding. A low observable aircraft gains advantages in how close it can come to air defense systems. Low observable aircraft do not get a free pass in the battlespace. Low observability has to be fine-tuned to defeat adversary systems as they establish and hand-off tracks and zero in on fire control solutions. Not much will prevent the big bump of long-range, low frequency radars used for initial detection. But, it takes much more than a blip on a "Tall King" radar to unravel a well-planned mission.

Over the past decades, it's never been easy to convey what low observable technologies actually do. Understanding them requires some grasp of physics, of radar phenom-

enology, of aircraft design, of how missions are planned and executed. One hears so often that stealth is not invisibility. The inverse corollary is that a single radar detection of an aircraft at a point in time and space does not equal an impenetrable battlespace. The British nickname “Chain Home” for their cross-Channel radar suite had it about right. It takes a chain of detections, interpretations, and correct actions by defenders to intercept an aircraft. Stealth breaks up the chain by removing, reducing, or obfuscating a significant percentage of those detection opportunities.

Much of *The Radar Game* is devoted to a basic discussion of how stealth works and why it is effective in reducing the number of shots taken by defensive systems. Treat this little primer as a stepping off point for discovering more of the complexities of low observability.

Of course, there is a wider electromagnetic spectrum to consider. While radar is the focus here, true survivability depends on taking measures to reduce visual, acoustic, and infrared signatures as well as minimizing telltale communications and targeting emissions.

The darling of passive technologies is infrared search and track. Those in combat ignore the infrared spectrum at their peril. Although it is not as often in the headlines, designers of all-aspect stealth aircraft have worked since the 1970s to minimize infrared hotspots on aircraft.

Finally, electronic countermeasures still have their role to play. As before, it will take a combination of survivability measures to assure mission accomplishment.

*The Radar Game* should also shed light on why complex technologies like stealth cost money to field. The quest for stealth is ongoing and the price of excellence is nothing new. Take, for example, the P-61 Black Widow, which was the premier US night fighter of late World War II. This all-black, two-engine fighter was crewed by a pilot in front and a dedicated radar operator in the back seat. Its power and performance were terrific advances. “All this performance

came with a high pricetag,” noted Steven L. McFarland in his 1997 Air Force history *Conquering the Night*. “With Northrop’s assembly line in full gear, a completely equipped P-61 cost \$180,000 in 1943 dollars, three times the cost of a P-38 fighter and twice the price of a C-47 transport.”

Winning the radar game still carries a substantial price tag—but stealth aircraft pay back the investment in their combat value.

Stealth remains at the forefront of design. One of the best signals about the ongoing value of stealth lies in new applications. Leading unmanned aerial vehicles for high-threat operations incorporate stealth. Navy ships have adopted some of its shaping techniques. Of course, the F-35 Joint Strike Fighter remains the nation’s single biggest bet on future airpower.

Success in the radar game will continue to govern the value of airpower as a tool of national security. Many of America’s unique policy options depend upon it. When and if the SA-20 joins Iran’s air defense network, it will make that nation a considerably tougher environment for air attack, for example. Already there are regions of the world where only stealth aircraft can operate with a good chance of completing the mission.

In fact, stealth aircraft will have to work harder than ever. The major difference from 1998 to 2010 is that defense plans no longer envision an all-stealth fleet. The Air Force and joint partners will operate a mixture of legacy, conventional fighters and bombers alongside stealth aircraft even as the F-35s arrive in greater numbers. The radar game of 2020 and 2030 will feature a lot of assists and the tactics that go along with that.

*Rebecca Grant, Director  
Mitchell Institute for Airpower Studies  
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## INTRODUCTION

Precision weapons and rapid targeting information mean little if aircraft are unable to survive engagements with enemy air defenses. In addition to costing the lives of pilots, high levels of attrition can ultimately affect the outcome of the theater campaign. One of the most critical factors in determining the success of an air operation is survivability. In the last several decades, the term survivability has been associated with analysis of how low observables and electronic countermeasures can help aircraft carry out their missions in hostile airspace. Discussions of survivability immediately bring to mind stealth aircraft, radar jamming and debates about the latest SA-10 threats. Yet the quest for survivability is not a fad of the Cold War or the high-technology 1990s. Its roots, and its importance to combined arms operations, go back to the first use of military aircraft in World War I.

Since the earliest days of military aviation, pilots and planners have taken advantage of whatever their aircraft can offer to increase the odds of survivability. Aircraft survivability depends on a complex mix of design features, performance, mission planning, and tactics. The effort to make aircraft harder to shoot down has consumed a large share of the brains and resources dedicated to military aircraft design in the 20th century.

Since the 1970s, the Department of Defense has focused special effort on research, development, testing, and production of stealth aircraft that are designed to make it harder for air defenses to shoot them down. Low observable (LO) technology minimizes aircraft signature in radar, infrared, visual, and acoustic portions of the electromagnetic spectrum, creating stealth. Future plans for the Air Force F-22 and the tri-service Joint Strike Fighter call for the nation to continue to procure advanced, LO aircraft for the military of the 21st century.

This essay tells the story of how the balance between the air attacker and air defender has shifted over time, and how the radar game changed the nature of aircraft survivability.

Examining the evolution of this balance provides a better understanding of the choices facing military commanders and defense planners as they consider what forms of survivability technology are needed to preserve the dominance of American airpower.

To begin with, the financial and strategic investment in stealth aircraft is one that not everyone understands. Stealth technology was developed and tested in secret. F-117 stealth fighter squadrons were practicing night missions in the Nevada desert several years before the Air Force publicly acknowledged the aircraft's existence. Even after the F-117's impressive performance in the 1991 Gulf War, an element of mystery and misunderstanding sometimes surrounds the operations of stealth aircraft. The F-117 and the B-2 stealth bomber have the ability to complete and survive missions that other aircraft cannot. Still, for the most part, the government has given only the most condensed and superficial explanations of what these low observable aircraft can do and why their mission is so important to joint operations. In addition, the mechanics of radar cross section (RCS) reduction and the effect of lower signatures in tactical scenarios are seldom discussed.

This essay will reveal no technical secrets or surprises. What it will do, however, is explain how the radar game became a major factor in air combat; how LO technology gained the upper hand in the radar game; and how the operational flexibility provided by low observable aircraft has become pivotal to effective joint air operations.

### The Origins of Aircraft Survivability

Survivability—defined as the ability of the aircraft and aircrew to accomplish the mission and return home—has always been an important factor in determining the effectiveness of air operations. Early in World War I, the use of aviation forces in combat revealed that survivability considerations would influence mission effectiveness. Efforts to improve



survivability quickly began to influence aircraft design as specialized aircraft types emerged by 1915. The whole idea of the Spad XIII fighter plane, for example, was to combine maximum speed and maneuverability to dominate aerial engagements. Bombers such as the German Gotha or the British Handley Page had a different mission and accordingly drew on different survivability measures. They relied on self-defense guns and armor plating for survivability since their extra range and payload precluded making the most of speed and maneuver.

As aircraft survivability started to contribute to aircraft design, aircraft were becoming more important contributors to combined operations with ground forces. Aircraft had to be able to operate over enemy lines to reconnoiter, correct artillery fire, and ward off enemy airplanes trying to do the same. By 1918, aircraft were an important element of combined arms operations because of their ability to extend the battle deep behind enemy lines. "The attack of ground objectives in the zone as far back of the enemy's front lines as his divisional posts of command often yields important results," noted a General Staff report in 1919. "The great mobility and speed of airplanes make it possible to utilize day bombardment tactically to influence an action in progress," continued the report.<sup>1</sup>

The last campaigns of World War I hinted that air superiority would be necessary for the most effective ground operations, but World War II made it an iron law. However, the invention of radar on the eve of World War II changed the aircraft survivability problem completely. In World War I, visual detection in clear daylight did not exceed ranges of 10-15 miles at best. Even in the late 1930s, defenders expected to listen and watch for attacking aircraft.

By 1940, radar could spot incoming aircraft 100 miles away. Early detection gave defenders much more time to organize their air defenses and to intercept attacking planes. Radar height-finding assisted antiaircraft gunners on the ground. Primitive airborne radar sets were installed in night fighters in the later years of the war. The radar game had begun. Gaining air superiority and the freedom to attack surface targets while protecting friendly armies rested on surmounting the advantages that radar gave to air defenses. The stakes of the radar game also affected combined arms operations in all theaters of the war. Hitler canceled the invasion of Britain when the Luftwaffe failed to win local air superiority over the English Channel coast in September 1940. The Allies hinged their plans for the Normandy landings on gaining control of the air over Europe and exploiting it with effective air interdiction. The rate at which airpower could accomplish its objectives therefore depended directly on survival rates of the bombers attacking aircraft factories and industrial targets in Fortress Europe. Once the Allies were ashore, they planned for airpower to help offset the numerical superiority of German ground forces.

The Cold War made aircraft survivability even more complicated. After WWII, radar technology leapt ahead and aircraft designs struggled to maintain a survivability edge. By the 1960s, radar dominated the air defense engagement. Longer range detection radars provided ample early warning. Radar-controlled surface-to-air missiles (SAMs) improved the speed and accuracy of attacks against aircraft. In the air, more advanced radars and guided air-to-air missiles changed the nature of aerial combat. Conventional performance improvements in speed, altitude ceiling, maneuverability, and other parameters pushed ahead but could not keep pace with the most sophisticated air defenses. If radar made aircraft easy to shoot down, the effectiveness of air operations would plummet.

As a result, combat aircraft had to incorporate additional survivability measures to stay ahead in the radar game. Electronic countermeasures (ECM) to radar were first employed in World War II. Research in the 1950s and 1960s led to much more advanced countermeasures that disrupted radar tracking by masking or distorting the radar return. When aircraft got closer to the air defenses, however, their radar reflections grew large enough to burn through the electronic smokescreen put in place by ECM.

### Winning the Modern Radar Game

In this context, the prospect of designing combat aircraft that did not reflect as much radar return was an enticing possibility. British researchers in the 1940s hypothesized about foiling radar detection. Low observable technology that reduced radar return would make it harder for defenders to track and engage attacking aircraft because they would not have as big an aircraft signature to follow. Less radar return meant less time in jeopardy, or time in which aircraft could be tracked and fired upon by other aircraft or by ground-based defenses.

However, coming up with an aircraft design that minimized radar return depended on many factors. It was not until the early 1970s that the physical principles of controlling radar return were understood well enough to apply them to aircraft design. Low observable technology was based first on a sophisticated ability to understand and predict the behavior of radar waves in contact with an aircraft.

Research into special shapes and materials made building a low observable aircraft a reality. The aim was not to make aircraft invisible, but to quantify and minimize key areas of the aircraft's radar return. Incorporating low observables required trade-offs that often appeared to go against established principles of aerodynamic design. The primary method for reducing radar cross section was to shape the aircraft's surface so that it deflected radar return in predictable ways.

Variations in the angle from which aircraft approached the radar, and the frequency of the radars used by the de-

fenders, also affected the radar return and required choices about how to optimize designs for the most dangerous parts of the cycle of detection, tracking, and engagement. As RCS diminished, other factors became important corollaries, such as reducing the infrared signature as well as visual, acoustic, and other electronic evidence of the aircraft's approach.

LO design offered immediate tactical benefits by cutting radar detection ranges and degrading the efficiency of search radars. Signature reduction now posed substantial problems for integrated air defenses (IADS) because it could delay early warning detection and diminish the ability of fire control radars to acquire and fire SAMs against the attacking aircraft.

### Aircraft Survivability and its Operational Impact

The payoff for low observables came from developing an aircraft that could tackle each stage of the radar game. Low observables offered a way to regain some of the surprise element of air attack and improve the odds in each individual engagement. Overall, LO aircraft would spend less time in jeopardy from air defenses and stand a much better chance of completing the mission and returning home.

The tactical benefits of increased aircraft survivability opened up a wide range of options for air commanders. Most important, spending less time in jeopardy could reduce attrition rates by lowering the probability of aircraft being detected, tracked, and engaged during their missions.

Highly survivable aircraft could be tasked to attack heavily defended targets with much less risk. As a result, desired effects—such as degrading enemy air defenses—could be achieved in a shorter period of time. Critical targets that might have taken repeated raids from large packages of conventional aircraft could be destroyed in a single strike by a much smaller number of F-117s able to penetrate close enough to use laser-guided bombs (LGBs).

The final section of this essay quantifies the effects of signature reduction in the tactical environment. Graphs show how reduced signatures lower the time in jeopardy, and how stealth degrades detection by early warning radar and subsequent tracking and engagement by fire control radars. Three hypothetical scenarios display the results of the analysis in high and low threat environments. Variations for altitude and attack profile are included. A short section also discusses in general terms the potential synergy between low observables and electronic countermeasures.

Since World War II, the radar game between attackers and defenders has determined who will control the skies. The winner of the radar game will be able to bring the maneuver and firepower of air forces to bear against the enemy. For the 21st century, highly survivable aircraft will contribute directly to achieving joint force objectives. They will do this by shaping and controlling the battlespace where joint air and surface forces operate. The ability to project power with efficient and effective air operations will depend on winning the radar game.

## SURVIVABILITY BEFORE RADAR

The best way to understand the impact of radar is to look back at the first air war. World War I duels in the air defined what it took to prevail in air combat and why survivability rates in the air component were important to combined arms operations.

Survivability in the most basic sense refers to the ability of an aircraft and its crew to carry out its mission and avoid being shot down. Before the development of radar, control of the air centered on a duel limited to the field of view of the human eye. Air combat in World War I began when enemy pilots or gunners on the ground spotted attacking aircraft. To control the skies, the biplanes had to survive the duel. Carrying out missions and assisting forces on the ground depended on ensuring that enough aircraft and crews would survive to fight in strength, day after day.

Survivability was as important to air operations in World War I as it is today. The technology and tactics were different, but the basic features of the duel for control of the skies were much the same. The essential elements of the

air-to-air engagement and the problem of ground-based air defense took clear shape between 1914 and 1918.

### Elements of the Duel

Air combat in World War I was a duel between attackers and defenders for control of the air. To perform their missions, aircraft had to survive encounters with hostile aircraft and with enemy ground fire. Their chance of survival depended on the technical abilities of the aircraft and on the tactical skill with which they were employed.

It may seem strange to speak of the "survivability" of biplanes with fabric wings and wooden two-bladed propellers. World War I aircraft were extremely vulnerable to close-in attack. France, Germany, Britain, and other warring nations consumed aircraft at staggering rates, running through supplies of tens of thousands of machines in the course of the war. Accidents, poor maintenance, dirt runways, and even exposure to the rain and wind claimed a heavy toll. Pilot inexperience also contributed to loss rates.

## Elements of the Duel

### Detection

#### ■ Observe and track enemy aircraft

- Visual, radar, infrared



### Engagement

#### ■ Close with and fire on enemy aircraft

- Air-to-air guns, missiles
- Surface-to-air guns, missiles



### Probability of Kill

#### ■ Damage or destroy aircraft

- Depends on the type of explosion and its proximity to the aircraft

However, World War I's air war sketched out elements of the duel for survivability that would reappear in air combat in World War II, Korea, Vietnam, and Desert Storm. By focusing on how the survivability duel emerged in World War I, it is possible to set a baseline for understanding how evolution in technology has changed the survivability duel today.

Encounters between attackers and defenders in World War I outlined three parts to their duel: detection, engagement, and probability of kill. Detection refers to the task of spotting and tracking enemy aircraft. Engagement represents a defending fighter attempting to close in during a dogfight, or ground-based air defenses tracking and aiming at incoming aircraft. Probability of kill involves a number of factors. In its simplest form, it assumes the aircraft is hit, but the chance of destroying the aircraft depends on the nature and extent of the damage sustained.

The defender attempts to complete each stage. Without detection, no engagement is possible. Without engagement, there is no probability of kill. On the other hand, the attacker's task is to thwart the defender at each stage. Ideally, the attacker would enjoy complete surprise and arrive over the target area undetected. If detected, pilots evade or prepare for engagement. If engaged, they seek to destroy or avoid enemy aircraft and to dodge enemy surface fire. If the aircraft is hit, probability of kill would depend on the nature and extent of the damage.

The distinctions between the three phases are artificial from the aircrew's perspective because each stage blends

into the next. However, analyzing each stage helps to illustrate the process of achieving survivability.

### Detection

The first task in the duel was to find the enemy, and in World War I, there was little that technology could do to assist in the process. Detection depended almost exclusively on the human eye. Defenders in the air or on the ground had to see the airplane, hear it, or perhaps be shot at by it, in order to know it was there. In the days before radar, no other means existed to detect and track enemy aircraft. The World War I aviator did not even have a cockpit radio to report locations of enemy aircraft.

Defenders constantly struggled to gain early warning of air attack. Airplanes could often be heard before they were seen. Pheasants, thought to have acute hearing, were placed at French listening posts to warn of approaching aircraft. In England, audio

detection formed part of the air defense screen around London.

Both sides mounted frequent patrols to seek out and destroy enemy aircraft. When troops on the line spotted aircraft, reports were relayed by telephone to the airfields. Airfield commanders might launch planes in time to intercept the attackers. The first two American kills of the war came from pilots scrambled to intercept German aircraft patrolling over friendly lines.

Once the aviator could see his opponent, both were vulnerable to the formidable short-range tracking capabilities of the human eye. The short range of visual detection placed a premium on the element of surprise. "The deciding element in aerial combat is usually surprise," explained an air service manual in 1919, so the "enemy will employ all means at his disposal to conceal his approach."<sup>2</sup> In air combat, aircraft might have to close to within 50 yards for a good shot at the opponent.

### Deceiving the Eye

A few means existed to thwart optical detection. Hiding in clouds, attacking out of the sun, and, most of all, approaching from above and behind the aircraft delayed optical detection. Camouflage paint schemes blended wing surfaces into the colors of the terrain below.

However, the single most effective measure against the enemy's ability to detect and intercept was to fly at night. World War I aircraft could operate almost at will under cover

of darkness. On a bright moonlit night enemy aircraft could be seen at just 500-600 yards; in starlight, their dark shadows materialized at 200 yards or less. As one scholar summarized:

*"There were several ways to meet the threat posed by the fighter: One was to increase the bomber's capability to defend itself; another was formation flying, which allowed planes to put up a collective defense; and a third was to have the bombers escorted by fighting craft of one's own. But the most effective response for planes with long-distance missions was simply to carry out those missions at night. The enemy fighter, so formidable by day, did not even attempt night interceptions until the end of the war."*<sup>3</sup>

Both sides took advantage of the cloak of darkness to reach deeper into enemy territory in search of iron works, concentration points, supply depots, railroads and other lucrative targets. Bases and towns along the front blacked out their lights. On nights with bright moonlight, German bombers routinely attacked French border towns such as Nancy. By late 1917, most of the city was evacuated and "caves had been built along the streets in which passers-by could take refuge in case the airplanes came," Billy Mitchell noted.<sup>4</sup> Searchlights and anti-aircraft guns did little to stop the attacks. On one moonlit night, German Gotha bombers scored two direct hits on an ammunition factory in Nancy, knocking it out of production for the remainder of the war. Describing another night raid near his hotel, Mitchell wrote that "the anti-aircraft guns were firing at the sound of the airplanes as much as anything else."<sup>5</sup>

The lack of long range detection linked to an integrated command and control system meant that for the most part, air operations in World War I did not encounter well-organized antiaircraft gun defenses. Enemy antiaircraft defenses could be severe at times and non-existent at other times. For the attacker, the survivability duel with ground defenses was one over which pilots felt they were the masters.

"No, we had little respect for the antiaircraft gun—unless it was protecting a balloon," wrote Eddie Rickenbacker. Point defenses around known targets like balloon emplacements could be lethal because they benefited from many of the advantages that would be featured in integrated air defenses decades later. Balloon defense crews knew their "sausages" were high value targets that would attract air attacks. Because balloons

operated at fixed altitudes as well as fixed locations, gunners protecting them could aim at expected attack routes. They could also predict the altitude of the attack and set the fuses of the antiaircraft artillery accordingly. As Rickenbacker described it:

*"If the balloon was two thousand feet up, then any aircraft attacking it must also be at or near the same altitude. When we came in to attack a balloon, therefore, we flew through a curtain of shells exploding at our precise altitude. We had to fly at that altitude for several seconds, for it took a long burst to ignite the gas. ... After the attack it was necessary to fly out through the wall of Archie on the other side."*

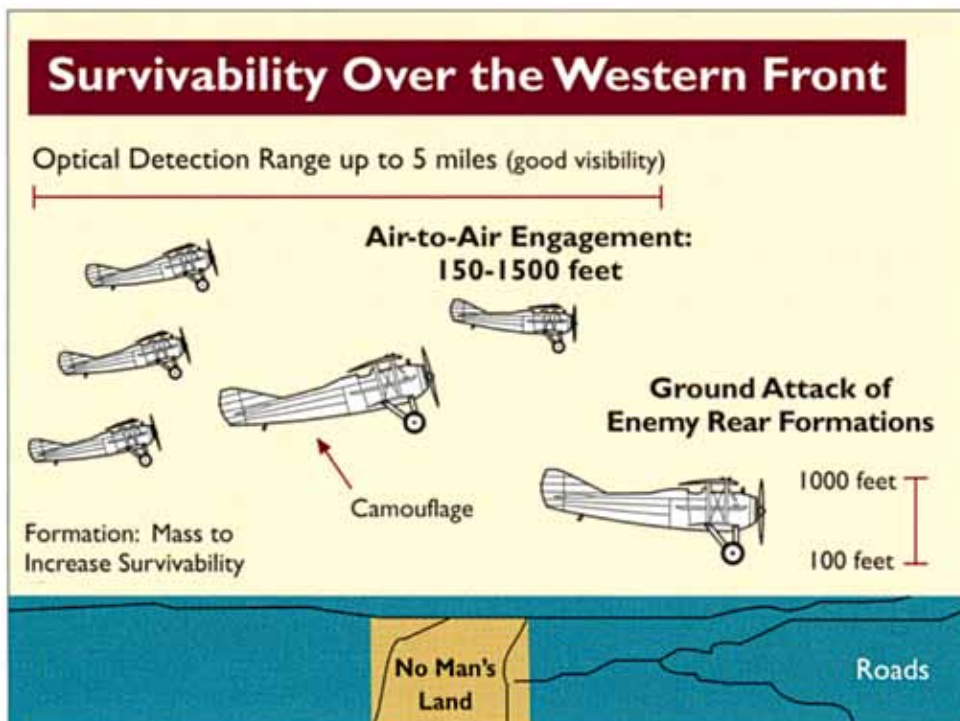
Finally, Rickenbacker added, "Balloons were of such military importance that, frequently, flights of Fokkers would be hovering above them, hiding up there in the sun."<sup>6</sup>

Pilot reports from air operations in 1918 documented everything from heavy but inaccurate antiaircraft fire all the way to the target, to very light or non-existent fire. Still, Rickenbacker's description foreshadowed the lethal air defense environment of World War II and beyond, when the limits of optical detection would be overcome and aircraft would lose much of their edge in surprise attack.

### The Engagement: Designing Aircraft to Survive

With advance warning and detection limited to the range of the human eye, the key to survivability in World War I was to prevail in the engagement phase. Structural design features were paramount.

The warring nations entered the conflict with general



purpose aircraft intended mainly for reconnaissance. But the air war quickly placed a premium on aircraft designed for specialized missions. In a dogfight, speed, rate of climb, and maneuverability could significantly influence the outcome. As one aviator later wrote:

*"The war has shown that there is no universal or multiple purpose plane, which can be used for pursuit, reconnaissance and bombing work. Each particular work calls for a different type of plane, specializing either in speed, maneuverability, climbing ability, carrying capacity, or long distance range. In order to embody one of these characteristics in a plane, others must be sacrificed."*<sup>7</sup>

By 1915, the new aircraft designs reflected distinct mission requirements. Survivability features were tailored to each type.

For example, the whole idea of a pursuit aircraft—a fighter, in today's terms—was to seek out and engage enemy aircraft, and shoot them down. Speed and performance gave a skilled pilot an advantage over his opponents. The British cheered the arrival of their fast and agile Sopwith Camels in 1917. The German Fokker DVII was one of the best machines of the war because of its increased speed, maneuverability, and performance. In 1918, a French pilot wrote: "Days of high spirits! We have received Spads! Now we're finally going to show the Fritzes about speed and maneuverability."<sup>8</sup> American ace-to-be Eddie Rickenbacker made a special trip to Paris that summer to pick up his new French-built Spad XIII.

Where mission requirements diversified, so did survivability features. Some pursuit aircraft, such as Britain's Sopwith Salamander, were built as armored trench-fighters. Machine guns pointed through the floor of the cockpit and 640 pounds of armor plating protected the fuselage from rifle fire at altitudes as low as 150 feet.<sup>9</sup>

In an entirely different class, observation aircraft carried two pilots and more guns because they could not rely on raw speed in their dangerous missions over the lines. Experienced French observation pilots counseled American trainees about the dangers from the faster enemy aircraft pursuing them: "Your planes will be slower, less maneuverable. Do not hesitate to run."<sup>10</sup> Additional self-defense features suited their mission of crisscrossing and lingering over enemy lines at lower altitudes. The rear observer was armed with a machine gun. Dedicated designs such as the Salmson incorporated a more rugged airframe and armor plating.

Self-defense firepower was also the prime ingredient in survivability for the bigger and slower bombardment aircraft. As one pilot put it, "Inasmuch as no bombing plane can hope to run away from pursuit planes, its defensive power lies in the strength of the formation."<sup>11</sup>

A Handley Page bomber clocked 95 mph. This was no match for a Spad XIII, staple of the later years of the war, which

could reach 120 mph. Pursuit tactics of the day frowned on escorting the bombers. Instead, pursuit groups met bombers over their targets to engage enemy aircraft, and again when the bomber formation crossed over to friendly lines. Bombers spent most of their missions in jeopardy with only a machine gunner seated behind the pilot to put up an arc of defensive fire. "A good formation of bi-place machines can fight off double the number of pursuit planes," contended a bomber pilot after the war.<sup>12</sup>

### Probability of Kill

The final phase of the survivability duel consisted of the likelihood or probability that shots fired during the engagement would disable and down the aircraft. Analysts would later term this "probability of kill." Depending on the systems involved, the probability of kill depended on any number of complex variables.

Aircrews sought to control these variables where possible just as they did in all phases of the duel. Through tactics and personal preferences, World War I pilots strove to protect themselves while ensuring that shots fired would be likely to hit their mark. Some aviators had their mechanics hand-load ammunition belts to help prevent the guns from jamming during a dogfight.

Once hit, structural factors could determine whether or not the aircraft survived to return to base. Bullets might hit oil lines. Steep dives might tear fabric off wings. On the other hand, armor plating could protect the pilot and the structural integrity of the aircraft. Near-misses became the material for legends of the first air war. At the same time, if the aircraft was detected, engaged, and fired upon, design factors might still save it.

Each stage of the duel for survivability contained its own complex variables. Solving them and maintaining the operational strength of the air arm was an important task because of the growing role of air in combined arms operations.

### Survivability and the Air Campaign

Aircraft survivability became important in World War I not because of the legendary exploits it produced, but because effective air attacks became a valuable asset to combined arms operations. By 1918, control of the air had become one of the desired prerequisites for ground offensives. Establishing temporary control of the air enabled aviation units to drive off enemy aircraft and deny them information about the offensive as it developed. Control of the air also allowed pursuit aircraft and bombers to conduct ground attacks in support of army offensives attempting to attack and maneuver to break the deadly stalemate of the war. The air war of World War I marked the beginning of a trend in which the air components would grow to have a shaping influence over theater plans and operations.

The air component's ability to play an effective role

hinged on survivability. Loss rates determined how many aircraft and crews would be available for sustained operations. The loss of even a few aircraft per day could debilitate the air arm quickly. The chart below plots the mathematical rate of attrition of a force that begins with 1,000 aircraft, each flying two sorties per day.

Losing two percent of the force per day would result in the loss of almost 70 percent of the 1,000 aircraft in just 30 days. Without replacements, the number of sorties flown would drop by almost 50 percent, greatly reducing the effectiveness of air operations. Even at World War I production rates, no commander could afford sustained attrition and hope to remain an effective force.

Air tactics and operational employment concepts sought to maximize survivability in order to keep up effectiveness. Survivability considerations directly influenced employment concepts such as flying in formations. "The employment of a large number of pursuit airplanes in attacking ground objectives increases the safety of the operations by multiplying the targets at which the enemy must shoot," reasoned Mitchell. As a postwar manual instructed, "Bombing and machine gunning of ground targets can only be carried out when air supremacy is attained." Air supremacy had to be "temporary at least" or the loss in machines would exceed the damage done to the enemy. An experienced pilot alone over enemy lines might survive. However, the limited nature of what the lone aircraft could accomplish meant that it was not worth the risk of the pilot's life.<sup>13</sup>

Daily attrition mattered especially as senior command-

ers began to depend on air operations as a routine part of combined arms operations. Under the right conditions, air attacks could be surprisingly effective at disrupting enemy forces behind the lines. Ideal targets for air attack were forces in concentration, either retreating from or marching up to the front lines, preferably in the earliest stages of a major offensive.

*"When an offensive is under way large bodies of troops, cavalry and transport are being brought up to the line. These targets are large enough to spot from some distance in the air. Fire can be directed on the group and a great amount of material damage as well as moral damage to the enemy can be done."<sup>14</sup>*

Every major offensive in 1918 used aviation both to harass and strike at the enemy's reserves and supplies. The Germans used airpower to sharpen their offensive in the spring of 1918, and by that fall, the Allies were employing mass airpower in conjunction with their own efforts to roll back the exhausted German lines. In the fall of 1918, at St. Mihiel, Pershing instructed Mitchell to assemble a coalition force to keep German aircraft back from the ground offensive and to assist by attacking German forces as they attempted to retreat. As long as conditions for survivability could be met, the air arm could make valuable contributions to combined operations.

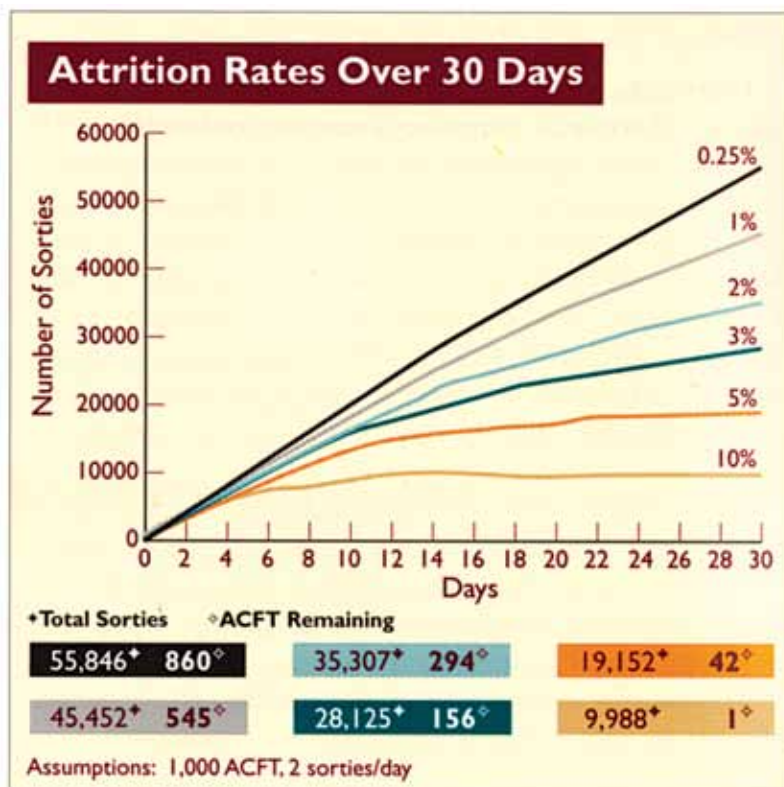
### The Interwar Years

Aircraft in World War I usually could not be detected in time to organize and integrate air defenses. That meant that the survivability duel depended on speed, maneuverability, armament, and other advantages in the engagement between aircraft or with ground-based defenses.

Aviation design in 1920s and 1930s still sought to master the duel between attackers and defenders by developing faster, more rugged aircraft as better technology emerged. For a long time, defense systems offered few advances over World War I in the problem of detecting and tracking aircraft. Both the Germans and the British developed listening devices to hear incoming bombers at long range.

Air tactics and doctrine between the wars continued to assume that aircraft would be detected only by the enemy's eyes and ears. Surprise could still be achieved. Cities and armies alike would remain highly vulnerable to surprise air attack, especially by long-range bombers.

In the 1930s, aviation technology started to yield significant advances that appeared to decrease the vulnerability of aircraft to detection. With their long range, speedy mono-wing designs and guns,



the bombers were expected to be highly survivable. They could attack with speed and surprise. Many new pursuit aircraft designs clung to biplane structures for extra maneuverability. But the drag from the wing spars of the biplane fighters slowed them down. Bombers of the 1920s and early 1930s could often outrun pursuit aircraft. As British Prime Minister Stanley Baldwin said in 1932:

*"I think it is well for the man in the street to realize there is no power on earth that can protect him from bombing. ... The bomber will always get through ... ."*

Such thinking reflected the reality that a mass formation could neither be heard nor seen soon enough for fighters and antiaircraft guns to destroy much of it. A more expert witness, Carl Spaatz, had written to a colleague in 1931 that bombers flying below 15,000 feet would need pursuit aircraft protection.

However, "at altitudes above 15,000 feet observation from the ground becomes difficult," Spaatz noted, "and above 20,000 feet bombardment airplanes can make deep penetrations without pursuit protection."<sup>15</sup> The analysis by Spaatz was based on realistic assumptions for the time.

To an observer in the mid- to late-1930s, the survivability duel contained much the same elements it had in 1918. Detection was difficult, giving the attacker the advantage of surprise. To shoot down an attacking aircraft, other aircraft or gun crews had to prevail in the engagement and assure a probability of kill, all in a relatively short space of time.

But the survivability duel was about to change beyond recognition. In Britain, by 1937, scientists had developed a device to detect aircraft at ranges far beyond that of the human eye. The effect on air tactics and operational-level plans would shape most of the decisive campaigns of World War II and the dynamics of air combat for the remainder of the century.

## THE RADAR GAME BEGINS

In World War II as never before, the fortunes of airpower would play an important role in the theater military strategy for each belligerent. World War II aviators flew in an air defense environment more lethal and consistent than anything that World War I aviators had found on the Western front. The battle for air superiority dominated operational-level plans both for air and for combined arms operations across the European theater of war. Control of the air was becoming a prerequisite for success in major ground operations.

For the first time, the survivability and effectiveness of the air component was a major weight in the balance of combined-arms operations. But neither the aircraft nor the doctrine of the interwar years were ready for the next phase of the survivability duel.

In the summer of 1938, the German corporation Telefunken

was testing a reliable radar device. Telefunken's head of development, Prof. Dr. Wilhelm Runge, was ready to demonstrate it for the Luftwaffe. Gen. Ernst Udet, a World War I ace, was then serving as Quartermaster General of the Luftwaffe, and came out to see the test. Runge recalled:

*"When I explained that it could be used to cover a 50 km area, and that in spite of fog, or at night, it would locate an aircraft easily within that range, his reaction was astonishing. 'Good God! If you introduce that thing you'll take all the fun out of flying!'"<sup>16</sup>*

Udet correctly sensed that radar early warning would strip attacking aircraft of the element of surprise and set in motion a grueling duel between attackers and defenders. The radar

Radar Timeline I									
1873	1886	1900	1904	1912	1932	1933	1934	1935	1938
Maxwell predicts propagation speed of electromagnetic waves	Hertz detects radio waves	Tesla writes on using waves to detect objects	Hulsmeyer builds telemobiloscope and detects ships	First aircraft shot down by AAA in Italo-Turkish War	Former PM Baldwin states that the bomber will always get through	British propose acoustic mirrors for Thames Estuary	<ul style="list-style-type: none"> <li>■ German warship Hessen uses primitive radar to navigate Kiel harbor</li> <li>■ US Naval Research Laboratory tests radio aircraft detection system</li> </ul>	<ul style="list-style-type: none"> <li>■ Watson-Watt writes memo on aircraft detection</li> <li>■ In Daventry experiment, British track bomber at 8 miles and 10,000 ft</li> <li>■ Marconi develops crude radar set for Italian Army</li> </ul>	<ul style="list-style-type: none"> <li>■ British set up Chain Home radar network</li> <li>■ HMS Sheffield detects aircraft at 53 miles and 10,000 ft</li> </ul>

game forever changed air combat tactics, and its effect on survivability rates rapidly came to dominate operational plans for air warfare.

Radar took airmen by surprise. While the basic principles behind radar waves had been understood by at least a few scientists for years, it was not until the mid-1930s that intensive research solved several important technical challenges.

In 1904, just one year after the first flight at Kitty Hawk, a German engineer named Christian Hulsmeier invented the first telemobiloscope. The device generated radio waves to detect ships at ranges of a few miles. Hulsmeier obtained a patent for his invention but failed to find customers for his device, and the patents lapsed. But 30 years later, in 1934, researchers in America, Britain, France, Italy, Germany, and the Soviet Union were at work on radar detection projects. The Leningrad Electrophysics Institute had a device to detect aircraft two miles away. The French luxury liner *Normandie* boasted a microwave obstacle detector.

The British brought together a research team that had the first success in using radio waves to find the range, azimuth, and height of an aircraft. In the summer of 1935, Robert Watson-Watt's experiments at Orfordness detected and tracked aircraft at a range of 40 miles and measured height to within 1,000 feet. Radio Direction And Ranging, better known by its nickname radar, had been born.

### How Radar Works

Why were aircraft so vulnerable to radar detection? In short, for all the reasons that increased their aerodynamic qualities and performance. Metal skins, large vertical control surfaces, big powerful engines with massive propeller blades: All the features that made the German Me-109 Messerschmitt and the American Boeing B-17 bomber faster and more reliable also made them excellent radar reflectors.

Radar detects scattered radiation from objects, and is particularly good at detecting highly reflective metallic objects against a less reflective background such as the sea or the sky. Waves are generated and transmitted in the radio-frequency part of the electro-magnetic spectrum. The radar receiver then captures the reflection of the waves as they are encountered and are transmitted back from objects of interest. Since the speed of radio wave propagation from the radar is a known constant, radar systems can determine the position, velocity, and other characteristics of an object by analysis of very high frequency radio waves reflected from its surfaces.

Hulsmeier was readily able to develop and patent a radar detection device in 1904 because the principles of electromagnetic waves had been thoroughly researched in the latter part of the 19th

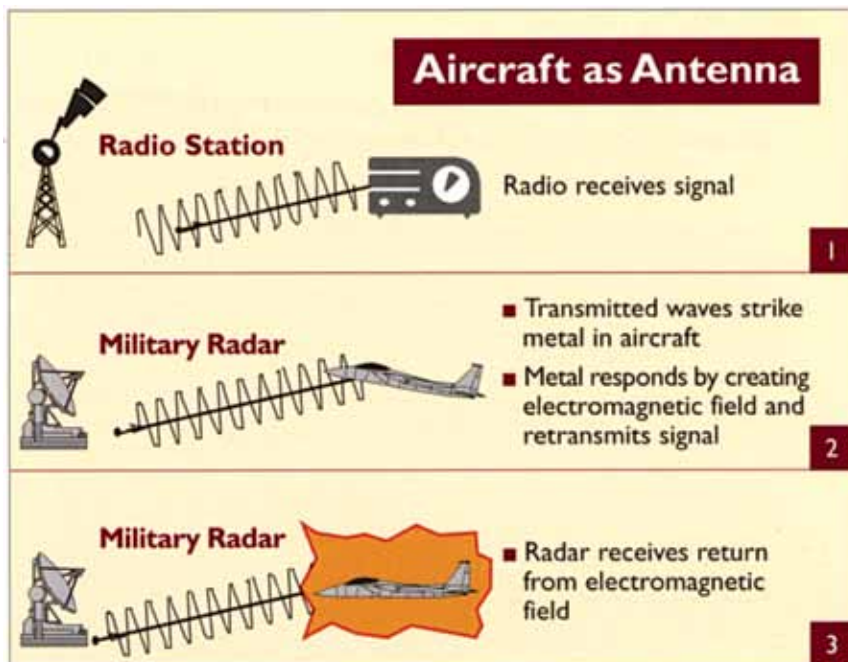
century. An electromagnetic wave consists of two parts: an electric field and a magnetic field. These fields rapidly fluctuate in strength, rising to a peak, falling away to zero, then rising to a peak again. This process repeats itself over and over as the wave travels (propagates) in a direction at right angles to the electric and magnetic fields. Waves are measured in terms of frequency and wavelength.

The frequency of a wave equals the number of crests or troughs that pass a given fixed point per unit of time. Wave frequencies are measured in terms of kilohertz (one thousand cycles per second), megahertz (one million cycles per second), and gigahertz (one billion cycles per second). Wavelength, the distance between two successive peaks of the wave, is directly related to the physical size of the antenna. Increasing the frequency of a wave decreases the wavelength.

British experiments with the first operational detection of aircraft essentially sought to swap an airplane for a radio antenna to transmit back a signal. To grasp this process, it is important to understand that radar energy striking an aircraft does not simply bounce off the target in the way that a ball bounces when it strikes a wall. When a radar wave meets an electrical conductor, such as a wire, it creates within that electrical conductor electromagnetic currents at the same frequency as the wave. The electric and magnetic fields that form the wave are polarized and retransmitted. This retransmission is the same thing that occurs when listeners tune into radio signals using a radio receiver and antenna.

Panel 1 shows how electromagnetic waves from a distant transmitter at the radio station induce a small current within the antenna of the radio. The radio receiver amplifies it and transmits it through the speakers.

Panel 2 shows that when a radar wave hits an aircraft, it induces within the aircraft electric and magnetic currents.





These currents then create new electromagnetic waves, depicted in Panel 3, that are emitted from the aircraft in various directions and, depending on where they strike the aircraft, are seen by the radar receiver as reflected echoes. These echoes are significantly weaker than the original electromagnetic waves transmitted by the radar.

The first test of British radar—the Daventry Experiment—was conducted on Feb. 26, 1935. In essence, the Daventry experiment treated the aircraft like a flying antenna that could transmit waves back to the receiver on the ground for detection.

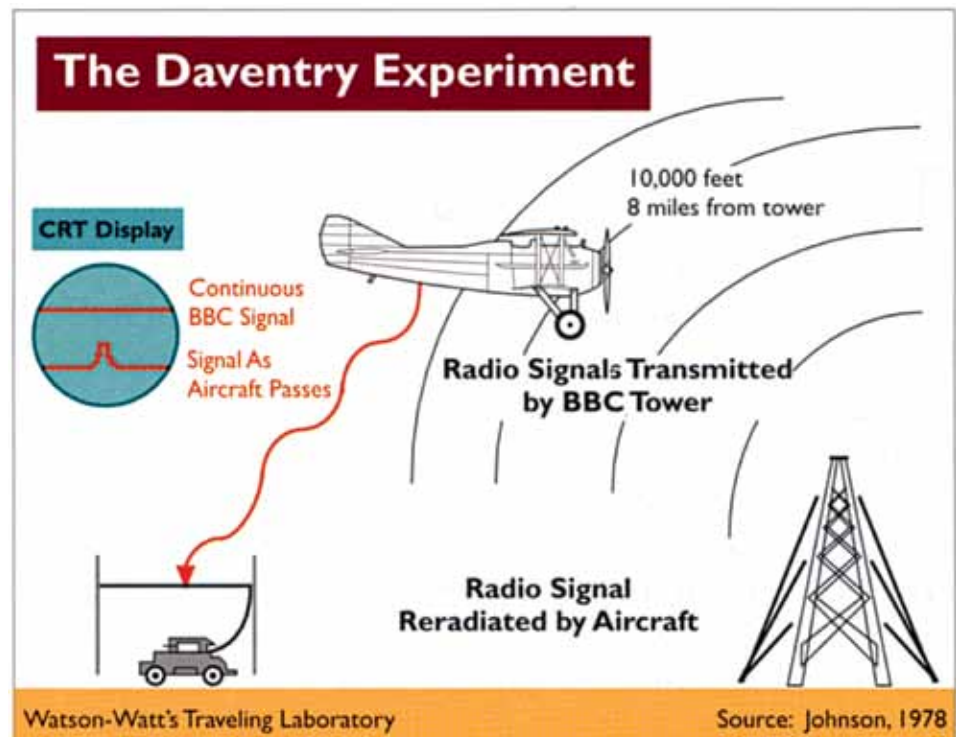
Watson-Watt's team carefully calibrated the wavelength of the transmitted signal so that the aircraft wing would generate a strong return. British scientists knew from their work on radio antennae that a wire whose length corresponded to half the wavelength of the radio signal would re-radiate strongly. Assuming that the wing of an aircraft would behave in the same manner, the engineers settled on a frequency whose wavelength would be twice that of the typical German bomber, or about 25 meters (80 feet). Thus the engineers chose 49-meter wavelength signals at 6MHz.

A BBC radio station served as a crude transmitter issuing a constant beam at a wavelength of 49 meters. A Heyford bomber, flying at 100 mph and 10,000 feet, eight miles distant, crossed the continuous beam and briefly transmitted reflected radio waves back to the receiver.

One initial problem with Watson-Watt's Daventry continuous-wave radar system was that outgoing signals interfered with incoming signals. By June 1935, the British had developed a pulsed transmitter, which sent out pulses of electromagnetic energy so that the receiver could distinguish among echoes. Pulse radar, now standard, uses a single antenna for transmission and reception. Pulse radar sends a high-power burst of radiation then waits for the return signal. The interval between pulses matches the time for a wave to reach a target at a given distance. This process takes place thousands of times per second in a typical pulse radar.

Upon seeing the blip appear on a cathode ray tube, Watson-Watt reportedly commented that Britain had become an island once more. The prospect of detecting aircraft en route to attack opened up profound possibilities for air defenders. Britain rushed to capitalize on them.

By April 1937, experimental stations had detected planes at a range of 100 miles, and by August, Britain had activated its first three Chain Home radar stations at Bawdsey, Canewdown, and Dover.



### Radar Early Warning: The Battle of Britain

The airplanes rolling off factory assembly lines on the eve of World War II were poorly prepared to cope with radar and its consequences. Planes flew faster, higher, and farther, with greater safety and reliability, than they had in World War I. They had sturdy metal skins and big engines that generated thousands of horsepower. However, in the radar game, aerodynamic advantages also contributed to the prospect of being detected, in advance, by radar. The radar game stripped away the element of surprise that dated from the days of visual and acoustic detection. It added a new and complex realm of vulnerability and opportunity to the aerial duel and made the detection stage of the duel critically important.

British air defenses were the first to score big benefits from the radar game. The Chain Home radar system now ringed the air approaches to the island.

During the Battle of Britain in 1940, radar early warning allowed the RAF to direct their scarce fighters to attack incoming German formations instead of patrolling assigned air defense sectors. In early August 1940 the Luftwaffe still believed that RAF fighters were "controlled from the ground" and "tied to their respective ground stations and are thereby restricted in mobility. ... Consequently, the assembly of strong fighter forces at determined points and at short notice is not to be expected."<sup>17</sup> The Luftwaffe judged that the RAF was already weakened and could be defeated in daylight operations by piercing thin sector defenses with stronger formations as the RAF attempted to patrol every sector of the southeast coast.

Instead, the RAF found that radar early warning made fighters effective in a way that had not been imagined. The

Chain Home radar early warning system detected approaching aircraft out to about 100 miles. Radar intercepts passed to sector operations centers alerted the RAF ground controllers when the Germans took off from the airfields across the Channel and formed up for attack. Early warning gave the RAF a much better estimate of the heading and numbers of German aircraft. Updated estimates of the bearing of the incoming formations clued in the RAF as to the objectives of the attack. Mission directors on the ground could then alert fighters to scramble, or even better, vector fighters already on patrol and at altitude to intercept the German formations.

Admittedly, the Luftwaffe's strategy counted on bringing the RAF up to fight. But the RAF's advantage in being able to mass for the encounters robbed the Germans of surprise and its advantages, such as selection of the time and location for aerial engagement. Radar helped compensate for inferiority in numbers in a way that would never have been possible had the RAF tried the kind of sector defense the Germans anticipated.

The Battle of Britain showed that early warning gave defending fighters the time and flexibility to mass for intercepts. For the RAF, the flexibility provided by radar stole the advantages of mass from the Luftwaffe. By mid-September 1940, the Germans did not believe they had established even local air superiority over the southeast of England and the Channel coast. Without air superiority in these areas, the amphibious invasion plan code-named Operation Sealion could not be mounted. In the

end, the failure to gain air superiority compelled the Germans to postpone the invasion of Britain indefinitely.

### Survivability and Air Operations

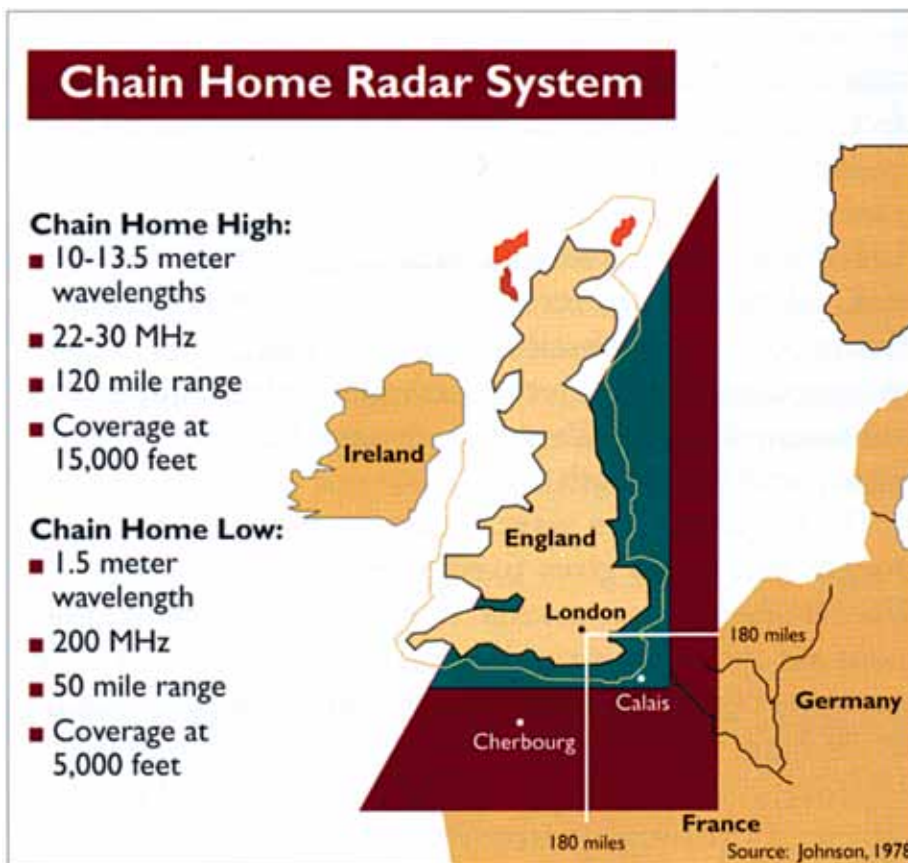
The survivability duel now depended much more on making use of early warning and detection. Just as early warning radar gave the British an edge in the Battle of Britain, it gave the Germans an advantage when the Allies began deep penetration attacks on targets in Nazi-held Europe.

Bomber survivability became the first key to offensive action in the air and to the design of the European theater campaign. What is seldom realized is that the Eighth Air Force's most legendary—and most costly—missions in 1943 focused on winning control of the air. Eighth Air Force's objectives were not based primarily on a strategic campaign that disregarded combined arms strategy in the European Theater of Operations (ETO.) Instead, they had a single overriding aim: to choke the Luftwaffe. All other priorities were subordinate.

In June 1943, the Combined Chiefs of Staff ordered the bombing campaign to concentrate on the German aircraft industry. In the Pointblank directive, they called on the air arm to "check the growth and reduce the strength of the day and night fighter forces." The "first priority of the British and American bombers based in the United Kingdom is to be accorded to the attack of German fighter forces and the industry on which they depend." As an Army Air Forces report later put it, "the success of future strategic campaigns and invasion of the continent depended on eliminating the Luftwaffe."<sup>18</sup>

German early warning radars like the Freya ringed the coast of Nazi-occupied Europe. Radar tracking allowed the Germans to organize an air defense that would direct fighters at forward bases to engage bomber formations. The deeper the bombers had to fly to reach their targets, the more time German fighters would have to engage them. This greatly increased what can be termed the time in jeopardy for attacking bomber formations. Time in jeopardy is defined in this study as the period during which defenders could track and engage attacking aircraft. Instead of being intercepted only over the target area, bombers might be repeatedly detected and engaged on their route to the target and back.

The Allies rapidly discovered that attacks on cities deep in Europe exposed the formations to repeated engagements staged out of the many Luftwaffe bases from the French and Dutch coasts to the interior. Radar tracking made this possible by alerting fighters and leading them to the general location of the bomber formations.



The Pointblank directive presented Allied bombers with significant survivability problems because German air defenses were much more effective with the use of radar. The only way to strike at the Luftwaffe was to hit its fighter production. German fighter production was concentrated at a few main industrial centers.

Eighth Air Force decided to pair a raid on Regensburg, which produced 500 of the estimated 650 Me-109s that rolled off the assembly lines each month, with a strike on Schweinfurt's ball-bearings industry.

The Regensburg force left the coast of England at 0935 on Aug. 17, 1943. German early warning radars first detected the bomber formations as they climbed to altitude and formed up over England. At 17,000 feet, the formation was already within range of the German radar screen with its 150-mile range. German airfields from Paris to Denmark alerted fighters to intercept the bomber streams.

En route to the target, the bombers spent nearly all of the next three hours in jeopardy from fighter intercepts along their radar-tracked flight path. Ground controllers passed the location and bearing of the bomber formations to the fighters. German fighters acquired the bombers visually and used electric gunsights to track and attack them. As the B-17s approached the target, antiaircraft guns, also cued and vectored by radar, put up a dense curtain of 88mm flak. Lead formations bombed Regensburg at 1143. The Schweinfurt force, delayed by fog, departed England at 1314 and spent the next four hours in jeopardy, bombing at 1457.

For the B-17, the engagement phase of the duel depended on the formation's defensive firepower and later, on escort fighters to defend the bombers against engagement by enemy fighters. When the formation reached the target area, more defenses awaited.

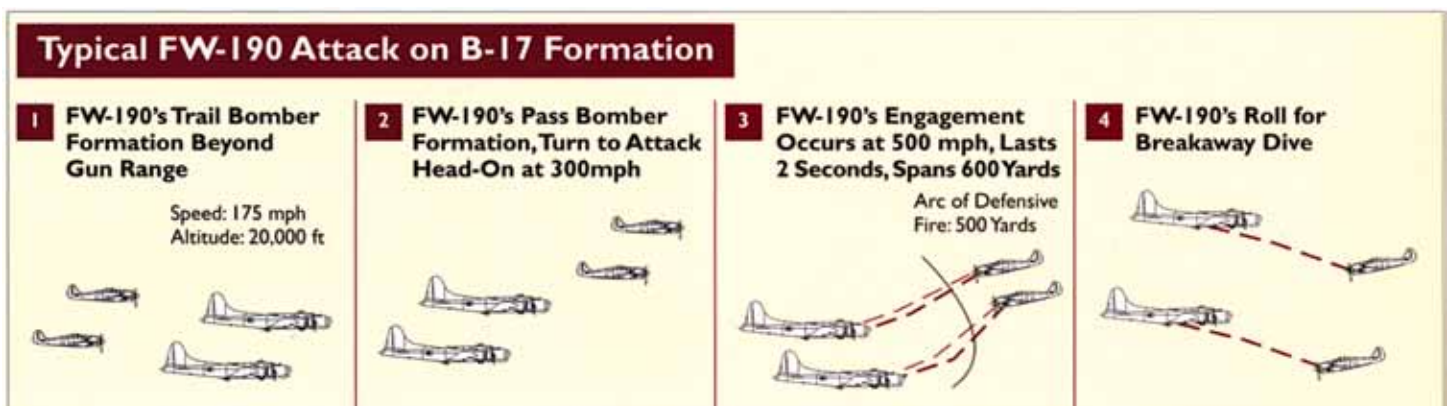
Bombers had to fly directly over their targets to release their bomb loads. Some targets, like the oil refinery at Leuna, were ringed with over 700 antiaircraft artillery (AAA) batteries.

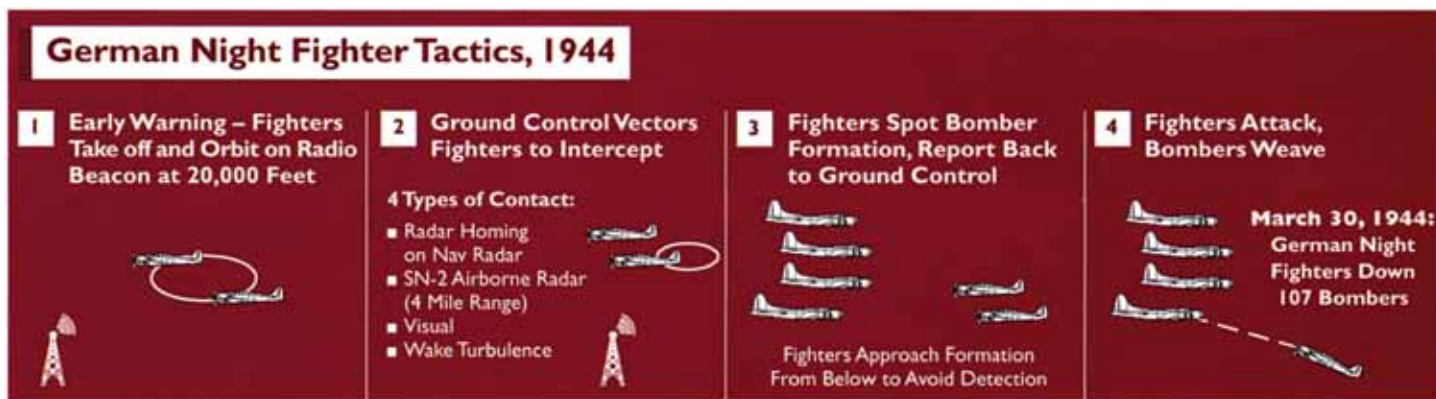


Ground-based flak batteries made use of radar for target tracking and height finding. From 1941, German units introduced gunlaying radar. Ground-based fire control radars aided the German antiaircraft guns in determining height and bearing. With accurate height estimates, fuses on artillery shells could be set to explode nearer the bomber formations. Over the course of the war, German air defenses also experimented with radar-guided flak rockets.

The Regensburg force flew on to land at bases in North Africa. The route was picked to avoid AAA and fighters on the return route. The Schweinfurt force returned to England along the same route, spending another three hours in jeopardy. All told, Eighth Air Force lost 16 percent of the dispatched force that day.

In the final analysis, the rugged design of the B-17 often helped the bomber and its crew survive attack by decreasing the probability of kill. The chart below diagrams a typical en-





agement against unescorted bombers. On deep raids, bomber formations withstood numerous assaults from fighters. With the advantage tilting toward the fighters, Eighth Air Force had to devise additional tactics to win air superiority.

An integrated air defense that employed radar for early warning and tracking could inflict losses on the attackers that compounded over time. A sustained loss rate comparable to the rate of 16 percent on the Schweinfurt and Regensburg raids would have ripped the bomber force in half after five days. In two weeks of continuous operations, the force would have been drained to less than 20 percent of its starting strength. The loss of machines paled next to the loss, injury, and capture of trained aircrews. Average losses in 1943 put the Army Air Forces on track to consume its entire force at a rate of two-and-a-half times per year.

With radar providing highly controlled intercepts, the bomber formations were spending too much time in jeopardy, subject to organized and persistent attack instead of sporadic encounters—conditions that aircraft designers of the mid-1930s had not anticipated. Since the tactics of formation flying did not compensate adequately, the additional measure of fighter escorts with longer range made up the gap, ensuring that the bombers spent less time in jeopardy on each mission.

What the fighters needed to do to help the bombers survive was to extend their range and to take the offensive. Luger drop tanks met the first goal in 1944. By sweeping ahead of the bomber formations, fighters regained the advantages of initiative and position. Jimmy Doolittle, who took command of Eighth Air Force in late 1943, later related that on taking command he spotted a sign saying the mission of the fighters was to bring the bombers back safely. Doolittle ordered it changed to read: "The first duty of the Eighth Air Force fighters is to destroy German fighters."<sup>19</sup>

Luftwaffe fighter ace and commander Gen. Adolf Galland wrote after the war that the day the Eighth Air Force fighters went on the offensive was the day the Germans lost the war. The duel between bombers, escorts, and Luftwaffe fighters turned in part on who devised the quickest remedies for aircraft survivability, and in part on production of aircraft. For the Allies, escort tactics curtailed losses and destroyed German aircraft, bringing attrition rates to levels that could be met by wartime production. For the Germans, the crucial survivability

factors ultimately came down to the loss of their trained and experienced pilots.

### Deception Techniques

Another clear example of radar's impact was the German development of night intercept operations. After the fall of France in May 1940, the RAF had begun night bomber attacks on German military and industry targets in the Ruhr and elsewhere. German early warning radar could still pick up formations on their approach but the problem of visual acquisition and tracking was much more difficult to perform at night. However, finding ground targets at night was also much more difficult. A 1941 report found that only one in five RAF sorties dropped bombs within five miles of the target. British Prime Minister Winston Churchill ordered high priority development of radar aids for navigation to improve accuracy. By early 1942, radar navigational devices were being installed in heavy bombers. The high performance H2S system was available on a number of aircraft by mid-1943, and on July 24, H2S pathfinders led a 740 aircraft attack on Hamburg.

The Germans countered these far more devastating night raids by perfecting a system of ground-controlled night fighter interception that also capitalized on radar. The German night intercept operations linked radar early warning to a system of ground control and led also to the use of airborne radar for fighter intercepts.

As shown in the four panels of the chart above, early warning first cued night fighters to take off and climb to 20,000 feet, where they took up station on a radio beacon, awaiting instructions.

When bombers entered the radar range of a ground station, German controllers vectored night fighters to an intercept course. Once on course, pilots relied on visual detection and even the buffeting of wake turbulence to find the bomber streams. Night fighter pilots radioed back the position and heading of the bomber streams, then were cleared to engage.

During the engagement, night fighters used special modifications such as upward-pointing guns and short-range airborne radar. They also employed airborne radar with a range of about four miles to detect the bomber stream.

On the night of March 30, 1944, German night fighters

brought down 107 British heavy bombers in their raid on Nurnberg. At their peak, German night fighters practiced “the most complex type of modern aerial combat,” in the words of an official American AAF account. The airborne radars of World War II had not yet evolved to the point where they could provide precise fire control to guide actual weapons to their targets. However, the increasing exactness of radar-controlled intercept was deadly enough to spur development of measures to prevent radar detection.

### Early ECM

Radar begat countermeasures almost immediately. As radar began to give air defenders a clear picture of the location, direction, and altitude of incoming attackers, the attackers sought ways to deny this information to the enemy. Early countermeasures primarily affected the variables of detection and engagement in the survivability equation.

Manipulating the electromagnetic spectrum through creating deceptive returns took three forms: generating clutter, jamming transmissions, and making objects appear larger to confuse controllers. All were pioneered in some form in World War II.

Generating false signals sought to neutralize the early warning radar that formed the backbone of the German night fighter intercept system. In a February 1942 commando raid at Bruneval, the British seized a Würzburg radar set which aided in the development of countermeasures. The product was “Window,” the codename for strips of metallic foil dropped from bombers to saturate enemy radar scopes.

Chaff complicated the ground controller’s job by creat-

ing numerous flashes and false blips and clouds on the radar screen.

Although countermeasures were developed swiftly, the RAF waited nearly 18 months to use them in battle. Senior planners feared that if the RAF employed countermeasures, the Germans would do the same.<sup>20</sup> In the July 1943 Hamburg raids, the RAF used 92 million strips of Window, which brought German radar scopes alive with false echoes. The RAF lost only 12 aircraft rather than what would have statistically been around 50 without the aid of Window.<sup>21</sup>

German air defenses were thrown into disarray by the RAF tactics. According to the Luftwaffe’s Galland:

*“Not one radar instrument of our defense had worked. The British employed for the first time the so-called Laminetta method (Window). It was as primitive as it was effective. The bomber units and all accompanying aircraft dropped bundles of tin foil in large quantities, of a length and width attuned to our radar wave length. Drifting in the wind, they dropped slowly to the ground, forming a wall which could not be penetrated by the radar rays. Instead of being reflected by the enemy’s aircraft they were now reflected by this sort of fog bank, and the radar screen was simply blocked by their quantity. The air situation was veiled as in a fog. The system of fighter direction based on radar was out of action. Even the radar sets of our fighters were blinded. The flak could obtain no picture of the air situation. The radar target-finders were out of action. At one blow the night was again as impregnable as it had been before the radar eye was invented.”<sup>22</sup>*

German counter-countermeasures followed rapidly. Skillful operators learned to sort out false signals and maintain the ability to provide vectors. The Luftwaffe engaged 4,000 engineers on projects such as the Würzlaus which detected the slight difference between slow-moving strips of foil and the bombers flying at 200mph. Other devices tried to pinpoint the faint radar modulation present on echoes from aircraft propellers. A set of special receiving stations was equipped to detect transmission from the British H2S navigation radar sets.

In the air, German night fighters switched to three-meter wavelength (90 MHz) radar that was unaffected by the Window strips that had been cut for 50 centimeter radar.<sup>23</sup> Some German



fighters could also detect emissions from the British H2S system on the pathfinders and a later tail-warning radar. The FuG 227 Flensburg radar receiver was tuned to match the frequency of the “Monica” tail-warning radar sets used by RAF bombers. The FuG 350 Naxos performed the same role but was tuned to the H2S radar set. The British learned of these German devices in early 1944 when a Ju-88G night fighter mistakenly landed in Essex.

Within 10 days of finding this aircraft, the British developed longer forms of Window (code-named “Rope”), removed tail warning radar sets from bombers, and ordered bomber crews to use H2S only when absolutely necessary.

A second major ECM device used in the war, codenamed “Carpet,” electronically jammed German radar. In October 1943, the Allies first used Carpet as both a broad band (multiple frequencies) and spot jammer (single frequency). The idea behind jamming was to transmit signals on the same frequency as the radar receiver so that the operator could not sort out the radar return they sought from signals sent by the jamming aircraft. The Allies used Carpet, Dina, Rug, Lighthouse, and other jammers that were effective in the frequency ranges of most German radar systems.<sup>24</sup> “Mandrel” jamming aircraft accompanied RAF bombers to disrupt Freya radar sets, “Piperack” countered the Lichtenstein radar, and “Perfectos” triggered German fighters identification friend or foe (IFF) sets to reveal their position.

Finally, the British experimented with ways to blanket the sky with large radar returns that would mimic a large attack force where none was present. “Moonshine” transponders emitted signals that made a single decoy aircraft appear on radar as a large formation of bombers. To obtain the necessary radio and radar frequencies for these devices, the British sent “ferret” aircraft of the secret 192 and 214 Radio Counter Measures Squadron alongside bombing missions to use sophisticated receivers to detect enemy transmissions.<sup>25</sup>

Two electronic armadas were part of the cast for the Normandy landings on June 6, 1944. As many as 600 radar and jamming systems guarded the coastline. Just before the invasion, Allied bombers destroyed key German jamming sites and hit radar installations, leaving a site near Le Havre damaged but functional as part of the ruse. Then the Allies projected two false invasion forces, known as Taxable and Glimmer, by employing a menagerie of forces to form large radar reflectors.

Taxable consisted of a formation of eight Lancaster bombers flying in a pattern dispensing chaff to make the Germans think a large invasion force was headed toward Cap d’Antifer. The Lancasters were equipped with “Moonshine” transponders that picked up German radar impulses and amplified them to depict a larger force. Below the aircraft, a flotilla of boats towed naval barrage balloons equipped with radar reflectors designed to make them look like large warships and troop transports. The Glimmer force made mock runs against Dunkirk and Boulogne and used jamming to conceal the true size of the force. Ships in the Glimmer group broadcast noise simulating anchor drops, and smoke screens concealed operations. Meanwhile, RAF

bombers dropped huge amounts of Window far to the west of the invasion site.<sup>26</sup>

Radar countermeasures helped preserve tactical surprise for the invasion force. In the end, only one German radar site picked up the actual invasion force, and that station’s report was lost in the chaos of false reports generated by detections of Taxable and Glimmer.<sup>27</sup>

## The Radar Game and the Theater Campaign

The air component directly affected the timetable of planning for theater level operations throughout World War II. At the operational level, control of the air was a prerequisite for successful ground operations. In World War II as never before, the air components set the parameters of theater military strategy for each belligerent. One historian wrote of the importance of the air operations in the Battle of Britain and how they were intended to precede a cross-channel invasion:

*“In previous campaigns, the aerial onslaught against the enemy air forces had taken place simultaneously with the army’s advance across the border: for Operation Sealion, it was to be a precondition to military action.”<sup>28</sup>*

Survivability and the role of the air component was no less important as the Allies took the offensive.

Seen in the light of operational planning, survivability had to be achieved even in the face of a radar game that took away the attacker’s element of surprise. The RAF and AAF won control of the skies over Europe, albeit at great cost. The payoff, as long expected, was the freedom to conduct attacks to shape and support the Normandy landings.

## Survivability and the Theater Campaign: Operation Overlord

Landing forces on the coast of France was a straightforward but ambitious task: “Pour men and equipment ashore at one or more points so fast that they could overwhelm the enemy defenses there, then dig in firmly to avoid being thrown back in to the sea by the first enemy counterattack.” Just as the Germans needed local air superiority to attempt Sealion, the Allies had to eliminate the Luftwaffe from the battle area before the invasion.

The reason was firmly rooted in the operational doctrine that had guided plans for the invasion all along. German forces in the Normandy region numbered nearly one million. The Allies would put ashore almost 325,000 troops within days after D-Day. However, the numerical superiority of the Germans had to be offset by denying Field Marshall Erwin Rommel the ability to reinforce and maneuver to defeat the invasion force’s toehold on the continent.

When aircraft were assured of a reasonable level of survivability, they could be counted on to execute missions with

direct impact on enemy ground forces. Air superiority gave Gen. Dwight D. Eisenhower the ability to even the balance of ground forces in the Normandy region. Allied air guarded friendly forces from attack, while going on the offensive to shape the battle behind the front lines. Air attacks on bridges, roads, and rail transportation prevented the Germans from moving in reinforcements. Allied airpower kept the road and rail transport system under constant attack. Motor transport moved only by night and even then under bombardment. "Rail transport is impossible because the trains are observed and attacked in short order," recorded Gen. Friedrich Dollman of the Seventh Army High Command on June 11, 1944. Dollman went on to report:

*"Troop movements and all supply traffic by rail to the army sector must be considered as completely cut off. The fact that traffic on the front and in rear areas is under constant attack from Allied air power has led to delays and unavoidable losses in vehicles, which in turn have led to a restriction in the mobility of the numerous Panzer units due to the lack of fuel and the unreliability of the ammunition supply."<sup>29</sup>*

The effects accumulated, for road transport was less efficient than rail transport, and road transport itself was more costly because of strategic shortages of rubber tires and petrol.<sup>30</sup>

Air interdiction restricted the enemy's ability to resupply, reinforce and mass for a major counterattack, thereby assisting the Allies as they pressed on with the liberation of Europe. The lack of a concerted challenge from the Luftwaffe enabled freedom of operation in the skies over Normandy that

allowed the tactical air forces to control the flow of enemy forces behind the front lines.

### In Summary

The course of the air war over Europe indicated that survivability was a fleeting balance of elements and that its components could change as different tactics, technologies, and objectives were rolled into the equation. Had any of the belligerents introduced their advanced aircraft designs in significant numbers, and at the right time, they might have tipped the balance of the air war by again altering the equation of aircraft survivability. The Me-262 "easily flew circles around our best fighters," admitted Doolittle, who after the war remarked, "I shudder to think of the consequences had the Luftwaffe possessed this aircraft in large numbers and employed it properly."

The radar game of World War II opened a new era of air combat. For the first time, aircraft survivability was a major variable in theater operational plans. The duel for survivability was now dominated by radar in the detection phase. These two changes came at a time when combined arms operations started to depend on the air component to set the conditions for major ground action and to ensure that attacking forces on the ground could count on not being stopped by enemy air.

World War II also marked clear trends that would continue to alter the duel between attackers and defenders. Experiments with airborne radar in fighters, and with radar-controlled flak and missiles, indicated that the engagement phase and probability of kill would soon become part of radar game, too.

## THE POSTWAR RADAR GAME

*"(I)n an all-weather Air Force, radar must be the universally used tool for bombing, gunfire, navigation, landing, and control. ... The development and perfection of radar and the techniques for using it effectively are as important as the development of the jet-propelled plane."—Theodor von Kármán, August 1945*

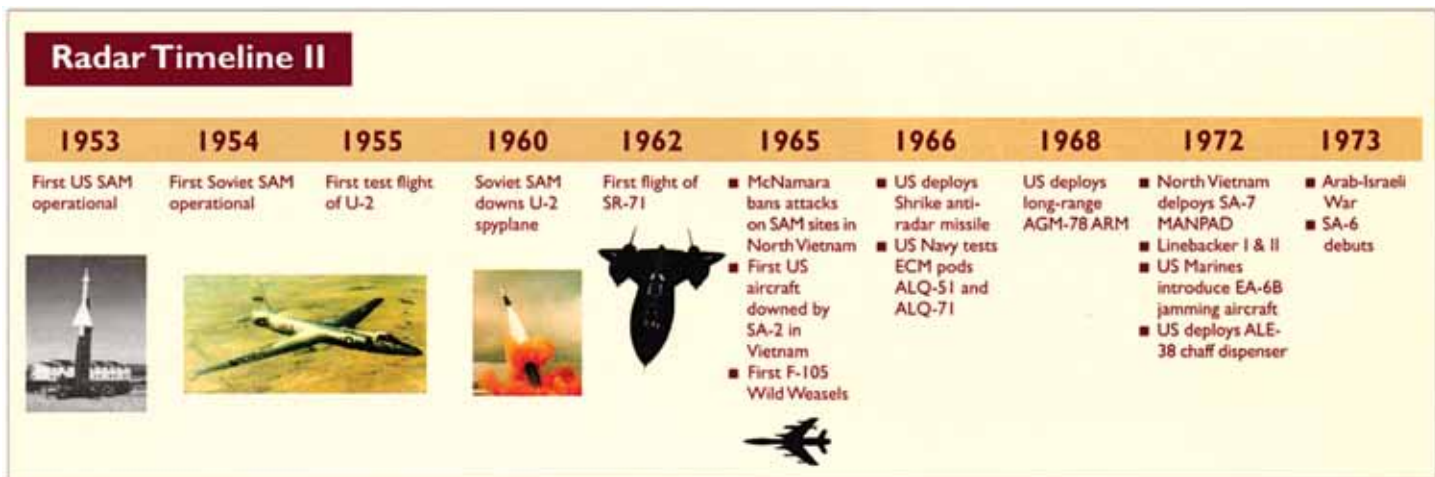
Developments in guided missile technology, combined with additional improvements to radar detection, would make the postwar radar game even more deadly. By the 1960s, radar's ability to guide each phase of the survivability duel would threaten to curtail the ability of aircraft to control the skies over the battle space.

Research on guided missiles had begun during World

War II. The German Enzian surface-to-air missile was just one of several experiments.

Postwar research, especially in the United States and the Soviet Union, concentrated on guiding missiles through on-board radar or infrared seekers to improve accuracy. NATO intelligence first discovered the existence of the Soviet SA-2 in 1953.<sup>31</sup> The first American surface-to-air missile became operational in the same year.

Both the US and the Soviet Union envisioned a need for air defenses to guard their territory from attacking bombers carrying nuclear weapons. An early US missile named Bomarc relied on a ground-controlled radar to turn the missile into attack position. A second radar guidance system would allow the Mach 2.7 Bomarc to lock onto its target in flight.<sup>32</sup> Vast quantities of these radar-guided SAMs with at



least a 25-mile range would be required to defend continental US airspace. The growing threat from radar-controlled missiles was putting aircraft survivability into some doubt. Radar and infrared seekers could guide missiles most or all of the way to the target. Radar now played a role in each stage of the duel: detection, engagement, and probability of kill.

US planners were also well aware that the Soviet Union was beginning to present more heavily defended targets to SAC's bombers. In 1947, discussions on requirements for the XB-52 stared these dilemmas in the face. To gain more payload, an atomic bomber "might even have to dispense with guns and armor in order to attain the speed and altitude necessary to assure its survival."<sup>33</sup> The lack of intelligence about threats to be faced over the Soviet Union created more complications. An air weapons development board raised questions:

*"Would it be possible for them to fly fast enough and high enough to evade the interceptors? Or would they still need to bristle with guns? If the latter were true, development became more complex. Bulky turrets had to be eliminated for aerodynamic reasons, while fire control systems had to cope with high speeds."*

To cap off the dilemma, if enemy fighters had flexible guns, speed would not yield adequate protection.<sup>34</sup>

The options for countering radar-guided missiles and antiaircraft fire started with traditional improvements, in categories like speed and performance. Mastering jet engines and making the early jet aircraft safer and more reliable consumed the attention of aircraft designers. Jet fighters were judged on the same general performance criteria as were the Spads of World War I: speed, maneuverability, power, and overall performance. Aircraft of the jet age had greatly improved performance, but their conventional designs remained just as easy for radar to spot.

The bombers that entered the force in the 1950s relied on altitude, speed, and a tail gunner's position. The B-47, for example, had a top speed of more than 500 knots. Concepts

for "parasite" fighters to be launched from and recovered by bombers themselves had proved impractical. The bombers would have to approach their targets in the USSR without escort. Attacking in numbers would also complicate the Soviet defense problem. By the time the B-52 went into production in 1952, Gen. Curtis LeMay knew that the big bomber would be conspicuous on radar, but reasoned that its size would eventually permit it to carry more electronic gear for radar-jamming.<sup>35</sup> Besides, SAC was not necessarily posturing for a sustained offensive. Talk of one-way missions and the knock-out blow of the atomic bomber offensive eclipsed the calculation of long-term bomber attrition. Still, the fact remained that the Soviet Union was developing long range early warning radars and radar-controlled SAMs to engage hostile aircraft.

The severity of this threat stood out clearly in a statement by Gen. Thomas D. White. In summer 1957, just before becoming USAF Chief of Staff, White stated that a mix of ballistic missiles and bombers in the nuclear fleet would "permit greater versatility for our forces by relieving manned bombers of those heavily defended targets where the cost of attacking with bombers would be too high and where precise accuracy is not mandatory."<sup>36</sup> It was around this time, though, that speculation blossomed that continued development of radar-guided missiles would usher in "the coming death of the flying air force."<sup>37</sup>

### On the Verge: The U-2 and SR-71

Meeting the challenge of integrated radar-controlled air defenses equipped with radar-guided SAMs became the chief preoccupation of strategic air war planners in the late 1950s and 1960s. Aircraft design was pushing the limits of high speed and high altitude flight, and for a time, these two areas became the natural resources for new survivability techniques.

New reconnaissance aircraft strove for maximum survivability because their mission was to overfly the Soviet Union. Only extreme combinations of performance attributes could keep aircraft out of jeopardy. One tactic was to fly at high



altitude. Built in 1955, the U-2 aimed to fly above the altitude ceiling of Soviet fighter-interceptors. The Soviets knew about the U-2 flights from the start. As one of the early pilots recalled:

*"I knew from being briefed by the two other guys who flew these missions ahead of me to expect a lot of Soviet air activity. Those bastards tracked me from the minute I took off, which was an unpleasant surprise. We thought we would be invisible to their radar at such heights. No dice."<sup>38</sup>*

Then on May 1, 1960, a barrage of 14 SA-2s brought down the U-2 piloted by Gary Francis Powers. It was the first US aircraft lost to a radar-guided SAM. Another U-2 was shot down in 1962. With the altitude sanctuary pierced, aircraft design would have to press to new extremes to prevail in the radar game.

To cope with these air defenses, the SR-71 combined an operational ceiling of 80,000 feet or more with a top speed of Mach 3+ to enhance survivability on deep penetrating reconnaissance missions.

The SR-71 was equipped with ECM to jam missile seekers, and its design probed at the possibility of minimizing radar cross section. However, its chief survivability characteristics were altitude and speed. SAMs fired at the SR-71 often exploded several miles behind the streaking aircraft. "We knew we'd probably get shot at, but it wasn't a big worry because at our height an SA-2 missile simply didn't have the aerodynamic capability to maneuver," one SR-71 crew member reasoned.<sup>39</sup> The attempt to build a bomber in the league of the SR-71 failed with the B-70. Lt. Gen. Otto J. Glasser, chief of staff for research and development in 1971, recalled, "The B-70 was capable only of operating very high, very fast, and when the SAM missiles came into operational use, the B-70 found it could not operate in its design regimen, and it had little residual capability to operate in other regimes."<sup>40</sup>

For aircraft without the SR's one-of-a-kind performance, survivability would increasingly rely on means of deceiving and thwarting the enemy's ability to detect, track, and engage aircraft. World War II-era attempts to mount electronic countermeasures to radar detection had paid off. When Allied ECM jammed German AAA fire control and ground-controlled intercept (GCI) radar, visual targeting of the 88 mm air defense guns proved much less effective against bombers flying at 25,000 to 29,000 feet. The addition of ECM was estimated to have reduced the Allied attrition rate by as much as 25 percent.<sup>41</sup> Now that radar

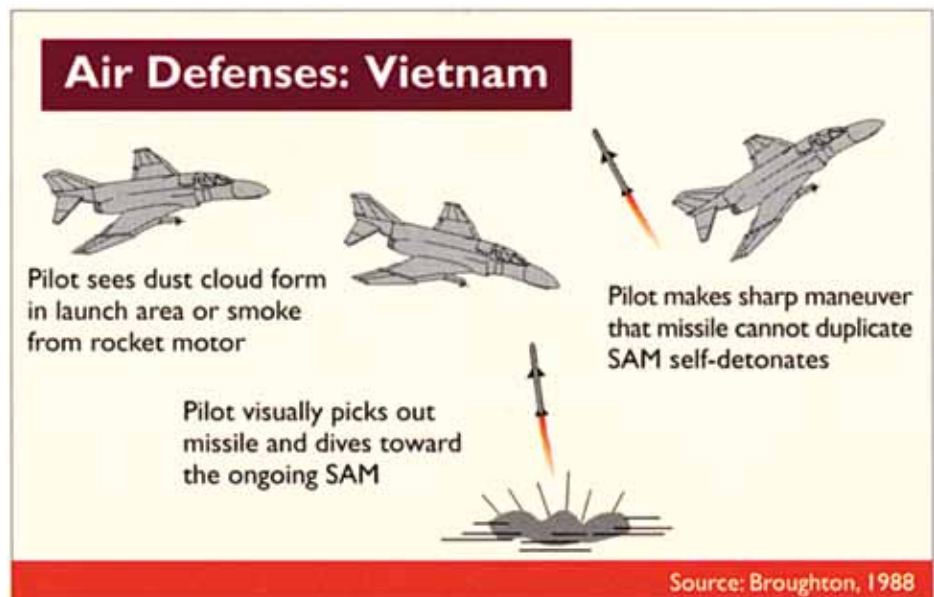
controlled each stage of the duel, evading or deceiving fire control radars and missile seekers became an essential part of the survivability duel.

### Operational Challenges: SAMs in Vietnam

Five years after the U-2 incident, a North Vietnamese SA-2 shot down an American F-4C on July 24, 1965. The problems of survivability were multiplied for the military aircraft that operated in Vietnam. Aircraft like the F-4, F-105, and the F-111 were designed with features like speed, range, and bomb-carrying capacity in mind. Like their old World War II-era cousins, the aerodynamic features of these aircraft made them large radar reflectors. Their crews might take it for granted that enemy radar would detect them at some point. However, the speed, maneuverability, and tactics that pilots relied on for survivability could not completely shield them and their warplanes from the threat of radar-guided missiles closing at Mach 2 or faster.

By the time the Rolling Thunder operations of 1965-68 were in full swing, survivability consisted of multiple duels between attacking aircraft and the fighters, SAMs, and anti-aircraft defenses they might encounter. Early warning radar-cued fighter interceptors. SAM batteries used their own acquisition radars to direct the fire control radar. Anti-aircraft guns with radar direction finding operated autonomously to acquire and shoot at aircraft.

The deployment of radar-guided SAM batteries created a new duel between attackers and defenders. Radar guidance forced the development of new and aggressive tactics for survival in the endgame. For example, the first SA-2 missiles reacted slowly once in flight. Aircrews rapidly developed tactics to evade the missile by carrying out extreme maneuvers that would cause the missile to overshoot and miss the aircraft. The chart on p. 25 diagrams one tactic de-



veloped to pit the maneuverability of the aircraft and the skill of the pilot against the missile's radar guidance and performance parameters.

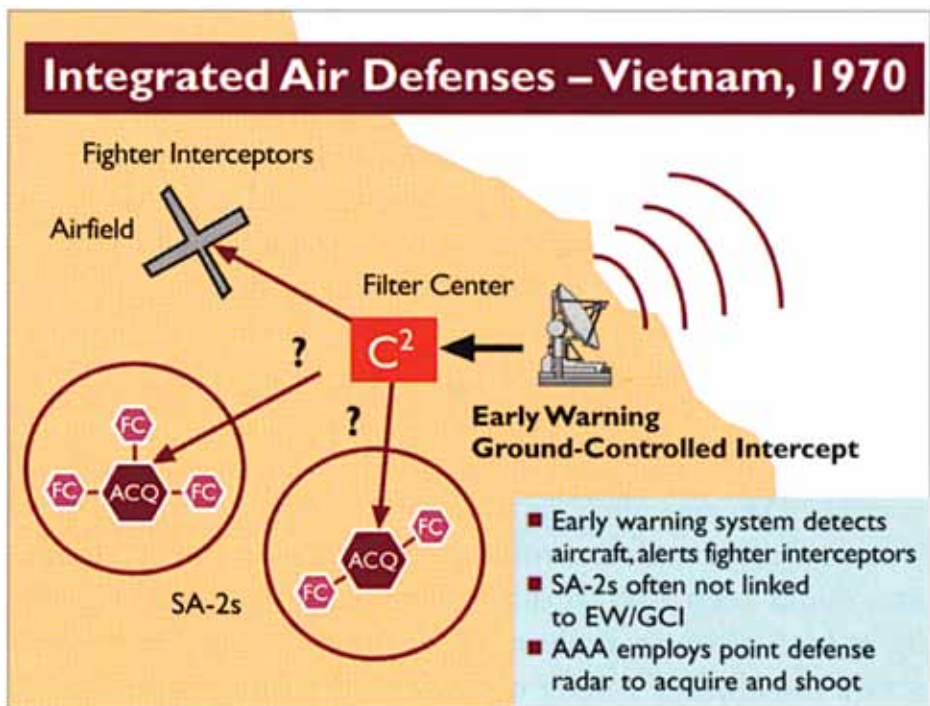
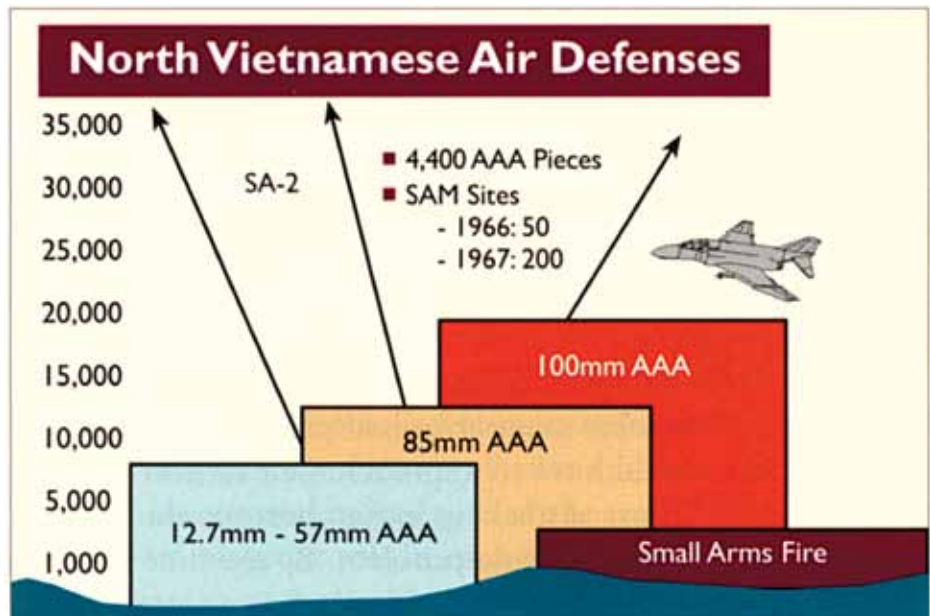
The risk of SAM engagement affected air operations by narrowing the options for tactical employment. If aircraft flew in at medium or high altitude, they would be detected, tracked, and potentially fired upon by SAMs. If they flew in low, the aircraft would gain protection from the nap of the Earth and be able to stay below the SAM's minimum engagement altitude. Low-altitude attacks, however, plunged aircraft into a region of dense anti-aircraft gun fire. The chart at top right shows how multi-layered defenses increased survivability threats at all normal operating altitudes.

Here, the survivability duel increased in intensity, as a barrage of threats posed significant risks to aircraft at all altitudes. As one author put it, by 1968, the "enemy's use of the electromagnetic spectrum to track and shoot down friendly aircraft was a serious problem, and the requirement to neutralize it spurred vigorous activity in both the traditional technical EC areas and the pragmatic world of fighter tactics."<sup>42</sup>

At the heart of the problem of countering SAMs was the system used to detect, track, and fire at aircraft. Radar assisted in all phases. In World War II, chaff and countermeasures primarily sought to blind the defenders' long-range detection for a period of time. By the late 1960s, ECM had to counter and defeat weapons engagement as well as to shroud attackers from early warning and tracking. The chart above illustrates how tenuous early warning links to operations centers attempted to handle target acquisition and pass information on to fire control radars to launch SAMs.

More integrated air defenses strung each stage of the duel together. Successful detection and tracking led to engagement and enhanced probability of kill. Radar linked the stages of the survivability duel together into an integrated air defense system that had the potential to be much more effective and lethal.

Electronic countermeasures brought back an element of tactical surprise and gave aircrews a better survivability advantage by making it more difficult to complete each



stage of radar tracking and engage the aircraft. Electronic countermeasures threw in a band of clutter that cut the effective range of acquisition and fire control radars. ECM optimized for different wavelength frequencies and engagements could jam a warhead seeker or jam the radar directing it. The tactical effect was to reduce the time for the enemy missile batteries to engage, as depicted in the top chart on p. 27.

Stand-off jamming was not unlike what the British and Americans accomplished in World War II. It masked aircraft from early warning radars to within a certain distance of the target. More powerful systems in dedicated aircraft such as

the EB-66 raised the noise level and could reduce the effective tracking range of early warning and fire control radar. By creating a belt of jamming, ECM limited the time the aircraft was vulnerable to detection and tracking, thereby shortening the enemy's response time.

Successful jamming depended on achieving an adequate "jamming-to-signal" ratio. The J/S is the measure of the strength of the normal radar return from an aircraft and the signal which the hostile radar receives from the jamming aircraft. It varies with the square of the distance from the jammer to the receiver being jammed, and thus at great distances, jamming systems are less effective.

Because of its size, the EB-66 could carry larger, more powerful radar jammers to extend protection to many aircraft. Still, getting the most effective results from jamming required a combination of techniques. In addition, an aircraft could produce only a limited amount of power to jam enemy radar receivers.

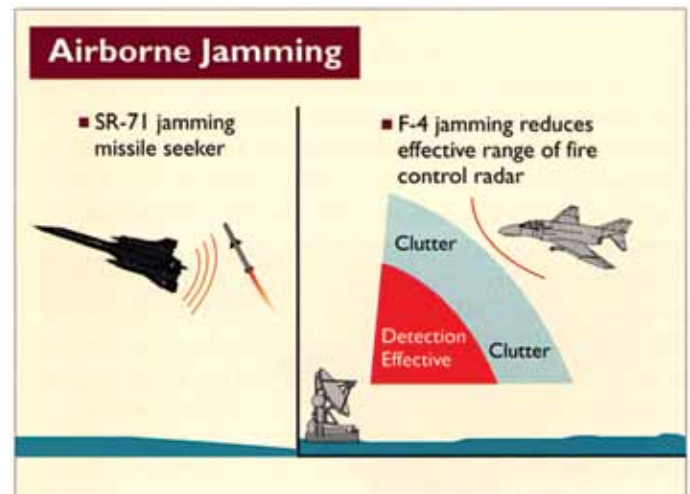
New methods of suppressing air defenses focused on destroying radars and SAM batteries outright. Lethal suppression of enemy air defenses (SEAD) developed as a way to break the effectiveness of individual batteries and of the enemy air defense system as a whole. Wild Weasel tactics, for example, combined an extremely sophisticated radar-seeking sensor with anti-radiation missiles that homed in on radar emissions.

The various electronic countermeasures (non-lethal SEAD) and lethal SEAD tactics for suppressing enemy air defenses led planners to schedule a veritable armada of aircraft to escort the bomb-droppers. Strike packages like the one depicted in the chart below sought to counter all the potential engagements that the air defense system could mount against a large number of aircraft being tracked by radar. Fighters defended against MiGs. Chaff and jamming masked the package's approach and shielded it to a degree from SAMs. The Iron Hand components sought out nests of missile sites and radar-directed antiaircraft guns and attempted to destroy them.

By combining both lethal and non-lethal SEAD, and fighter escort, the typical Vietnam strike package layered multiple techniques for surviving detection, tracking, and attacks by enemy SAMs, AAA, and fighters.

An operation at the end of the Vietnam War illustrated how the elements of the strike packages worked together to enhance survivability for bombers. "The strike package was perhaps the significant key to the success of Operation Linebacker," concluded an official USAF history.<sup>43</sup>

Linebacker II, the last major air operation of the Vietnam conflict, was an 11-day bombing campaign against high-value targets in North Vietnam. It pointed out how a host of electronic countermeasures now assisted in the duel. Some planning estimates for Linebacker II expected attrition rates as high as five percent because of heavy de-



fenses around the selected targets.<sup>44</sup> To protect the formations, a typical strike package for Linebacker II started with high-speed, low-level attacks by F-111s using terrain-following radar with a goal to take out SAM sites and crater enemy airfields.

F-4s then blanketed the area with chaff so that radar operators could not distinguish the B-52s from the false signals on their scopes. F-105 Wild Weasels also accompanied the strike package and used antiradar homing missiles to hit SAM sites.

For the first Linebacker II missions, 67 B-52s lined up one after the other in a 70-mile-long formation known as the "baby elephant walk." The B-52s attacked about 20 minutes to an hour after the initial assault and would come in waves, consisting of 21 to 51 bombers and 31 to 41 support aircraft, separated by a few hours each.<sup>45</sup> The bombers faced SAMs fired in shotgun patterns, in which the North Vietnamese sent up six-missile salvos at a time. One gunner spotted 32 SAMs fired at or near his plane.<sup>46</sup>

The B-52s were in the most danger when they had to overfly the target area to release weapons. At that moment, as the plane released its payload and made a 100-degree turn to depart from the target area, the B-52 exposed its



maximum radar profile to the enemy. Linebacker II's statistics confirmed the dangers inherent in these employment tactics. Twelve aircraft were lost in the first three days of the operation, including nine B-52s, partly due to this predictable move that exposed the tail section of the aircraft to radar.<sup>47</sup> Tactics changed on later missions but problems continued to hamper the formations. The B-52's giant RCS could not be concealed by jamming as it neared the target. Sometimes chaff corridors were dispersed too quickly because wind directions differed from forecasts; some of the B-52s were older D models and did not have upgraded ECM equipment. In short, the potential vulnerability of the B-52s was high.

The Air Force ultimately adapted by laying wide chaff blankets instead of corridors, varying flight patterns and bombing runs, and installing modified radar jammers to meet new enemy threats. However, in the end, 27 aircraft were lost in the 11-day operation, including 15 B-52s over 729 sorties, all lost to SAMs. The B-52 attrition rate of two percent would have proved difficult to sustain over several weeks or months, except for one fact. By the end of December about 900 SAMs had been expended, and Hanoi's SAM inventory was nearly depleted.

Linebacker II typified the short, intensive air operations that dotted the next decade. While Linebacker II was counted as a success for its role in restarting the peace negotiations, it had also delivered evidence of the increasing vulnerability of bombers and strike aircraft attacking heavily defended targets. As Soviet-made air defenses spread to many other nations, survivability and the ability to complete missions increasingly depended on how aircraft fared against integrated air defenses with SAMs as the centerpiece. In 1973, for example, Israel lost 40 aircraft in a single day in the Golan Heights. The 10 percent attrition rate forced Israel to halt air operations even as Arab forces threatened to overrun Israeli ground positions.<sup>48</sup> The Israelis refocused their efforts toward gaining air superiority and then helped destroy the invading forces.

Stand-off jamming became so important to air operations that dedicated platforms like the EF-111 and the EA-6B

were modified to perform the mission. In the 1980s, for instance, the EF-111 with the ALQ-99 could jam radar in the VHF to J-bands over a distance of about 124 miles. Thus, five EF-111s could provide standoff jamming coverage for a region ranging from the Baltic Sea to the Adriatic Sea.

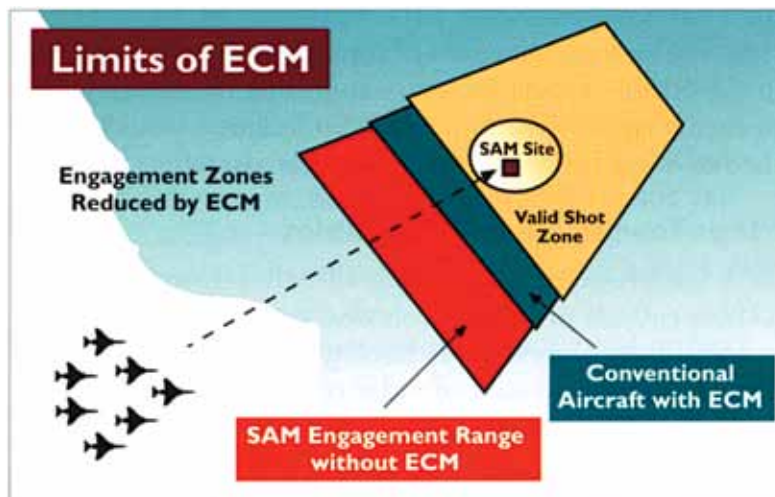
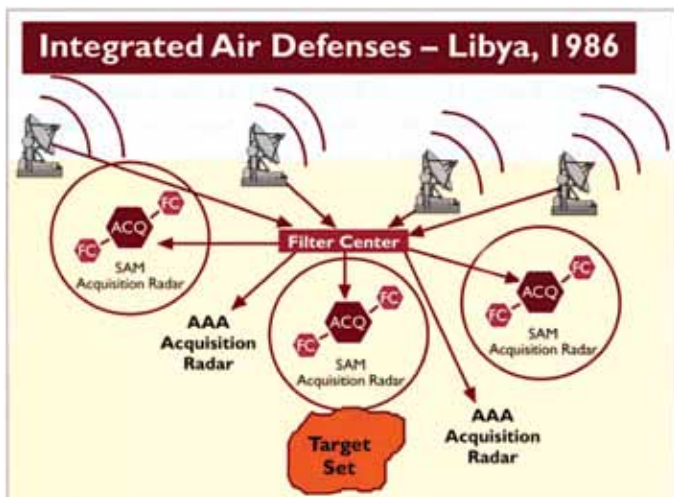
### The Libya Raid, 1986

In March 1986, US Navy warships in international waters crossed Libya's arbitrary "line of death," drawn near the 32nd parallel. A Libyan SA-5 SAM battery at Sirte fired at two F/A-18 Hornets from the USS *Coral Sea* flying combat air patrol (CAP) over the battle group. Fired at extreme range, the missiles did not hit their targets. But the SA-5 firings underscored the problems of launching a strike against an integrated air defense system.

The next month, April 1986, the US conducted a raid against targets in Libya to pre-empt far-reaching terrorist attacks that US intelligence indicated were being planned by the Libyans. Stand-off jamming was key to the execution of the operation. Libya's air defense system, supplied by the Soviets, was built to counter known US strengths to the greatest extent possible. The Libyans relied on dense, redundant coverage by radars operating on multiple frequencies and with different waveforms. All these features were designed to complicate the tasks of jamming and antiradiation missiles like the Shrike and the High-Speed Anti-Radiation Missile (HARM). Hardened landlines sought to protect against an attempt to shut down the system.<sup>49</sup>

The primary tactic of the Operation Eldorado Canyon raid was a high-speed, low-altitude night attack. As one study noted, "at attack speeds, given no advance warning, an enemy radar would have less than three minutes to locate, identify, track, and allocate a weapon before the attacker would be over the site."

Jammers could cut the time even more by screening the attackers from detection for a longer period. Indeed, the EF-111 and EA-6B jammers were at their best in jamming the older Libyan systems.



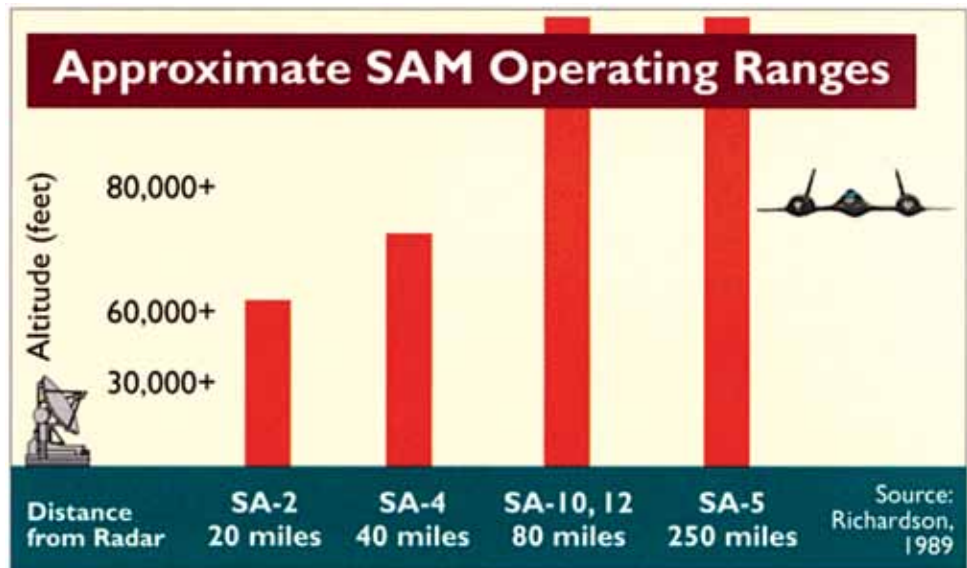
Still, SA-2, SA-3, SA-6, and SA-8 missiles came up against the strike package. Aircraft “encountered heavy surface-to-air missile activity near Tripoli and at one downtown target near Benghazi.”<sup>50</sup> The dense air defense environment was on a trajectory to greatly complicate sustained air operations.

### Evolving Air Defenses and the Limits of ECM

The proliferation of advanced SAMs and, increasingly, of integrated air defense systems, made the challenge of survivability all the greater. For example, in Vietnam, early warning radar intercepts were passed to both filter centers and command and control centers to manage fighter intercept operations. The dreaded SAM batteries, however, generally did not receive consistent early warning. In contrast, the air defenses around Libya in the 1980s gathered detection information at a single point and used the advanced warning to allocate air defense weapons. Still, the Libyan system was not the most modern and electronic countermeasures had been developed to use against it. It was the more modern and centralized Iraqi air defense system that would present a qualitatively different challenge some five years later.

Overshadowing all the Third World systems was, of course, the integrated system of the USSR. Rapid advances in computing technology increased the flow of information through the air defense system. Central direction and integration of air defenses improved their efficiency and lethality. The emergence of advanced SAMs like the SA-10 would pose increased survivability challenges.

As long as attack aircraft remained strong radar reflectors, it would take a great deal of jamming to conceal their signatures. ECM had inherent limits. Weight restrictions meant



that the power of the airborne jammer would never be as great as the potential power of the ground-based radar attempting to track aircraft. Moreover, changes in frequencies could invalidate the countermeasures process. As then Lt. Gen. Joseph Ralston, deputy chief of staff for plans and operations on the Air Staff, reflected in 1994:

*“After Vietnam and during the 1970s, it seemed we were engaged in a never-ending struggle to provide our aircraft with modern radar-warning receivers and jammers to counter each new threat. Frequencies changed, new SAMs were fielded, wartime modes surfaced ... it seemed we were in an infinite ‘go to’ loop of ECM and ECCM.”<sup>51</sup>*

According to Ralston, much of the “allure of stealth was in its ability to get us away from electronic warfare.” Survivability again placed a limit on the effectiveness and efficiency of air operations. Thus, the next phase in the radar game would be to master the science of reducing radar returns.

## WINNING THE RADAR GAME

Minimizing aircraft radar return was an idea that occurred to British engineers during World War II. In August 1941, British researchers submitted a round of proposals for modifications to aircraft to render them “undetectable by normal RDF” or radar. Their plan was to adjust the aircraft’s radiation to match the background level of radiation from the air around it. Increasing the resistivity of the aircraft’s skin might short-circuit the radio wave; and instead of reflecting back, the wave could be shunted into a gap where the wave-

length would be impeded. If material with the right intrinsic impedance was found, a modified matching system could prevent reflection, but only at certain frequencies.

Although they never took the idea beyond a few theoretical papers, these British engineers had hit upon a concept that would become much more compelling by the 1960s. If an aircraft could perhaps be shaped to make the return signal less powerful, the net effect would be to make the aircraft appear on the radar operator’s scope later than

expected, or perhaps not at all, thereby giving the aircraft an added measure of surprise.

Across the Channel, an unusual German aircraft design had also grasped at radar-defeating features. In 1943, the shortage of metal led Walter and Reimer Horten to design an aircraft with improved performance, plus shaping and coatings that might have reduced its radar return. The Horten twin-engine flying wing bomber/reconnaissance aircraft used plywood and charcoal materials that efficiently absorbed the long centimetric wavelengths of the period. The Hortens' initial interest in the flying wing design stemmed from their desire to eliminate sources of parasitic drag. There were no vertical surfaces on the plane, and the cockpit and BMW 003 turbojet power plants were housed entirely within the wing itself.<sup>52</sup> The center section of the wing housed the engines and cockpit and was made of conventional welded steel-tube construction. The rest of the plane was covered with plywood sandwiched around a center of charcoal except for the engine exhausts, which were coated with metal.<sup>53</sup>

In early flight tests, the Horten, also designated the Go 229, attained a level speed of 497 mph but the prototype crashed during landing and was destroyed. Aircraft maker Gotha still had production prototypes in work when US troops captured the Friedrichsroda plant in late April 1945. At that time, one Go 229 prototype was being prepared for flight testing, and several others were in various stages of production. Had the aircraft gone into service, its estimated maximum speed would have been a formidable 607 mph and its maximum ceiling about 52,500 feet, with a range of 1,181 miles.<sup>54</sup>

Reducing radar return was not forgotten after the war. In March 1953, when the Air Force drew up specifications for a new reconnaissance aircraft, Paragraph 2(g) of the specifications stipulated that "consideration will be given in the design of the vehicle to minimizing the detectability to enemy radar."<sup>55</sup> Within a decade, designers would take the first steps toward a low observable aircraft.

### Steps Toward Low Observables

By the 1960s, speed and high-altitude performance were not enough to evade the newest generation of guided missiles. Low observable (LO) technology grew out of the need to minimize the amount of radar reflected back from the aircraft. In theory, it was widely understood that special coatings, materials, and shapes could make objects less easy to detect. Both the U-2 and especially, the SR-71, explored these concepts even while putting the primary emphasis on altitude and speed for survivability.

The SR-71 was the first aircraft to incorporate low observables as a design feature. Lockheed engineers kept the tails of the SR-71 as small as possible and constructed them with as much radar-absorbing material (RAM) as possible. Designers of the aircraft also modified the rounded fuselage

by adding a chine—a lateral sloped surface that gave the fuselage the appearance of a cobra—that left the belly of the aircraft essentially flat. This reduced radar cross section by as much as 90 percent.

In addition, Lockheed made extensive use of RAM in all the sharp horizontal edges of the aircraft that might be hit by radar waves, including chines, wing leading edges, and elevons. The RAM consisted of a plastic honeycomb material that made up 20 percent of the aircraft's structural wing area. Although the SR-71 was 108 feet long and weighed 140,000 pounds, it had the RCS of a Piper Cub. In fact, the SR-71 had lower radar cross section than the B-1 bomber built two decades later.<sup>56</sup>

As tantalizing as their promise appeared, low observables depended on capturing so many variables in the aircraft's signature that it took a revolution in computing technologies to make the engineering tasks feasible. Balanced signature reduction ultimately came to include not only radar return, but infrared, visual, acoustic, and laser cross section reduction, and reducing emissions from the aircraft radar. However, the first challenge was to understand and quantify the behavior of radar waves as they encountered the many different shapes and surfaces on an aircraft.

### Calculating Radar Return

More than 30 years passed between the British hypotheses about blending aircraft into background radiation, and the events that made shaping an aircraft to lower its observability to radar a reality. A major breakthrough came when Lockheed Skunk Works engineer Denys Overholser saw something in the work of a Russian radar scientist. The Russian, Pyotr Ufimtsev, had rediscovered that the equations of Scottish physicist James Clerk Maxwell could be used to predict how a certain geometric shape would reflect electromagnetic waves. In a paper first published in the mid-1960s, Ufimtsev applied this principle to calculating the sum of the radar cross sections of different geometric shapes.

Calculations of radar return depend on laws governing the properties of electromagnetic radiation. Electromagnetic waves behave the same whether their wavelength puts them in the radar or optical light regions. Maxwell's equations, formulated in the late 19th century, established boundary conditions for the behavior of electromagnetic waves. Ufimtsev postulated that Maxwell's equations would make it possible to calculate the behavior of radar waves retransmitted from a reflective object. The radar return would depend in part on the shape of the object. By treating an aircraft as a group of geometric shapes, each with its own radar-reflecting properties, it would be possible to calculate the RCS of the aircraft as a whole. Then, in theory, an air vehicle could be designed with geometry that minimized the radar return.

Building on the direction suggested by Ufimtsev, RCS engineering used principles from physical optics to estimate

the type of scattered field that would be created when radar waves encountered an aircraft. The radar range equation and the equation for calculating RCS are both based on physical optics methods.

The sum of the major reflective components of the aircraft's shape is defined as radar cross section. RCS is the area (width and length) of the scattered wave field being returned toward the radar. Generally, the size of the radar cross section of a conventional aircraft is much larger than the physical size of the aircraft. The RCS of an aircraft determines the amount of the sending radar's power that is reflected back for the sender to receive. An RCS is typically measured in square meters or in decibels per square meter, often abbreviated as dBsm.

Radar waves reflect and scatter in many different ways. Each feature of an aircraft, carefully designed for its power, strength, and aerodynamic qualities, can have quite a different meaning when considered from the standpoint of radar cross section, as shown in the middle chart.

To design low observable aircraft, engineers had to reliably predict and control the multiple forms of radar return that add up to the RCS.

Principles of physical optics define several different types of radar wave reflection and scatter that form the aircraft's radar return. For example, specular reflection occurs when waves are reflected back at a known angle. Diffraction takes place when waves encounter an edge—like a wingtip—and are diffracted in all directions around a cone. Traveling waves can be created that are not reflected or diffracted immediately, but travel on a long, thin body nose-on to the incoming wave. Similarly, creeping waves are like traveling waves that propagate around the shadow area or back of the target. Waves generated in the object by the emitted radar waves are kept in check by the object's electromagnetic currents. When waves hit a crack, slope, or different material, they scatter.

Waves do not simply bounce off and return from surfaces. Waves may bounce around in cavities and ducts and generate additional return. Similarly, radar waves can scatter inside a cavity such as a cockpit or engine inlet.

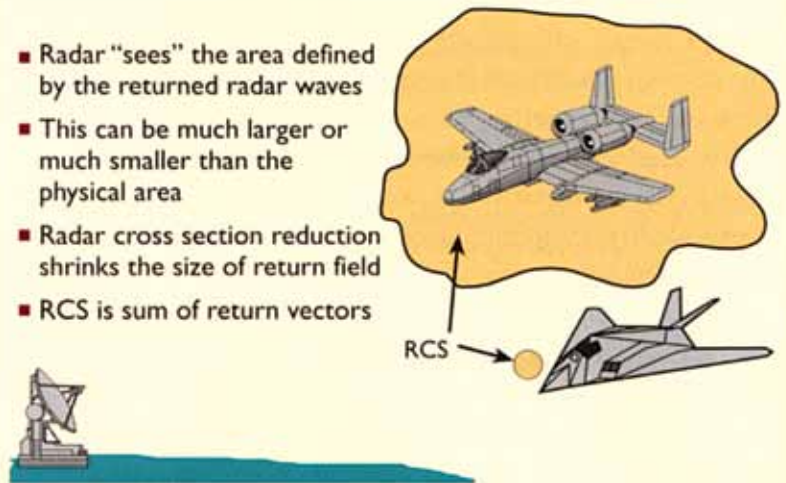
The principal contributors to radar cross section each demand distinct analysis of their behavior. Examining each of these mechanisms in turn demonstrates the many different variables that designers must control to achieve a reduced RCS.

### Specular Reflection

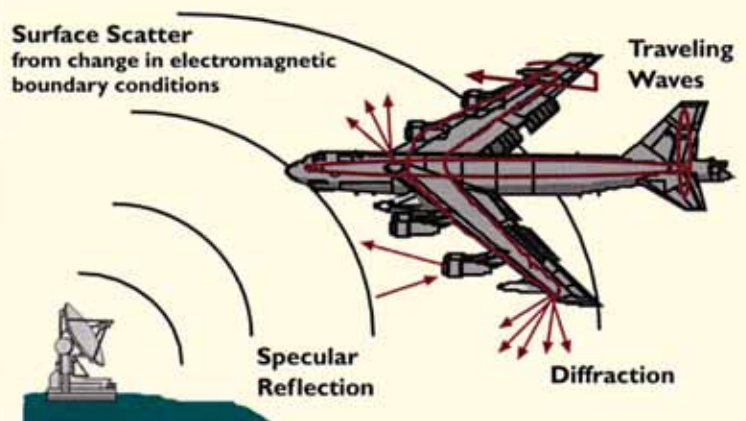
Specular reflection is the major source of radar return, and minimizing specular reflection is the first task

## What the Radar Sees

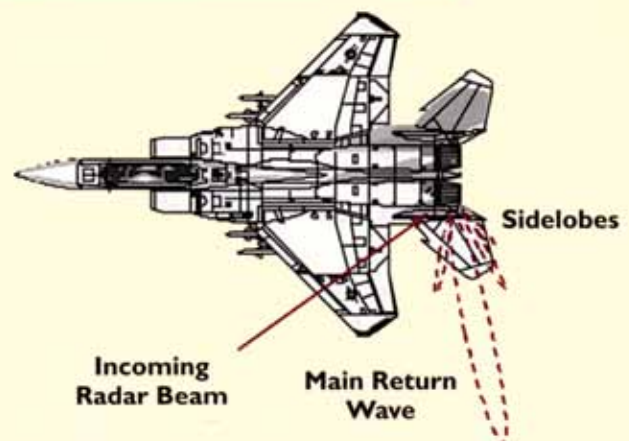
- Radar "sees" the area defined by the returned radar waves
- This can be much larger or much smaller than the physical area
- Radar cross section reduction shrinks the size of return field
- RCS is sum of return vectors



## How Radar Waves Scatter



## Radar Reflection from Tail



of LO design. A large, flat plate reflects radar return like a mirror. Conventional aircraft with large vertical stabilizers are textbook examples.

In its physical properties, specular reflection is like a mirror. The direction of the reflected waves depends on physical laws that relate the angle the wave strikes the target to the angle at which the wave is reflected. These laws also allow different aircraft shapes to produce different radar returns.

In specular reflection, the angle at which a wave strikes an object also determines the angle of the reflection.

When waves strike an object at right angles, more of the reflected waves return in the direction of the sender. Vary the "incidence angle," or angle at which the waves strike the object, and—to satisfy optical laws—more of the waves are directed outside the plane transverse to the viewer.

The mirror-like return caused by specular reflection makes it the largest single contributor to RCS. In the simplest terms, the angle of the object can determine reflection. A vertical plate will have maximum reflection when perpendicular to the direction of the incoming wave. A plate slanted so far back that it is almost flat will direct more of the scattered field away from the sender's plane of view. Geometric shape affects specular reflection. A diamond shape will reflect waves in an X-shaped signature that angles return away from the principal plane of the viewer. A square plate will have a different pattern resulting in a larger RCS.

Specular reflection can be calculated because it must satisfy physical laws. An observer walking past a car on a sunny day will see the maximum glint or specular reflection from the car's windshield at a specific point.

This point corresponds to the moment the observer intersects the reflected angle, as determined by the angle of the sunbeams. The angle at which sunbeams strike the object must correlate to the angle at which the beams are reflected by the object.

When an object is perpendicular to the radar, the angle of the reflection will be more likely to fall within the radar's plane of view. When the object is tilted away, the incidence angle from the same source is more acute. To satisfy the optical laws, a greater amount of the radiation is scattered at an angle away from the plane of the sender's radar.

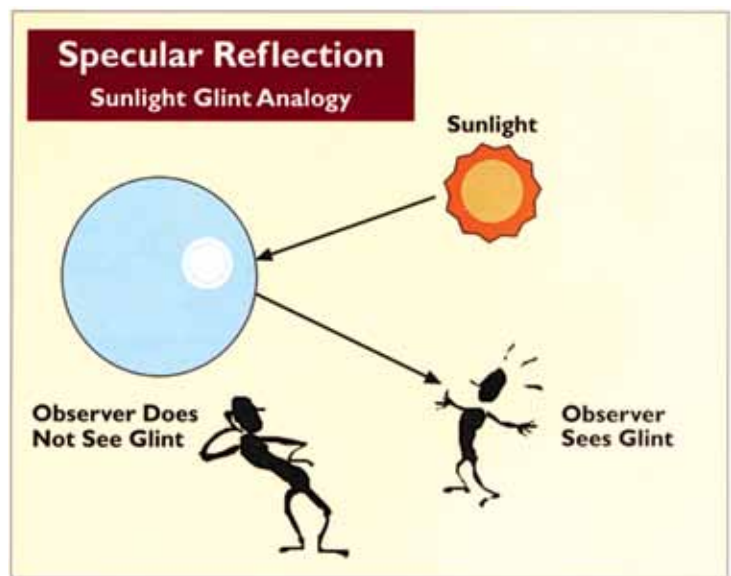
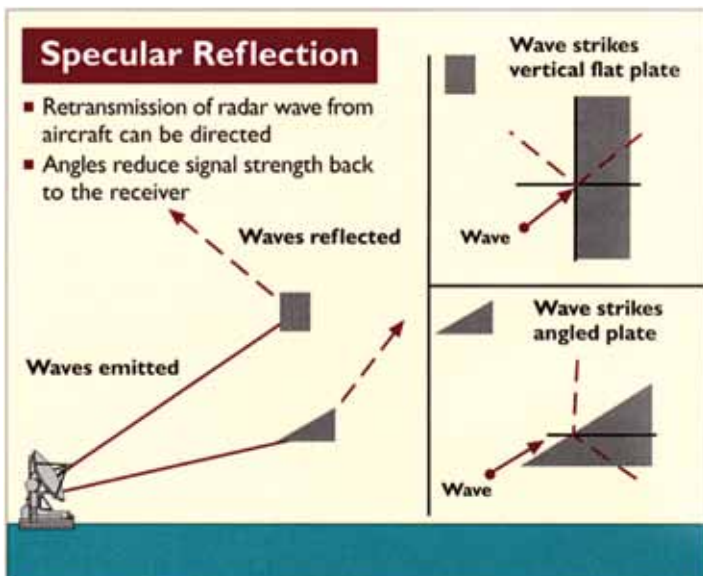
The types of shapes that contribute most to RCS are dihedrals, also called retroreflectors—plane surfaces at 90 degrees to one another. They appear on many modern aircraft for sound aerodynamic reasons. For instance, viewed from the side, the F-15 Eagle has a surface area of about 25 square meters. Yet because of the aircraft's numerous dihedrals and surfaces pointing flat to the radar, a side-aspect RCS for the aircraft is many times larger, about the size of a house. One solution to the side aspect problem is to eliminate vertical stabilizers, as was done with the B-2 stealth bomber.

### Diffraction

When specular reflection is reduced, other scattering mechanisms from many features of an aircraft can greatly affect the radar cross section. Diffraction occurs when waves strike a point such as a wedge or tip. The source of diffraction can be as small as the head of a screw that is not flush with the surface and is not covered with RAM material. Diffraction scatters waves in all directions, obeying physical laws that shape the diffraction like a cone. Signature reduction requires ensuring that the scattered electric field is controlled and directed away from the sending radar.

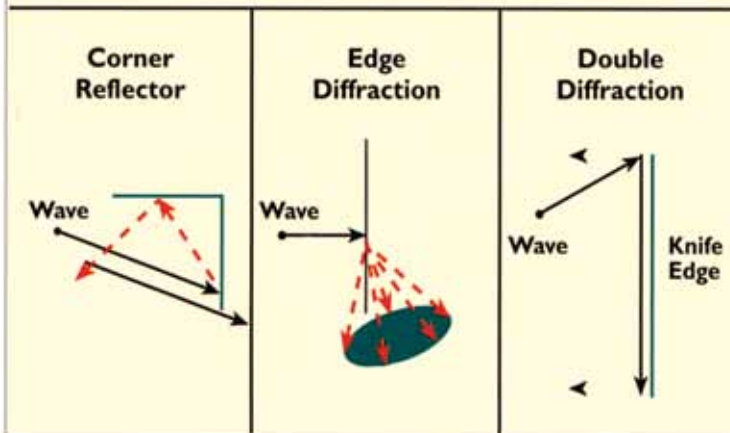
Diffraction from aerodynamic features on conventional aircraft can be a large source of RCS. Conical points, sharp corners, and even rounded tubular surfaces each cause their own unique diffraction patterns.

A special case of multiple diffraction occurs inside a cavity. Waves inside a cavity like a cockpit or an engine inlet scatter in complex ways.

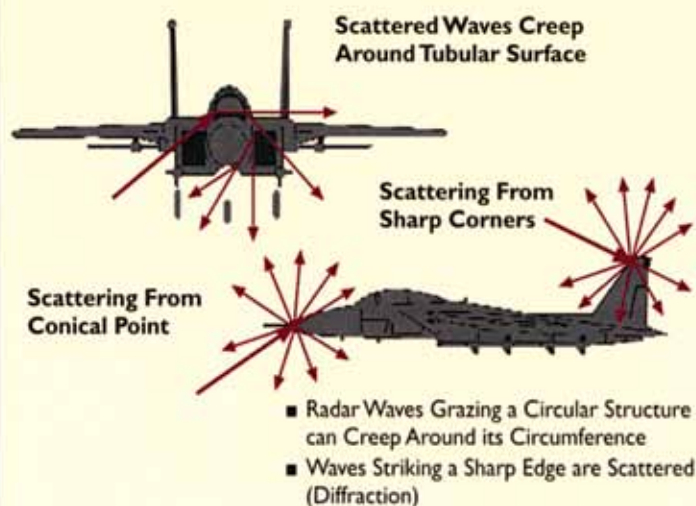




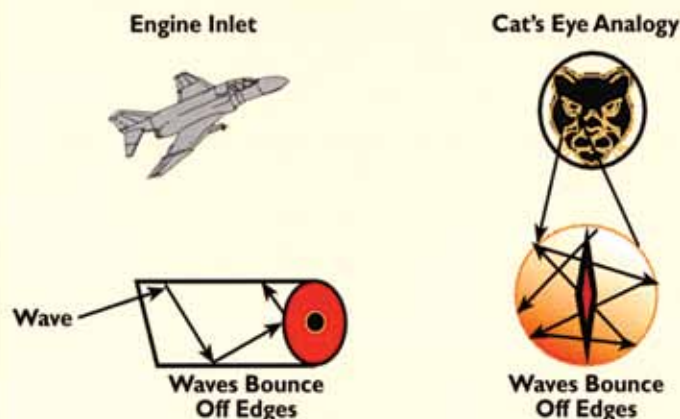
## Principles of Diffraction



## Diffraction from Aircraft



## Cavities and Ducting



This cavity diffraction is the same effect that causes a cat's eye to glow. A small shaft of light enters the rounded cavity of the eyeball and bounces around inside it, producing a bright flash or glow. The intensity of the scattering in cavities and ducts can significantly increase the RCS of an object, especially when specular reflection and diffraction have already been controlled.

## Traveling Waves

Traveling waves present a unique case because the target object becomes an antenna and a transmission line. When grazing angles are slight, the target collects energy and transmits it along the surface. A discontinuity like a crack, slope or rough spot of material with a different conductivity can cause diffraction of the traveling wave.

Very thick materials would be required to dissipate the traveling wave's energy, so the primary technique is to deflect it. For example, swept edges on a trailing wing edge can direct the transmitted energy away from the direction of the threat. Also, on doubly curved bodies, adding a thin wire to the end of the object can attract the traveling wave and retransmit it like an antenna.

Traveling waves create challenges on the shop floor and in future maintenance, too. As one Lockheed F-117 engineer put it, "We couldn't allow even the tiniest imperfection in the fit of the landing gear door, for example, that could triple the airplane's RCS if it wasn't precisely flush with the body." Any protrusions, such as small fairings, grills, domes, and wingtips, can project radar waves back to the sender. Even rivets and fasteners can act as radar reflectors.

## Radar-Absorbing Material

Once the aircraft's basic shape has been designed for lower RCS, a second step is to apply materials to the surface area that further reduce RCS. One important technique, serrated edges, is actually a geometric absorber. A knife edge tends to scatter more waves back toward the receiver. Serrated edges use the geometry of the rows of pyramids to diffract waves away from the sending radar.

Radar-absorbing materials are used to attenuate radar waves. In World War II, RAM covered German submarine snorkels, which were becoming easy prey for Allied aircraft equipped with centimeter-wave radar. Sumpf, a sandwich of rubber with carbon granules embedded in it, was supposed to absorb radar pulses, reducing the strength of the echo and making them less detectable to radar. In laboratory tests, Sumpf was effective, though it was less useful in sea trials, as the salt water tended to remove the covering and diminish its electrical properties.

An early experiment in RAM for aircraft was the U-2's ferrite-laced paint. The presence of iron in the paint changed the magnetization of the radar waves in order to diminish

return. However, since iron is a good conductor, the loss of energy was not small enough. Other materials reduced radar return through passive cancellation or impedance. The British proposals of 1941 speculated on the possibility of impedance. Use of materials with different electric conducting properties would introduce a second scattering mechanism that cancels out the first.

### RCS Reduction Features for Aircraft

Making a good stealth airplane is a little bit like making a bad transmitting antenna. The sender would receive so much less radiated power that the aircraft's return signal would fall below the radar's detection threshold until the aircraft was very close to the radar. However, lowering radar cross section requires a trade-off between ideal low observable features and aerodynamic performance needed for a combat aircraft.

Aircraft like the A-10 were designed for performance, not stealth. For a conventional aircraft, the largest returns come from side aspects, because of its vertical stabilizer, fuselage, and from spikes on the nose, from engine inlets.

Low observability to radar was not a major design feature for the premier US fighter and attack aircraft that entered service in the 1970s and 1980s: the F-14, F-15, F-16, and F/A-18. However, in a few cases, certain features built in for aerodynamic performance helped reduce RCS. Outside the US, for example, the Soviet Su-24 had an engine duct design that reduced the propagation of radar waves. A conical nose section aids supersonic flight on advanced fighters, and it also minimizes nose-on RCS.

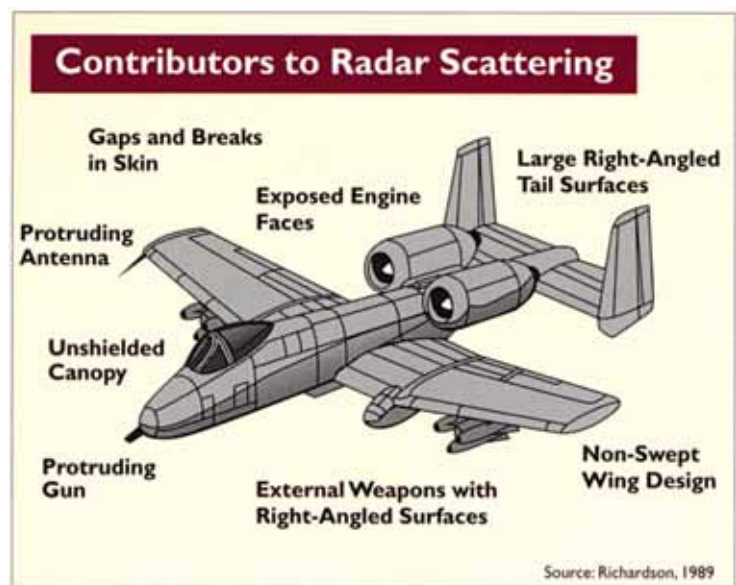
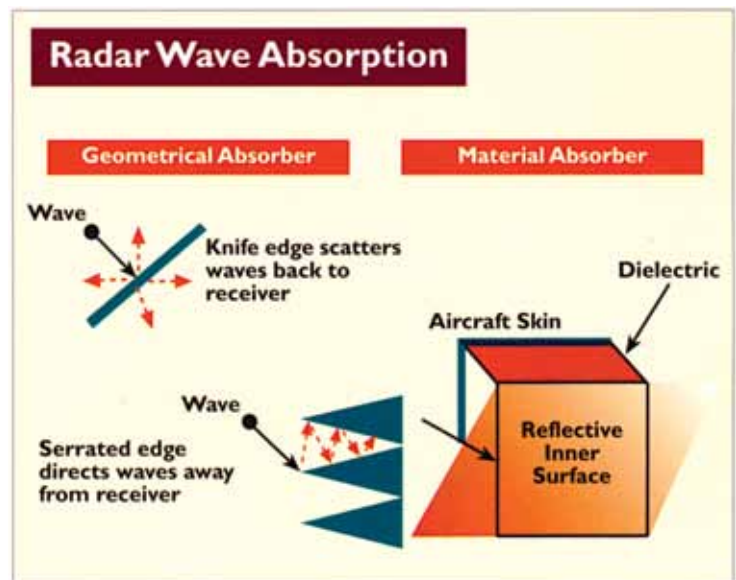
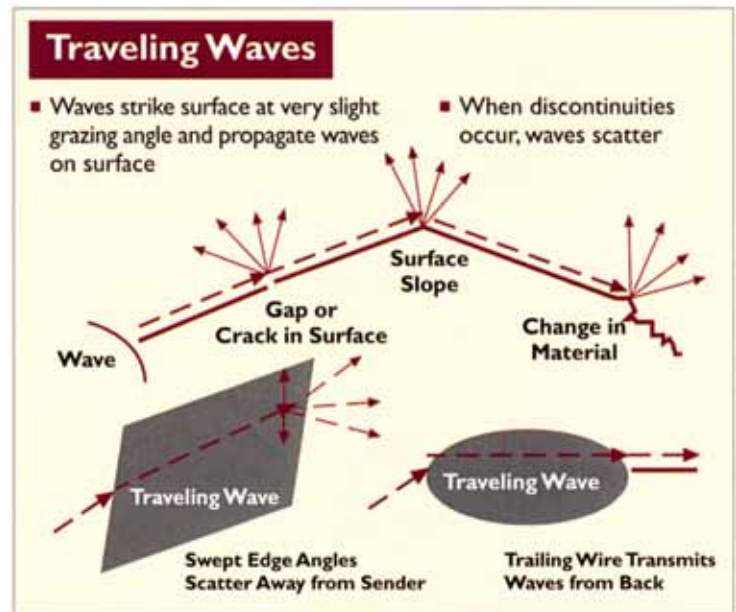
The goal of low observables is to reduce RCS. Significant reductions in RCS put the F-117, B-2, and F-22 into the stealth zone. The standard scale (p. 35) from a textbook on radar cross section engineering shows the contrast.

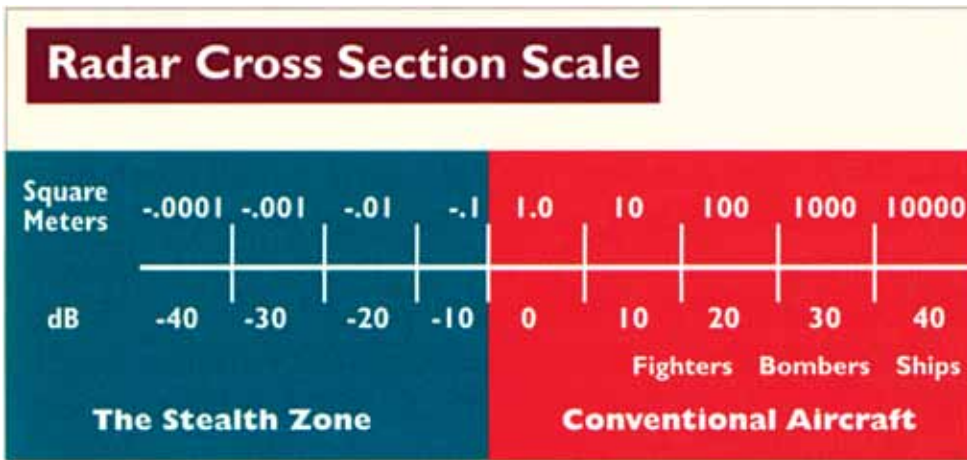
When stealth aircraft achieved lower signatures, what that meant, in practice, was that lower RCS decreased the effective detection and tracking area of the radar.

Current combat aircraft fall at many different points on the stealth spectrum. For example, modifications to conventional aircraft can help minimize radar return, especially in the front-aspect.

On the F/A-18E/F, for example, a number of signature reduction techniques are scheduled to be applied. A grill covers the air intakes. Applying RAM to leading edges can also reduce return. Modifications tend to reduce RCS most from the head-on aspect where aircraft are most vulnerable.

A true stealth aircraft is one where RCS reduction was a major design objective from the start. Stealth aircraft begin with shapes that both minimize and control reflection and diffraction, thereby reducing RCS. The F-117 was the first aircraft with low observables as the major design criteria. Flat, angled plates controlled specular reflection and reduced





diffraction. The aircraft's collage of parallels reflects a geometric design intended specifically to control radar return.

Swept wings redirected radar energy away from the frontal sector of the aircraft. RAM applied to tight tolerances minimized diffraction from traveling waves while applying geometric scattering and impeding wave return. A screen covered the engine ducts and the canopy was shielded.

Diffusers and baffling prevented radar waves entering the engine intake from hitting the engine itself and reflecting back to the receiver. Diffusers covered the front of the intake and screened out radar waves by using a wire mesh that was smaller than the wavelength of the radar, similar to the screen on a microwave oven's glass that prevent microwaves from leaving the interior of the appliance. The intake on the F-117 was covered with a fine grill mesh whose gaps were smaller than the wavelengths of enemy radar. Any radar energy not trapped by this mesh was absorbed by RAM lining the duct leading to the engine.

In sum, the F-117's principal points of radar return were controlled to be well away from a head-on aspect. As the chart at right below shows, shaping diminishes radar return

and directs it away from the radar, resulting in a dramatic overall signature reduction for the given area.

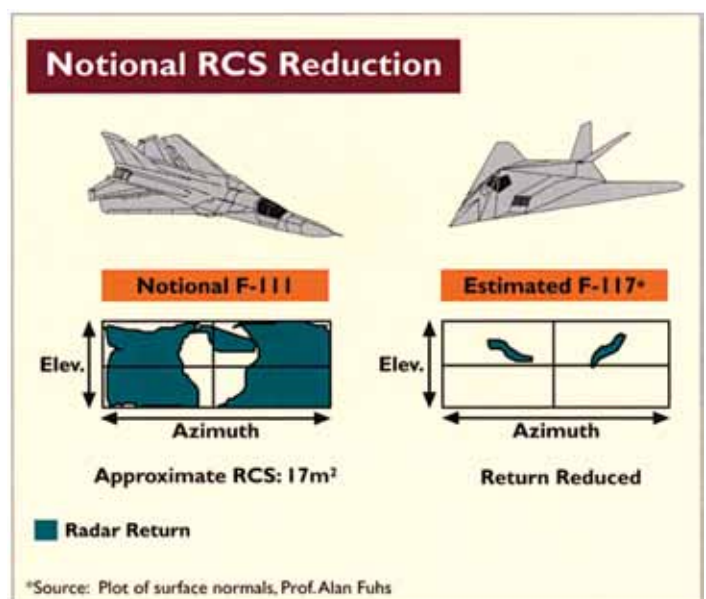
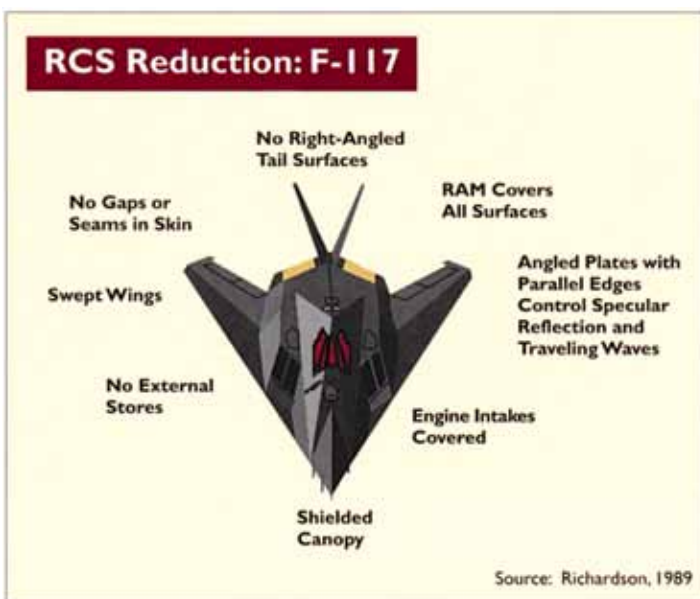
Faceting literally focuses or aims the strongest points of return away from the direction of the radar. Other measures constrain diffraction that might enlarge the aircraft's signature.

In the 1980s, the design of the B-2 followed similar principles, but took them a step further to include smooth, rounded surfaces. The large size of the B-2, designed for long range and high payload, created new design challenges. Accordingly, the B-2 met the

challenge with advanced shaping techniques and curved surfaces that enabled it to achieve dramatic signature reduction despite its physical size.

The B-2 went into production with 10 distinct trailing edges at constant angles to ensure that radar energy was reflected from the trailing edges of the wing into two directions well away from the immediate rear of the aircraft. The flying wing design eliminated vertical control surfaces and made it easier both to incorporate RAM and to hide engines and ordnance within the fuselage because the entire aircraft body produces lift and causes little drag.

The F-117 and the B-2 both traded some features of aerodynamic performance in order to achieve stealth. In the early 1980s, the Air Force developed a requirement for an advanced tactical fighter that would achieve strong aerodynamic performance and maintain a very low observable RCS. The advanced tactical fighter would combine air-to-air combat capabilities with an air-to-ground role. After a competitive fly-off in 1991, the Air Force selected the Lockheed YF-22 prototype over the Northrop YF-23.



The F-22 was designed as both a stealth aircraft and a fast, highly maneuverable fighter. Its rudders are set at an angle to limit return. Thin swept wings point the surface normals of radar return away from the head-on aspect. From all aspects, the F-22's design follows the principles of controlling and minimizing radar return through shaping. The trailing edges of the wing and elevator are parallel, as are many other series of lines around the aircraft's body and wings. Air inlets and dumps have serrated edges and metal mesh covers to limit electromagnetic waves. At the same time, the F-22 has more wing area than the F-15, making it capable of high G-force maneuvers.

Another aircraft, the Joint Strike Fighter (JSF), is still in development. Plans call for the tri-service aircraft to achieve signature reduction and to perform multiple roles. The Air Force, Navy, and Marine Corps each plan to procure models of the JSF that are signature-reduced and tailored to their specific mission requirements.

Reduced RCS is the central factor in survivability because of the long range of radar detection. However, survivability also depends on reducing return in other areas of the electromagnetic spectrum, as the next section will discuss.

### Other Components of Stealth

Diminishing radar cross section is the major component of low observability, but it is not the only task. Lowering the RCS can make other signatures stand out more dramatically. Visual, acoustic, and infrared signatures may have been overshadowed in an older aircraft with a very large RCS. However, a stealth aircraft design must also work to control the signature across the electromagnetic spectrum.

Noise can convey significant information about an aircraft. Noise contributes to detection, although the range varies substantially with frequency. Distinctive noises like helicopter rotor blades can help classify the type of aircraft. Steady

tones may provide information to determine a Doppler shift. Minimizing major sources of sound, especially from engines and airframes, is an important corollary to stealth.

Stealth aircraft also incorporate reductions to infrared (IR) signature. All objects radiate a pattern of heat, except those at absolute zero. Although engine heat and exhaust are the most significant source of IR, friction between the aircraft's skin and the air can also create heat.

Detection of IR signatures can give defenders high resolution of targets at short ranges. Infrared waves can be attenuated by clouds and other atmospheric conditions, but IR sensors are passive, making them difficult to counter. Heat-seeking missiles embody the use of infrared for the final engagement.

Consequently, reducing IR signature is important to survivability in certain environments. To reduce IR signature, stealth aircraft try to mask the tailpipe and engine metal heat. An additive mixed with the SR-71's fuel limited exhaust temperatures. The F-117 and B-2 do not use afterburners or attain supersonic speeds, which can increase IR emissions by as much as 50 times.

Another means of reducing IR signature is to mix cool outside air with hot exhaust air before it leaves the aircraft. Sawtooth trailing edges can create shed vortices to mix cooler ambient air with hot exhaust air. Exhausts can be shielded from direct view through the use of louvers and through placement on the top of the fuselage. Stealth also requires reducing the temperature of the engines through diversion of large amounts of air through the engine bay.

Each of the basic techniques of signature reduction involves a complex trade-off between survivability and aircraft design parameters. Once an LO aircraft is designed and tested, however, it makes radar detection, tracking, and engaging much less efficient, as the next section demonstrates.

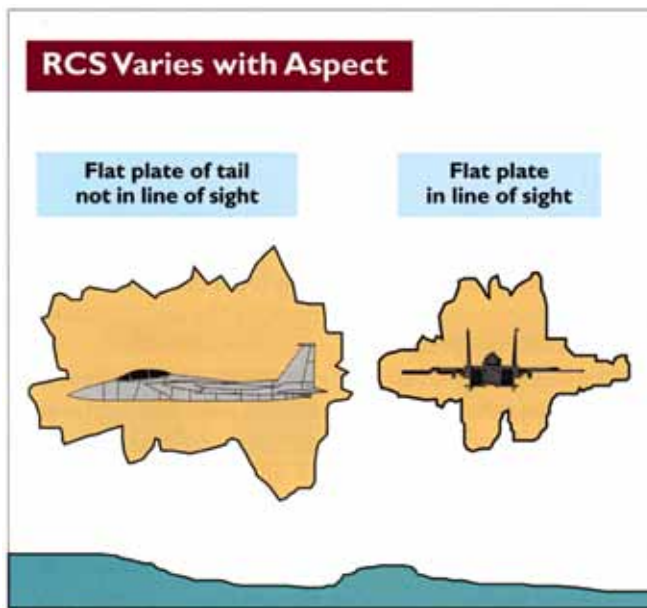
## SIGNATURE REDUCTION AND MISSION PLANNING

Once the principles of radar return are understood, the next step is to determine the overall effect of signature reduction, and how it delivers benefits for tactical mission planning. Radar cross section varies with aspect and with the frequency of the radar attempting to track it. Both concepts have important implications for netting the tactical benefits of stealth.

First, even a low observable aircraft will have what might be called its good sides and its bad sides. Since RCS is a three-dimensional polygon, the scattered electric field can appear as a different shape depending on aspect, effec-

tively making the signature larger or smaller and the aircraft more or less vulnerable to detection, tracking, and engagement. An aircraft passing through the enemy air defense environment may be visible from several different angles as it approaches the target, attacks, and departs. The RCS of an aircraft will be different depending on what aspect or angle the enemy radar sees.

Sound tactics call for minimizing the larger radar reflecting aspects. Head on, a high-performance fighter's conical nose will minimize return, but its air intakes may cause specular reflection. Waves may be diffracted from bouncing off



the intake walls and from diffraction inside the cockpit area. Waves will travel along the wings until they are diffracted from the wing tips and returned from the trailing edge. From the side, the RCS will be much larger. The flat plate of the vertical stabilizer presents a large specular reflection, plus corner and edge diffraction. Pods, ordnance, or drop tanks under the wings will also cause larger returns.

The ideal for a stealth aircraft is to reduce the signature in all aspects. All-aspect reduction is valuable because enemy fighters and ground-based air defenses might observe the attacking aircraft from multiple angles as the aircraft flies its mission. However, in practice, signature reductions are not uniform. Aerodynamic trade-offs also force compromises in signature reduction.

The analysis in this section will examine three different hypothetical signature shapes. Combat aircraft in today's in-

ventory employ a number of different techniques for reducing their radar cross sections. The Fuzzball, Bowtie, and Pacman shapes are highly simplified symbols for basic patterns of signature reduction. In this analysis, the signature is constant at all frequencies. Actual aircraft signatures are considerably more complex, and of course, information about them is restricted. The intent of the three shapes is to depict how general patterns of LO reduction give attackers a revolutionary edge in mission employment.

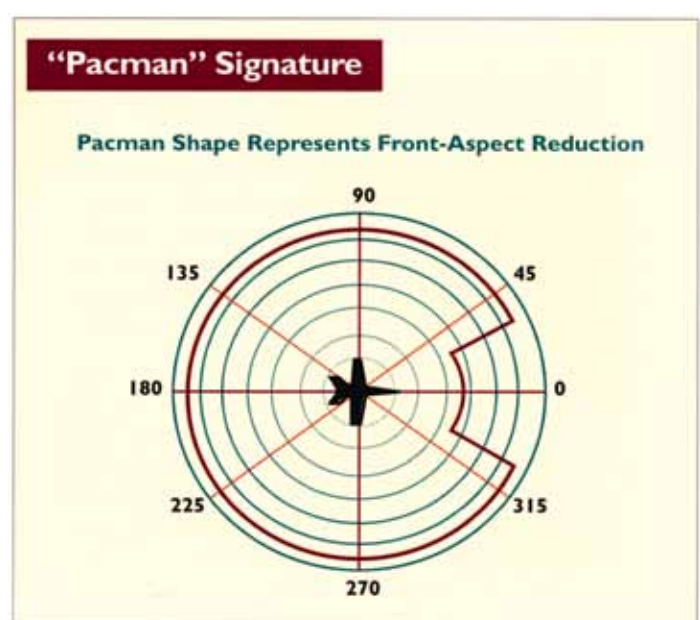
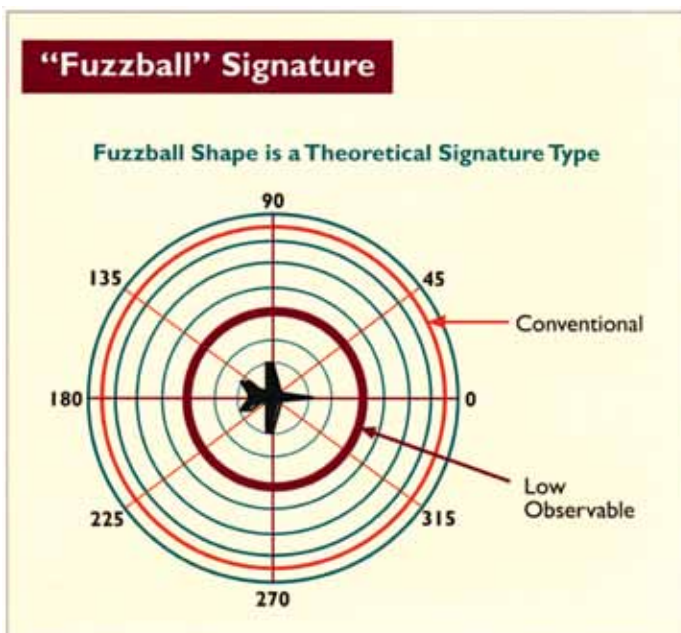
The Fuzzball signature is a hypothetical shape that is constant from all aspects. The ideal shape—the Fuzzball with uniform reduction at all angles—could in theory achieve remarkable results at the lowest levels.

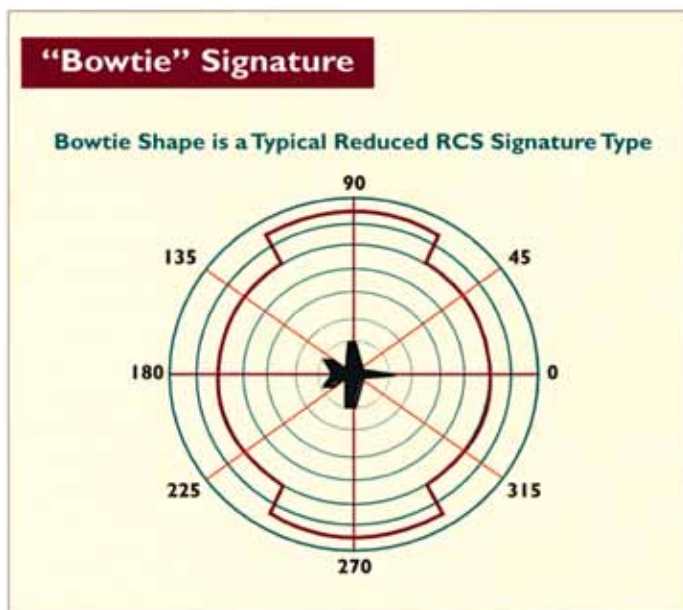
The Fuzzball shape is a theoretical signature that is reduced evenly, from all angles. It is representative of the magnitude of detection reductions that are possible with a perfect shape—a perfect shape that probably would not conform to any actual aircraft design. Theoretically, a perfect Fuzzball with a uniformly reduced cross section in the range of -55dB would deny any radar return at all. A very low observable aircraft could, in effect, approach the target area from any angle without triggering crucial components of the integrated air defense system.

In reality, aircraft are either designed as LO platforms from the outset, or retrofitted with modifications that reduce specific aspects of the signature, such as the nose-on RCS. Pacman and Bowtie are more realistic sketches of the signature reductions that can be achieved once aerodynamics and other survivability features are balanced with LO design.

The Pacman signature type is a simplified approximation of a conventional aircraft that has been retrofitted to reduce its signature in the front aspect only.

Within certain parameters, retrofitted modifications can





reduce radar cross section and improve survivability. Applying radar-absorbing material to forward surfaces, shielding inlets, ducts and canopies, and minimizing ordnance and other protrusions are some of the measures that can lower RCS from the nose-on angle. Rear and side aspects would not be reduced in the same way. Thus, in this notional case, a retrofitted aircraft might have a signature reminiscent of the creature in the old 1970s Pacman video game.

An aircraft designed from the start to be low observable can seek to minimize the signature from all aspects. The F-117's slanted tails, flat bottom, and diamond shaping sought all-aspect reduction by removing or altering the large radar reflector surfaces associated with conventional

aircraft. The B-2, which has no vertical stabilizer, represented another step forward in all-aspect reduction.

However, the level of signature reduction is still likely to be uneven. The hypothetical signature type may still be smaller in front and rear aspects, and larger from the side. That would form something like a Bowtie, as shown at left.

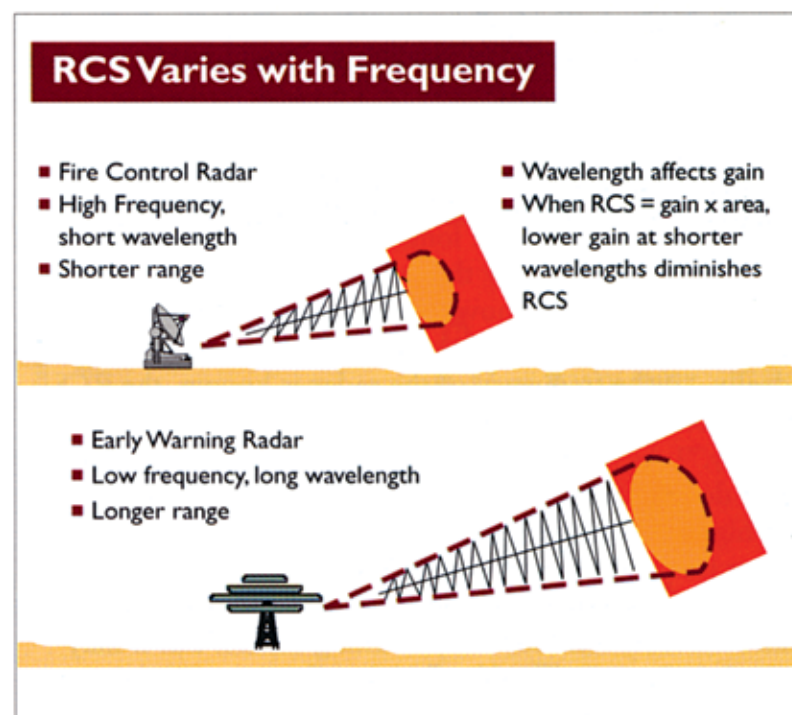
To capture this concept in simplified form, the theoretical Bowtie shape has a 15 dBSM reduction in RCS over front and rear aspects.

### Signature Varies with Wavelength

For any of the signature shapes, the low observability of aircraft also depends on the wavelength of the radar attempting to detect and track it. Simply put, RCS also varies with wavelength because wavelength is one of the inputs that determines the area of the radar cross section. One way to understand this concept is to depict RCS as equal to the gain of the returned radar signal multiplied by the reflecting area of the object.

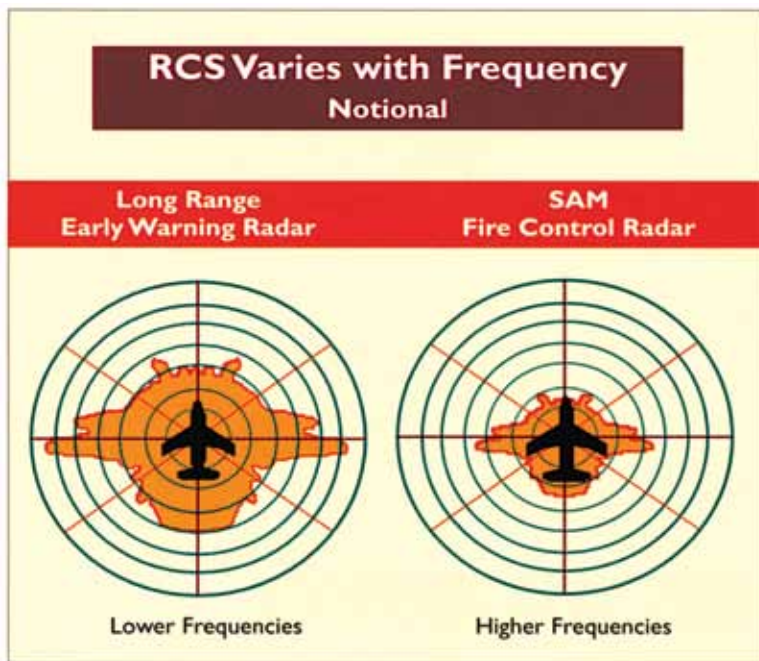
Shorter wavelengths will excite transmission from a smaller area of the target object. Recall that as wavelength decreases, frequency increases. As shown previously, the larger wavelength of a lower-frequency wave hits more of the object. Imagine that the crest and trough of the waves define the size of a circle behind the object. The radius of the circle varies with size of the wavelength. This imaginary circle determines the amount of power (called gain) concentrated in the beam returning to the sending radar. Hence, RCS varies with wavelength. For a constant area and range, the difference between X-band and VHF wavelengths results in a dramatic variation in RCS.

Long-range surveillance radars, the first types of radar invented, emit a long wavelength. Centimetric wavelengths were common in World War II. Higher frequency radars found in fire control radars and in surface-to-air missiles, have a shorter wavelength which improves the clarity of their detection but cuts their range. The net result is that RCS varies with the frequency of the radar.



Radars are designed to operate at specific frequencies to fulfill different functions: long-range surveillance, high-resolution tracking, etc. By the same token, "if a platform is to face a radar with known specifications, the target can be designed with the radar's performance in mind." Ideally, "if the frequency of the radar is known, the RCS reduction effort need concentrate only on the threat frequency."<sup>57</sup> As the principles of physical optics suggest, aircraft design can reap greater payoffs in minimizing RCS for higher frequencies such as fire control radars, than for lower frequencies employed by early warning radars.

In practical terms, this means an LO aircraft can reduce its RCS for early warning radars. But it may *greatly* reduce the RCS for fire control radars that direct



formula known as the radar range equation. The time at which a radar detects an aircraft depends on many variables, such as the power and frequency of the radar. However, the size of the radar reflecting area of the aircraft itself is an extremely important variable—and the major one that aircraft designers can control. Objects with a larger radar reflecting area return more energy to the radar and will most likely be detected sooner. Lowering RCS diminishes the effectiveness of the radar and, in effect, shortens its acquisition range.

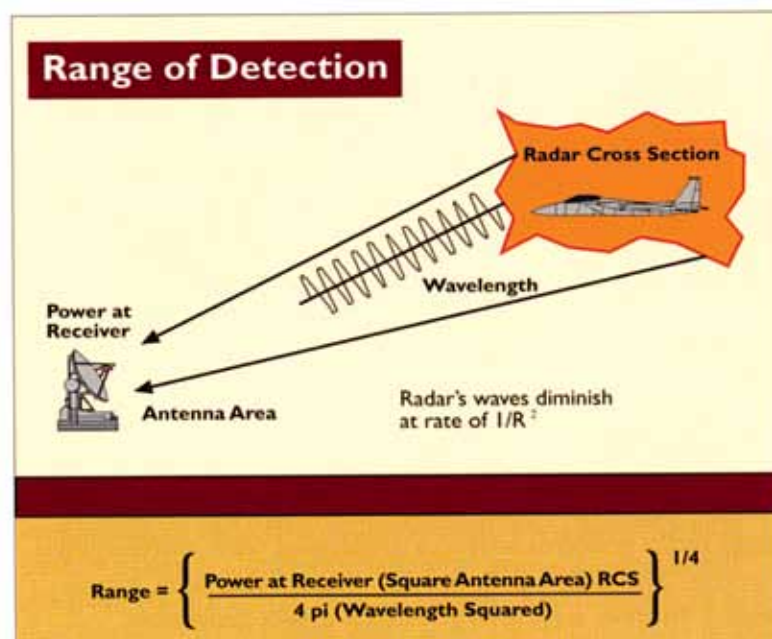
The radar range equation shows the drop in detection range of a given radar as the RCS of the aircraft diminishes. A reduction in RCS does not result in a proportionate reduction in the range at which a radar can detect an aircraft, for such measurements depend on the radar range equation. The radar range equation indicates the range at which an object of a given size will be detected. Detection occurs when the return is above a threshold specified for the radar.

SAM shots, for example. This difference means that although the enemy air defense network may know a stealth aircraft is present, the network may not have the means to track and engage it with fire control radars.

Degrading the efficiency of the search radar is the primary benefit of stealth. The goal of LO aircraft in a tactical environment is to deny timely flow of information about the aircraft's position, elevation, and heading to the enemy's integrated air defense system. The basic goal of this process is to reduce the range at which different radars in the air defense system detect and track the aircraft.

## The Radar Range Equation

The value of low observables comes together in a simple

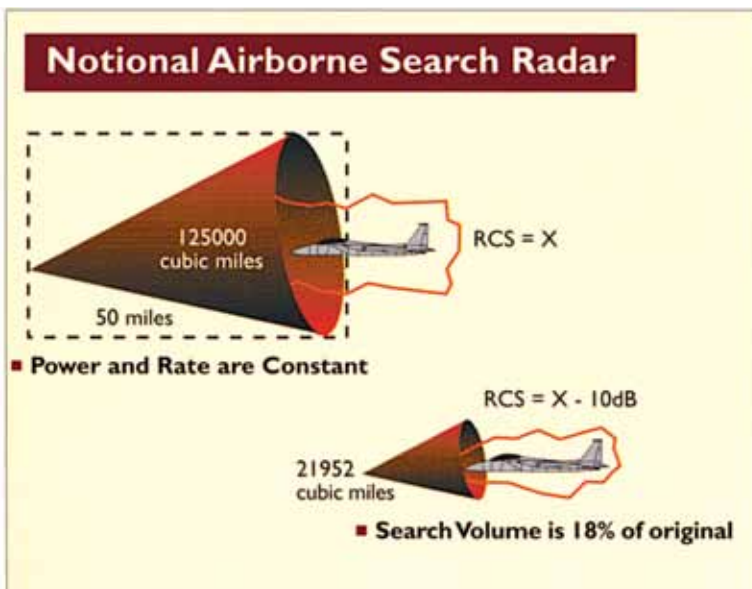


Range of detection is a function of the power of the sending radar waves multiplied by the size of the radar cross section, with that result then affected by wavelength. To examine the first variable, the wattage of radar energy sent out by the radar affects how many of the waves are returned to the antenna area off a given reflective area: the RCS. More wattage will boost this number; but the RCS variable will continue to divide out a significant portion of the potential return.

Reduced RCS is the prime variable in the radar range equation for radar detection of range. Changing the variables changes the range. Range of detection varies with the fourth root of the result of the radar range equation. For example, the radar range equation can be used to demonstrate logarithmically that a 40 percent reduction in RCS causes only a 10 percent reduction in the detection range. Also, doubling the power of the radar yields a 19 percent increase in range of detection.

Range is not the only important measure of the effects of RCS reduction. A lower RCS also reduces the efficiency of the radar's two-dimensional search area and, for airborne radar, of its three-dimensional search volume. Stealth actually emerges in three dimensions. As the attacking aircraft's RCS becomes smaller, it degrades the efficiency of radars attempting to track it in three potential dimensions.

The principles are the same as the radar range equation. A radar must receive a return signal of a certain strength to register detection. At the same time, the radar is assigned to search a given area in a given time with a fixed amount of power in its transmitting signal. As discussed, power is a variable in the radar range equation. When a certain amount of



power is spread over a fixed area in a given period of time, the power of the signal returned from the aircraft determines whether the radar will detect it. Because the power at the radar and the length of time for its search are held constant, the lower RCS means that the radar spends more of its allotted time searching areas that produce no return, or whose return is not above the threshold required for detection by the radar.

As a result, the radar's search pattern efficiency is degraded in all three dimensions when RCS is lowered. In the example depicted in the chart above, the volume of air-to-air search for a  $-10\text{dB}$  reduction is just 18 percent of the original efficiency, when radar power and search rate are held constant.

The lower the signature, the more the aircraft gains in survivability: to a point. At some fixed point, the radar's power will be such a big variable in the range equation that it burns

through or overwhelms the threshold of detection. At this point the radar will pick up enough return, even from an LO aircraft, to result in detection.

The radar's power can increase in two ways. First, the aircraft approaches very near to the radar. Second, the output power of the radar can be increased. However, it is easier to increase the output power of the radar at lower frequencies of early warning radars than at the higher frequencies of fire control radars. Tactically, the attacking aircraft counts on delaying detection by fire control radars as long as possible in order to evade engagement.

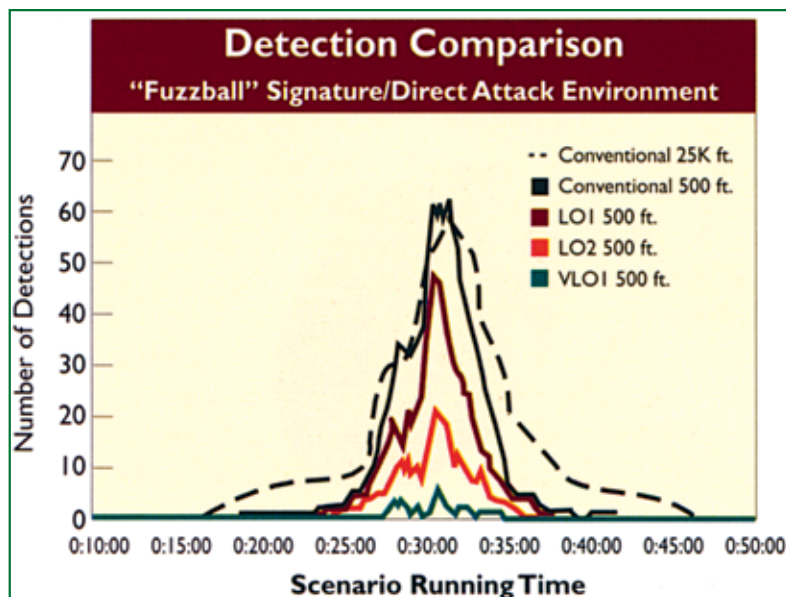
### Shrinking the SAM Rings

Another payoff of low observables is a reduction in the amount of time the combat aircraft is subject to the full tracking and engagement capabilities of integrated enemy air defenses that fire SAMs or control anti-aircraft artillery. A reduced RCS cuts the detection range of the radars that form the IADS. For example, it may allow the aircraft to penetrate farther toward its weapons release point before being detected by long range radar. Then, it may shrink the range of the fire control radar of the SAM. Shrinking the SAM rings reduces the amount of time the attacker spends in jeopardy.

In the chart at left below, a theoretical Fuzzball signature is reduced equally from all aspects. Using an air defense simulation of an attack ingress and egress, the Fuzzball follows a medium-altitude straight-in flight plan for a direct attack against a target area that is heavily defended with many modern, overlapping long- and short-range SAMs.

The black line on top shows that the conventional Fuzzball is engaged by fire control more than 50 times in this scenario. However, the number of engagements drops when the Fuzzball's overall signature is reduced as shown by the next three lines. At the extreme, radar return from the very low observable (VLO) Fuzzball is so small that the shape produces no valid shots at all.

In the previous scenario, the uniformly reduced Fuzzball signature shape RCS degraded the efficiency of the integrated air defense in stages. The next section explores in detail how lowering RCS defeats each phase of the engagement between the attacking aircraft and the air defense system.



### Defeating the Integrated Air Defense System

Low observable aircraft can gain advantages over the air defense system at several stages. Each component in an IADS is optimized for a specific task. Just as an integrated air defense has many nodes that make it function, aircraft with low observables have many opportunities to stifle the system's ability to detect, track, and engage against them. Shortening the detection



range of acquisition and fire control radars limits the amount, quality, and timeliness of the information that is fed to the air defense system. With less time to acquire, track, and fire a missile, the defenders stand much less chance of shooting down the aircraft.

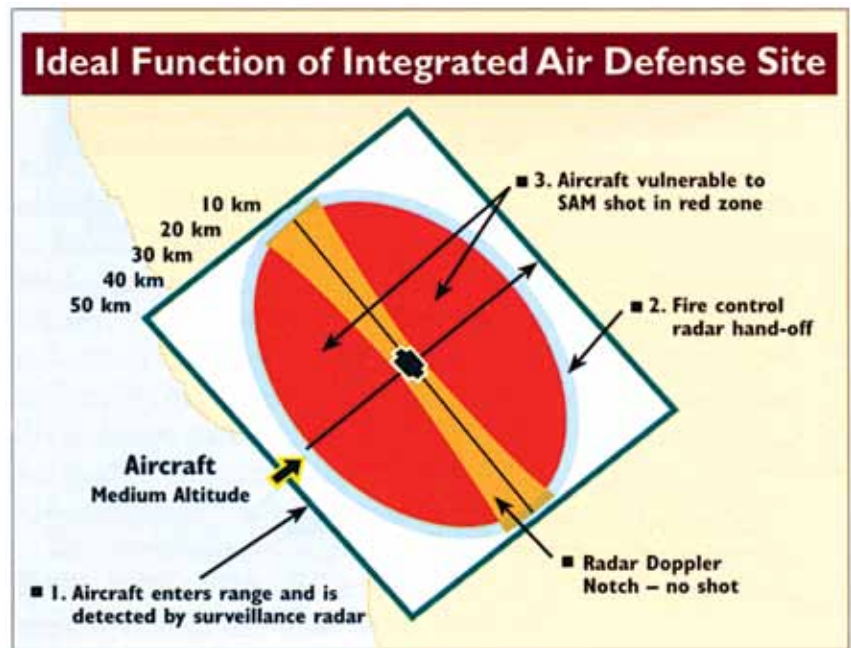
The next series of charts depicts what happens to the components of a notional threat system when a single aircraft enters its detection, tracking, and firing area. The system's components are calibrated to function as shown in the chart at right. In the white area, the surveillance radar acquires targets farther out, then hands them off to the fire control radar, as shown in the pale blue line. When the hand-off is completed the system can take a valid shot in the area marked in red. Two additional caveats are important to how the system functions. When detection sets up a valid shot, the surface-to-air missile must be launched at the aircraft within certain parameters. Also, the missile's seeker must then lock onto the aircraft. This chart illustrates the ideal function of a notional air defense site.

A valid shot can occur anywhere inside the red box. The orange band in the middle is the Doppler notch of the fire control radar. In the Doppler notch, the aircraft is too parallel to the radar to track via the Doppler effect. No engagement is possible in the notch. As the aircraft passes across the center of the system, radars can re-engage it on egress.

The goal of stealth is to pre-empt detection and break down the chain of events. This series of charts depicts how the system fails when it must attempt to detect, track, and take a valid shot against a notional aircraft with a reduced signature shape. Watch for the red valid shot area to shrink as the overall signature of a hypothetical aircraft shape is reduced. As the red area shrinks, different color bands reveal what part of the air defense system has failed to engage the aircraft at any given point on the ingress and egress. Note that these next charts zoom in on a closer range.

The signature levels fall into five categories. Conventional is an aircraft with no signature reduction and a large RCS. Low Observable 1 (LO1) and Low Observable 2 (LO2) postulate levels of RCS reduction that enter the stealth zone, but still are not as low as aircraft may achieve. Very Low Observable 1 (VLO1) is a highly desirable and achievable state of RCS reduction. Very Low Observable 2 (VLO2) is a hypothetical extreme not likely to be achieved, and is used in only one chart for illustrative purposes.

The best way to illustrate the effects of signature reduction is to start with a conventional Fuzzball entering the range at medium altitude. The chart at top left on the next page di-



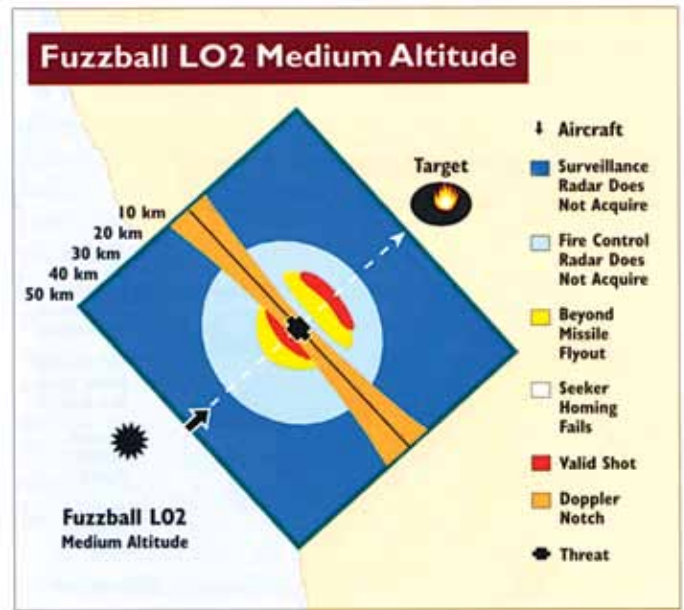
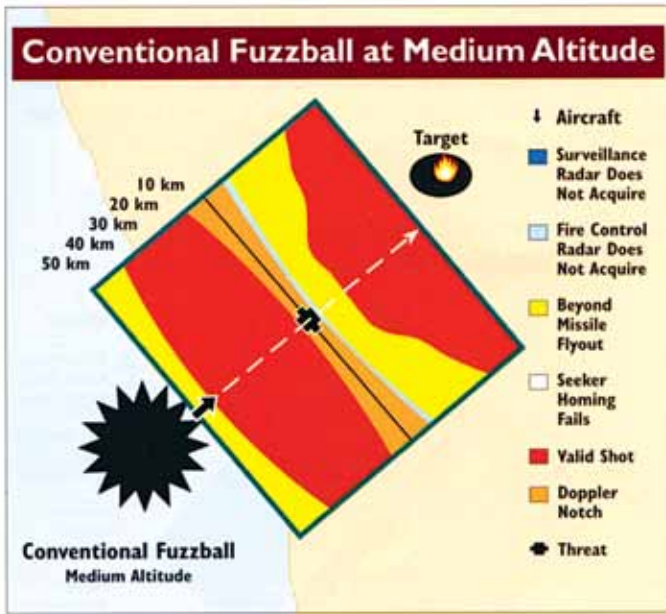
agrams the route of a conventional aircraft. The black arrow represents an aircraft flying downrange along the track of the dashed white line. The legend on the right side indicates what part of the air defense system is not able to fulfill its task when the aircraft reaches that point. In the yellow zone, the SAM cannot be properly guided to the target. However, in the red zone, the air defense system works perfectly. Red indicates that an intercept is likely, in this case, at almost 40 km out. The red zone shrinks as the signature of the aircraft shrinks.

The next chart (p. 42, bottom left) shows the same flight profile for an aircraft with LO1 reduction. The red intercept zone recedes to less than 30 km out. In the light blue region, it is the hand-off to the fire control radar that breaks down due to the low observability of the aircraft.

More signature reduction yields greater results. When the air defense system does not pick up the LO aircraft in time, it cannot hand off this information to other system components. In the LO2 chart (p. 42, top right), the surveillance acquisition radar is the first link to fail in the air defense chain. Inside 20 km, missile fly-out again poses the problem. The red zone now consists of a narrow patch just 10 km from the threat.

VLO shapes may be able to defeat the system altogether. In the VLO1 chart (p. 42, lower right), the surveillance radar does not acquire the signature of the VLO1 Fuzzball until it is about 20 km away. At that stage, it is detected, but the fire control radar cannot pick up the hand-off and acquire the shape. Consequently, no red intercept zone appears on the chart.

Stealth is complete. The Fuzzball shape is not detected until very late, and, at that stage, it cannot be tracked or engaged.



While the Fuzzball is a perfect and therefore hypothetical shape, similar effects occur with a more practical approximation of a real aircraft signature. For example, at first, the Bowtie (represented by the charts on p. 43) with limited RCS reduction defeats the air defense system by fooling the fire control radar. However, at this minimum level of signature reduction, a large red intercept zone still remains.

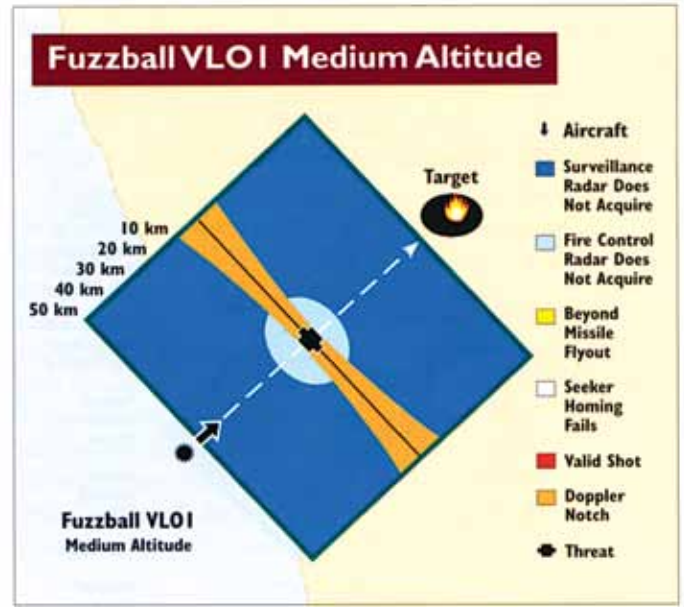
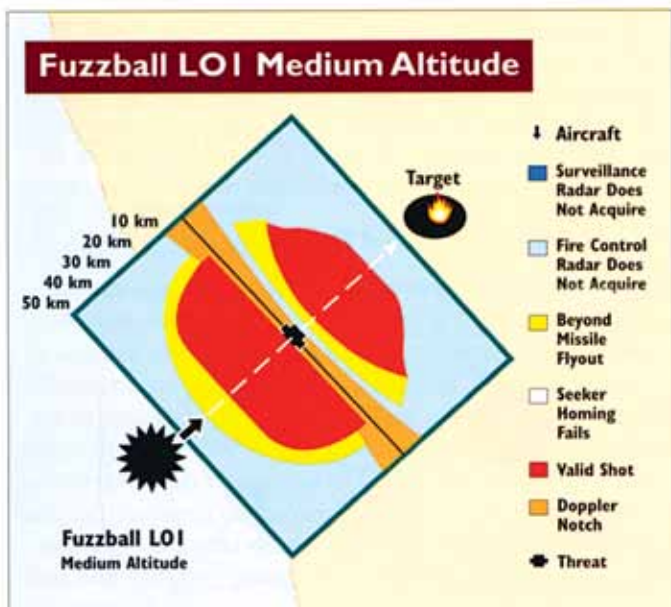
The next step in signature reduction causes much greater reduction of threat to the aircraft. The surveillance acquisition radar is fooled. In another crucial step, the fire control radar struggles to attain a fix in time as the aircraft transits the crucial 20 km. The red zone appears around the 10 km point.

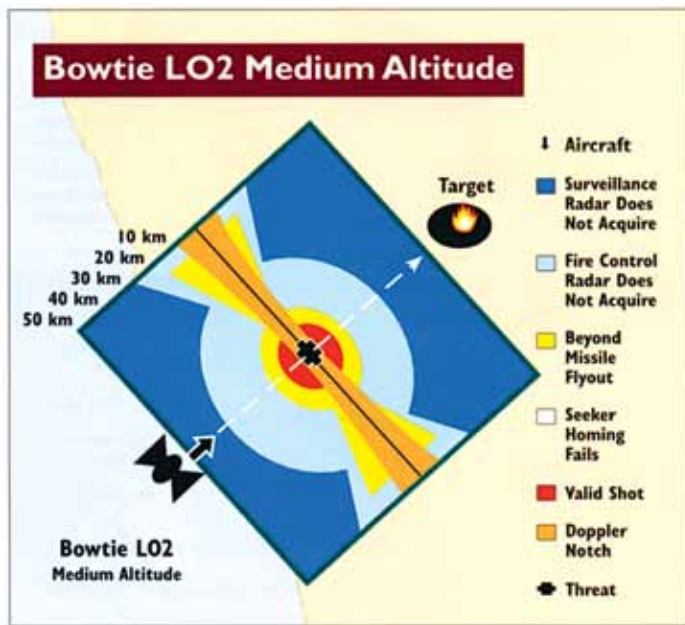
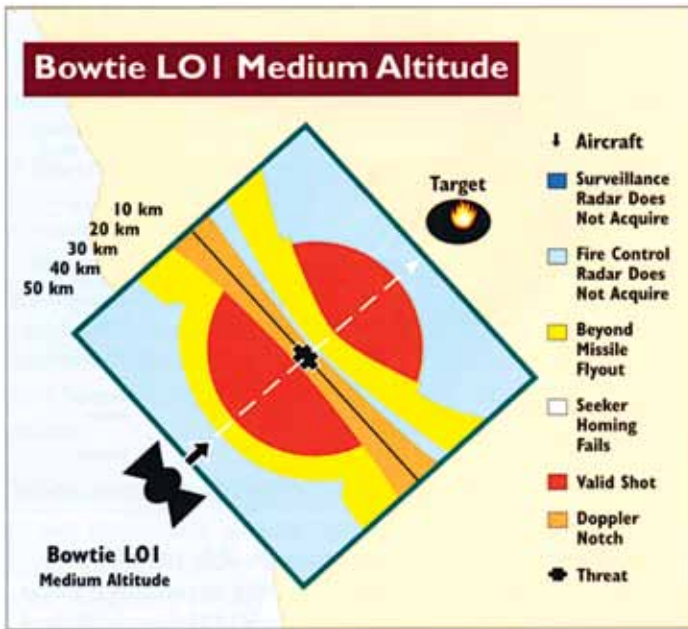
The red zone represents real danger for an aircraft at-

tempting to overfly the target. However, the smaller the red zone, the less time the aircraft would spend in it. Employing a weapon with just a few kilometers of standoff range could keep this out of the red zone on ingress.

Major RCS reduction shrinks the red zone again and makes direct attack much more feasible. As the aircraft egresses, it also fools the seeker homing device in the missile, as shown in white on the Bowtie VLO1 chart (p. 43). On egress the red intercept zone is very small.

Soon the aircraft is again beyond the range where fire control or surveillance radars can detect and track it. By systematically defeating parts of the integrated air defense, an LO aircraft can vastly improve its survivability. This makes a VLO aircraft eligible for missions that other aircraft would have difficulty completing.





### Tactical Advantages of Stealth

The simulations above pitted one aircraft against one SAM system. The real benefits of signature reduction come when an attacking aircraft faces multiple threats. In a tactical scenario, striking aircraft do not plan to overfly the air defense radars. Instead, pilots plan missions to fly around some threats, and through the lesser threats to the maximum extent possible. The next chart (p. 44, left) depicts a notional mission where aircraft must penetrate dense air defenses to strike at a high-value target. In the conventional strike chart, air defenses are placed so as to provide overlapping coverage and seal off attack routes.

Aircraft attempting to fly this mission would encounter multiple threats and spend considerable time in jeopardy.

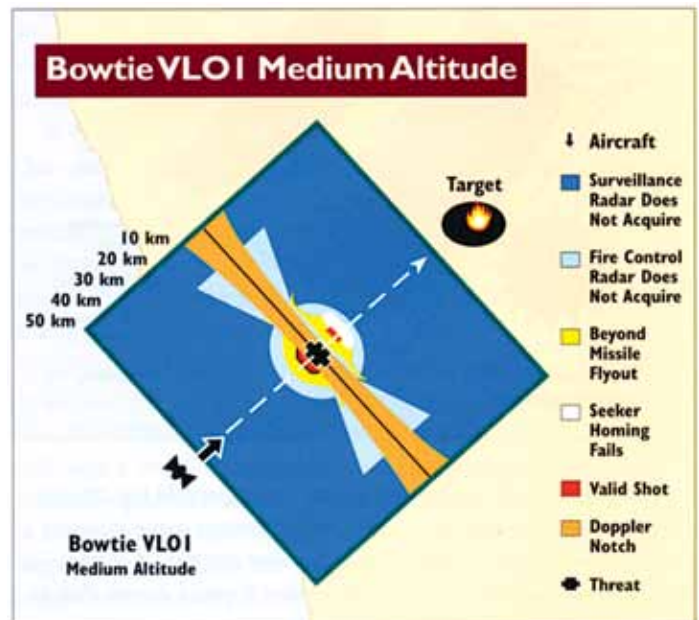
Instead, as shown in the chart on p. 44 depicting a stealth strike scenario, low observables “shrink” the distance for early warning detection and perhaps more dramatically, for fire control radar. RCS reduction can, in effect, open up narrow gaps in what was intended to be overlapping SAM ring coverage. With careful planning, an LO aircraft can greatly increase its chance for survival in the duel with the ground-based air defenders by flying through the gaps in coverage. The chart shows how a stealth aircraft can thread its way between the degraded SAM detection rings.

When applied across multiple radar sites, the effects of low observables are compelling. All SAMs require a minimum amount of time to detect, track, and acquire a target. The process, while relatively fast, still requires several steps. The SAM must positively identify the target, rotate and elevate the launcher, prepare the missile, and fire. All SAMs have a minimum range that is determined by the reaction time of the radar system and the acceleration and maneuverability of the missile. Reducing the range of early warning detection and of fire control radars yields tremendous advantages because it breaks this cycle.

### The Benefits of Radar Cross Section Reduction

What is the payoff for signature reduction? Stealth does not render aircraft invisible, as the preceding discussion has demonstrated. The reality is more complex. Achieving a lower RCS degrades the ability of the enemy radar to detect, track, and engage aircraft. Most significantly, lower RCS shrinks the distance at which aircraft are detected.

Several important caveats are essential to understanding the effects of stealth. A combat aircraft’s RCS varies with aspect and with the frequency of the radar attempting to track it. According to theoretical principles, very low fre-



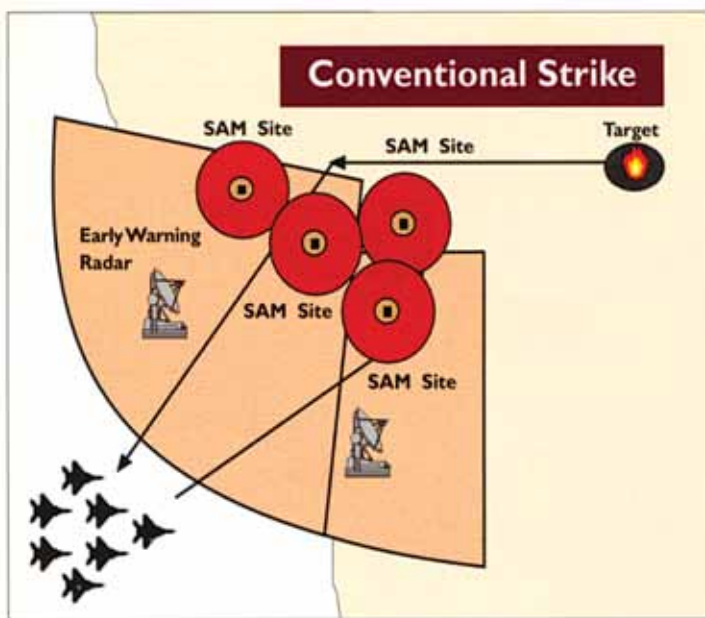
quency radar waves may often be able to detect aircraft. However, if RCS reductions are optimized to the higher frequencies of fire control radars, significant benefits can be achieved.

In historical context, the ability to lower vulnerability to radar detection restored enormous advantages to air attackers. For a B-17, in World War II, little could be done to prevent early warning. The earlier the Germans could detect formations of B-17s and B-24s, the more opportunity they had to direct fighters and antiaircraft fire toward them.

Lowering the aircraft's observability to radar can allow the aircrew to complete more of the mission before becoming vulnerable to radar-controlled weapons. This provides the attacker the advantage of avoiding the threat and minimizing the time in the "red zone" where detection leads to valid

SAM shots. Also, stealth enables attacking aircraft to get closer to their targets. For example, shrinking SAM rings makes the SAM site and the targets it attempts to defend much more vulnerable to attack.

Today and for the future, air defense environments will vary enormously in the type of SAMs and the level of integration employed by the air defense networks. For this reason, the current and planned inventory of military aircraft each have strengths and weaknesses that depend on the scenario in which they may be employed. The principles of stealth place great emphasis on mission planning to achieve maximum survivability and effectiveness. The next section will explore survivability tactics: the art of pulling the most current survivability options together for maximum impact in the joint campaign.



## LOW OBSERVABLES IN THE OPERATIONAL ENVIRONMENT

Low observable aircraft provide enormous flexibility in tactics and mission planning. As a result, they expand the options for air component operations. Planners who seek ways to destroy important but heavily defended targets find that LO aircraft mitigate risk in three ways. First, stealth aircraft are far less likely to be shot down. Second, they can destroy targets at a more rapid rate, before the enemy can move or reconstitute valuable capabilities. Third, highly survivable aircraft can attack integrated air defenses directly and early on, lowering the risk to less survivable conventional aircraft.

The final segment of this essay explains how LO aircraft reduce risk and increase effectiveness in air component operations, and why this provides indispensable benefits for the

Joint Force Commander (JFC)). Desert Storm is the starting point for any discussion of the operational impact of stealth. The next section examines F-117 operations on the first night of the Persian Gulf War to illustrate how having a highly survivable platform influenced planning for the air component's first night of operations.

### Stealth in Desert Storm

Air operations in Desert Storm illustrated that reduced RCS could indeed enable the F-117 to accomplish missions in air defense environments that would have been too hazardous for aircraft with conventional signatures. The missions flown by the F-117 outlined the principal benefits of and tac-



at about 100 sites stood watch for the SA-2, SA-3, SA-6, and SA-8 batteries. Also included in the air defense system were as many as 8,000 antiaircraft pieces.<sup>59</sup>

Planners at first considered sending a mix of stealthy F-117s and conventional F-111Fs and A-6s with jamming support to attack targets in Baghdad. The F-111's long range and its ability to launch laser-guided bombs could knock out command and control and key air defense sites. However, in computer simulations run before the war, about half of the F-111Fs and A-6s were lost to Iraqi air defenses, even when standard electronic countermeasures were employed.<sup>60</sup>

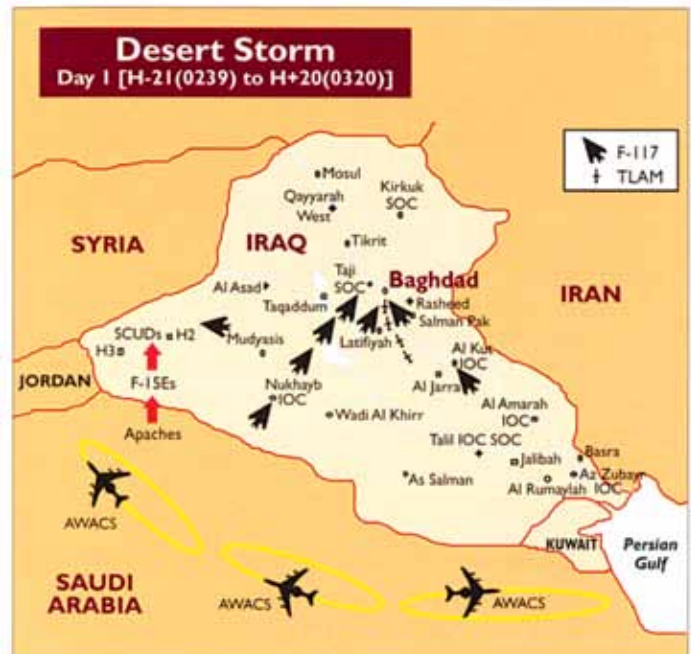
On the night of Jan. 17, 1991, two F-117s crossed the

tics for the use of stealth. At the operational level, the F-117 illustrated the role of stealth in the air campaign as a whole.

The F-117s drew the most dangerous missions of the first night of the war because their stealth attributes gave them the best chance of accomplishing the mission and returning safely. Iraq's early warning radars, whose coverage reached well below the border into Saudi Arabia, were designed to detect attacking aircraft as they approached Iraqi airspace. Sector operations centers (SOCs) would then coordinate tracks of the attackers, alerting SAM batteries and fighters as the mission profiles emerged, as shown in the map above.

When Coalition aircraft neared their targets, overlapping coverage from the fire control radars would ensure multiple chances to fire missiles at the attackers. Antiaircraft fire would blanket the lower altitudes and reach as high as 20,000 feet.

Iraq's air defenses were so numerous that it was impossible to take out all the individual SAM batteries that ringed key targets with overlapping coverage. The Coalition's initial task "was to fragment and eventually destroy the Iraqi IADS," recorded DOD's official report to Congress after Desert Storm.<sup>58</sup> Fragmenting the IADS with attacks on specific nodes like the SOCs would reduce the efficiency of the information-dependent system well before its numerous individual elements were destroyed. Reaching the SOCs and other high-priority targets exposed the first waves of attackers to an extremely dense threat environment. Five hundred radars



border well before H-Hour and one attacked the SOC at Nukhayb in Western Iraq at 0251.

Another destroyed the central communications facility in central Baghdad. Six others flew tailored routes and struck other targets in Baghdad and other SOCs. Other stealthy "aircraft," namely the Navy's Tomahawk Land Attack Missiles (TLAMs), and USAF Air Launched Cruise Missiles (ALCMs) launched by B-52s, assisted by destroying soft targets. As a postwar survey described it, the F-117s "flew into, over and through the heart of the fully operating air defenses."<sup>61</sup> By doing so, they struck targets that weakened enemy air defenses and military command and control, with important effects for subsequent air operations.

Tactics for the F-117 included careful mission planning to keep the aircraft outside the now much-reduced range of detection of fire control radars as calculated for the F-117's LO shape. The F-117 flew at night to prevent chance visual detection. Overall, the F-117s logged 1,297 sorties in Operation Desert Storm with no losses. With no attrition, the Joint Force Air Component Commander (JFACC) was free to employ the F-117s against any high-value target. As an official Air Force study concluded, "Throughout the war, they attacked with complete surprise and were nearly impervious to Iraqi air defenses."<sup>62</sup> F-117 pilots often returned with tales of heavy anti-aircraft fire over their targets. However, the F-117s had successfully deceived enemy defenses with a combination of low observables, careful mission planning, and, on occasion, supplementary stand-off jamming.

The F-117 strikes destroyed numerous key strategic targets. They also contributed to the overall air campaign by using their enhanced survivability to knock out air defenses, making it safer for conventional aircraft to fly missions. After the initial F-117 strikes that opened the war, other aircraft attacked in strike packages using a variety of tactics to cope with the medium- to high-density threat environments.

F-117 operations in Desert Storm demonstrated that direct attacks in heavily defended regions could be carried out by LO aircraft. "Stealth was an essential ingredient of the original strike force," noted one analyst, because "it allowed planners to insert strikes against enemy command and control nodes."<sup>63</sup> Highly survivable aircraft set the parameters for air operations in 1991. The next section explores the role of low observables and how they yield a strong tactical edge for survivability duels of the future.

## Duels of the Future

The record of the F-117s in Desert Storm pointed toward many future applications for low observable aircraft in the joint air campaign. However, future scenarios will not be identical to Desert Storm. Heavily defended areas may have more air defenses than Iraq did in 1991. On the other hand, a number of scenarios will involve what might be described as a medium-threat environment, where a mix of mobile SAMs

presents planners with a different type of challenge. On top of this, strike objectives of the future could also vary.

In this section, simulations of three different threat environments of the future will illustrate how different levels and types of signature reduction become controlling factors in aircraft survivability and in air campaign planning. These three scenarios were studied using a simplified version of a common air defense simulation model. The objective of each scenario was to portray how different levels of signature reduction improve survivability in a given environment. Each environment mirrors the types of attacks that the Joint Force Commander may call on the air component to perform in the future.

The three future attack scenarios, as shown below, set up different types and density of threats.

The Direct Attack scenario simulated a mission into a heavily defended region to attack a high-value target such as a command and control center or a weapons of mass destruction (WMD) storage site. The Tactical Attack scenario ran a simulation of an attack on a target that is part of a fielded military force. Finally, the Threat Avoidance scenario diagrammed a carefully planned route around known air defense sites to attack a time-urgent target in an isolated area.

The simulation itself employed a mission-level model that focused on events occurring within the integrated air defenses. The model captured variables like the decisions made by the command and control system, the allocation and operation of SAMs, and the ability of the various radars in each component of the system to track the attacker and fire a valid shot. Several variables were simplified in order to extract the unclassified results presented here.



The results produced a measure of valid detections that could lead to the firing of a surface-to-air missile. Graphs recorded the number of detections that were assessed to lead to a valid shot. For this simulation, once a shot was fired, the action did not stop. The model continued to run so as to record the total number of detections that could result in shots fired at each signature shape on ingress and egress. No attempt was made to assess how many shots it would take to kill the aircraft, or how many missiles the air defense system possessed. Instead, the simulation sought to assess the relative reduction in number of valid detections leading to a SAM shot for different signature levels, countermeasures, and tactics.

The next series of charts measures the relative numbers of valid detections leading to SAM firings for different signature shapes. One of the most interesting ways to view the data is to track the time in jeopardy for each shape as measured by the time fire control units begin to register valid shots. Two different altitudes are used in some charts to show the effect on survivability.

### Direct Attack in a Dense Threat Environment

The future equivalent of heavily defended, vital target complexes like Schweinfurt, Hanoi, or Baghdad is likely to be a capital region. The direct attack scenario posited a city in 2010 whose key military targets are ringed with overlapping modern long- and short-range SAMs of a modern IADS. Integrated air defenses are generally positioned so as to maximize the area of coverage. Typically, only regions of major military importance are worth the financial investment of redundant, overlapping coverage. SAMs are not so cheap and plentiful that nations can afford to sprinkle them everywhere. However, where SAM detection rings overlap, the coverage is so dense that it is intended to ensure a kill against the attacking aircraft.

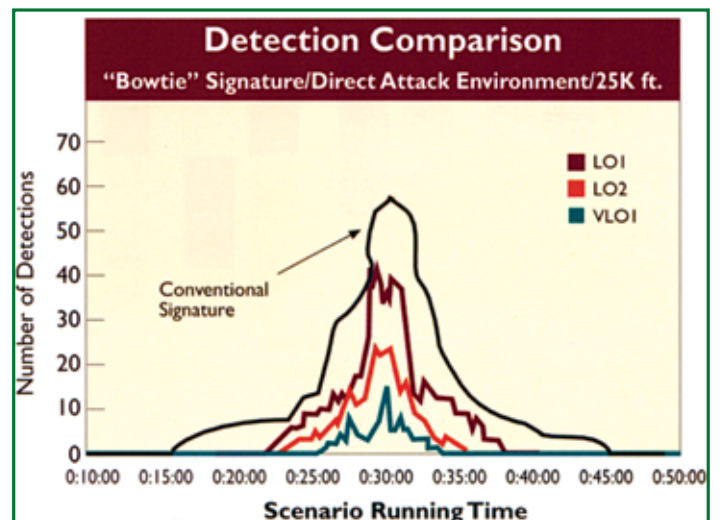
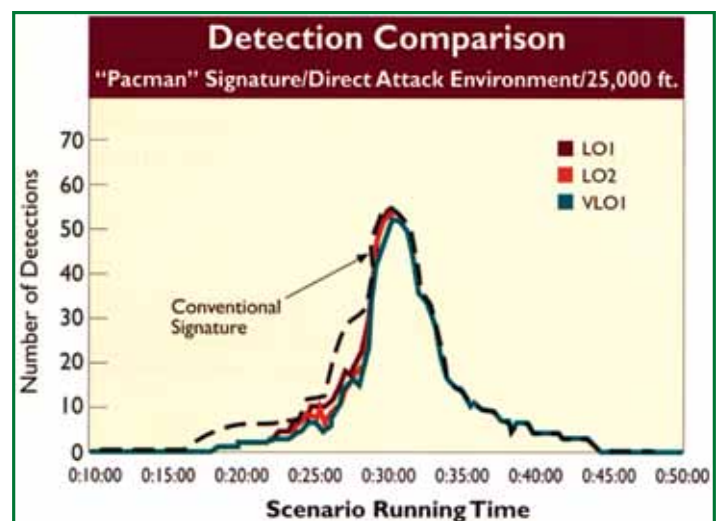
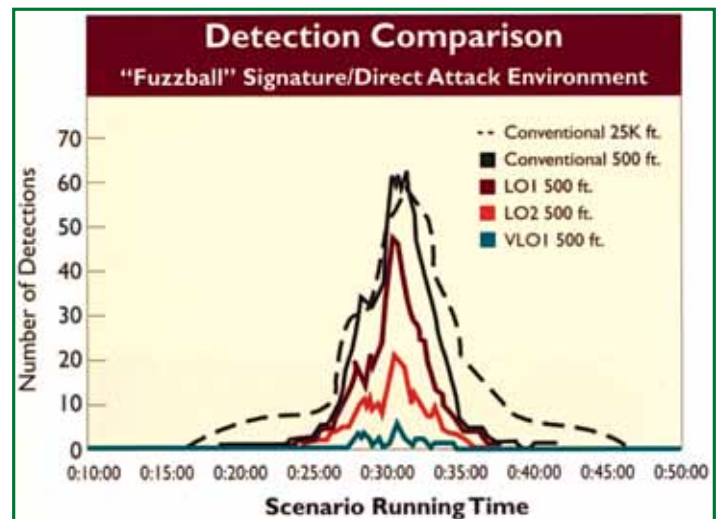
To attack, the aircraft must penetrate to its weapons release points even with threats from SAMs coming from all sides. As the chart on the previous page shows, the direct attack environment exposes the aircraft to numerous radars as would be expected in an attack on a capital region or other high-value location.

In this most demanding environment, a conventional aircraft signature suffers from both sustained, early detection and from a gigantic spike in detection over the target area.

The next chart (top, right) shows the conventional aircraft signature in black. The dashed line represents the attack mission flown at 25,000 feet.

The solid black line shows that flying the mission at low altitude, about 500 feet, yields some survivability improvement, but not much. The red, green, and blue lines show how perfect signature reduction of a Fuzzball shape improves survivability.

More practical signature shapes fare differently in the



direct attack environment. As portrayed in the next chart, a Pacman shape with some LO reduction on the nose fares only slightly better than the conventional shape.

The Pacman shape is detected four minutes later than the conventional shape. At the 27-minute point, Pacman shape detections are still less than 20, while the conventional

shape has hit 30 detections. Pacman’s detection rate spikes dramatically to 50+ detections directly in the target area, at the mid-point in the scenario.

As a result, the Pacman reductions would be of minimal value to the campaign planner in this scenario. Even if the nose-on reductions will put that part of the signature in the VLO category, the number of engagements remains high. As it flies away from the target it exposes the large areas where its signature is not reduced. The Pacman shape would not have a good chance of completing the mission successfully. Together, these facts would make it difficult for the JFACC to count on sending aircraft with Pacman shapes to attack heavily defended nodes. In all probability, the JFACC would devise a very different air campaign plan that focused on rolling back air defenses prior to launching direct attacks of this sort.

However, the Bowtie shapes, with significant levels of all-around reduction, display a functional increase in survivability. Reducing the Bowtie’s RCS has two effects. First, the aircraft’s time in jeopardy diminishes. Second, signature reduction causes a drop in the number of valid shots measured by this model in the Bowtie detection comparison chart (p. 47).

The Bowtie shapes at signature levels LO1 and LO2 take far fewer shots from the overlapping SAMs in this scenario. The VLO1 signature reduces the number of shots taken and spends only about eight minutes in jeopardy, compared to a full 30 minutes for a conventional signature shape in the same scenario.

For the air component, the tactical advantages of aircraft with Bowtie signatures are potentially enormous. Front and rear aspect reduction, especially at the lowest signature levels, greatly increases survivability against overlapping SAM coverage. The VLO1 shape pounces on the air defenders, not even coming into the region of vulnerability until it is very near the target. Even over the target region, the air defenses that recorded a spike of more than 50 shots against the conventional aircraft now score just above 10. Practical low observables do not make the aircraft invisible by any means. But they greatly increase its odds of success and its chance of surviving this type of mission.

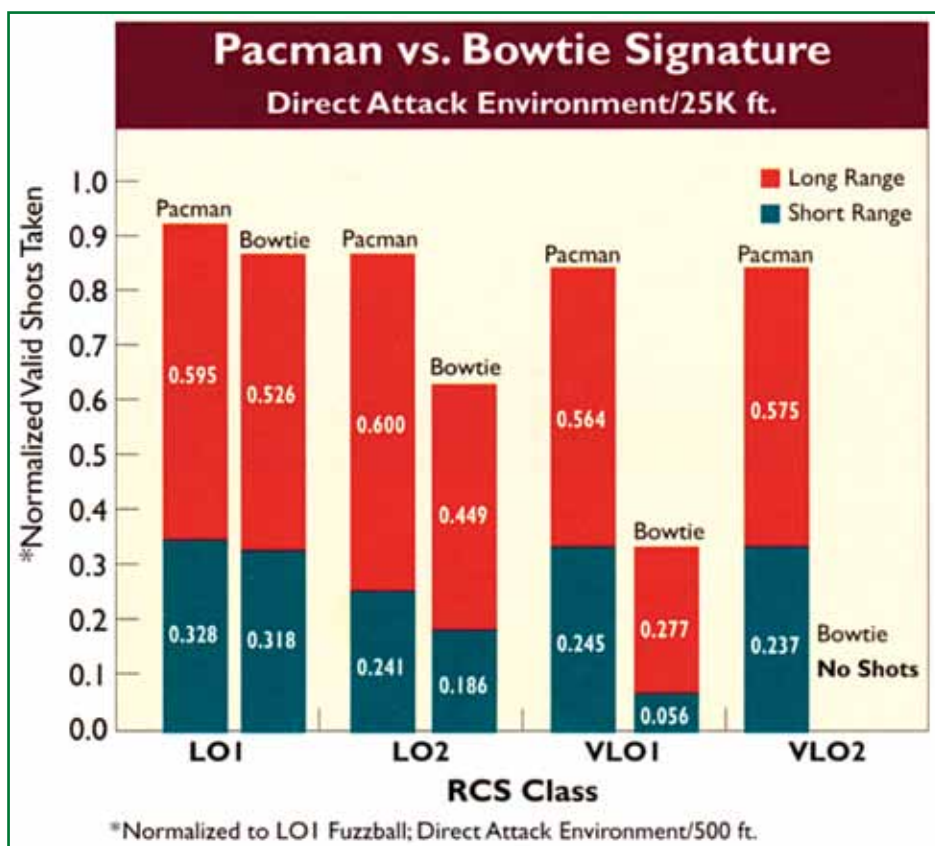
Using the same simulation data, the chart on this page indicates the ratio of long-range and short-range SAMs taking shots at each signature shape. For the Pacman shape, signature reduction yields only a marginal improvement in survivability.

Signature reduction in the Bowtie shape diminishes the number of shots taken, while the VLO1 Bowtie shape scores a particularly sharp drop.

### Tactical Attack Environment

The Tactical Attack Environment is a scenario in which the air defenses are less dense, but where numerous sorties will be flown either as part of peace enforcement operations, or as part of wartime attacks on enemy forces in the field. SAM systems and IADS components have spread throughout the world as part of the international arms market. US forces and Coalition partners are likely to encounter many situations where a mix of air defense systems pose a potential threat to air operations over an extended period of time.

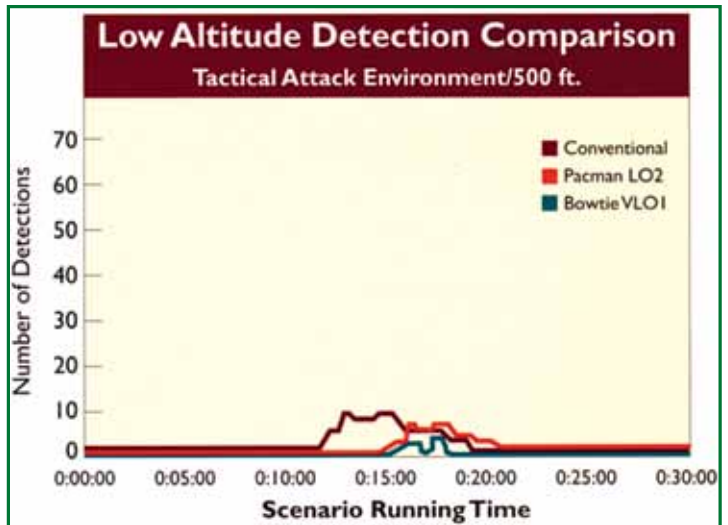
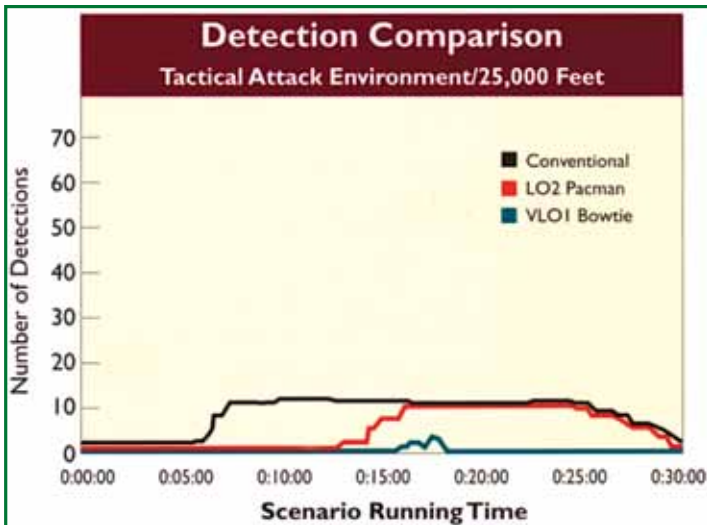
Some of the most critical and demanding types of air



operations involve attacking fielded military forces. In Desert Storm, for example, more than 70 percent of all sorties flown were in the Kuwait Theater of Operations (KTO) against a tactical threat environment. The tactical attack scenario postulates an environment where forces on the move will bring with them mobile, shorter-range SAMs.

Because the tactical attack scenario is a less dense threat environment, different signature shapes have a greater chance of achieving success. The next graph (p. 49, top left) begins with the simulated engagement track of a conventional aircraft shape. While the overall detections are low-





er than in the dense threat of the direct attack scenario, the conventional shape is still fired on for a long period of time. In contrast, the nose-on reduction of the Pacman shape is not tracked on ingress until much later. Reducing the nose-on signature helps primarily with the threats encountered as the aircraft flies toward a target. Once inside a certain range, the large side and rear signature areas make the aircraft nearly as vulnerable to radar tracking as a conventional shape. The VLO1 Bowtie achieves much better results. Few shots are taken and the time in jeopardy is brief.

Pacman’s survivability advantages must be tightly tailored to the scenario in which they can make the maximum contribution. Nose-on RCS reduction of this type might be useful when an aircraft is part of a package performing lethal SEAD that intends to knock out fire control radars before turning to egress and exposing the large signature areas. Attrition risks will still be higher for the Pacman shape than for the Bowtie shape. However, the prospects for successful employment are improved.

Altitude is another tactical consideration. The chart above left represented the tactical attack scenario at medium altitude, about 25,000 feet. Survivability improved for both the conventional shape and the Pacman shape when the aircraft attacked at a low 500-foot altitude (chart above right). For the VLO1 Bowtie shape, altitude does not make a significant difference in this scenario. The lower, more balanced signature is more survivable.

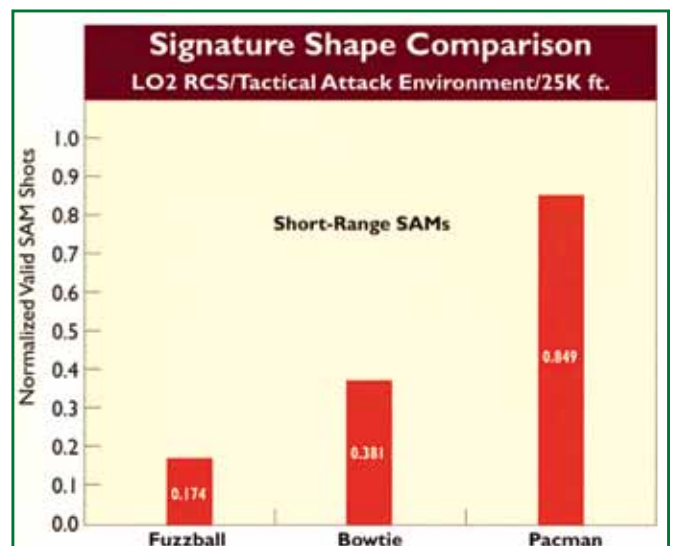
Compared to balanced signature reduction, nose-on signature reduction illustrated by the Pacman shape has its limits. Even in the tactical environment, with a VLO1 level of reduction, where the Pacman shape performed best, it has a significant probability of detection compared to full or partial all-aspect reduction. The chart at right reveals the relative differences.

Even at low levels, the lack of signature reduction in areas other than the nose-on aspect begins to corrode the Pacman shape’s survivability. Low altitude will also hold dense

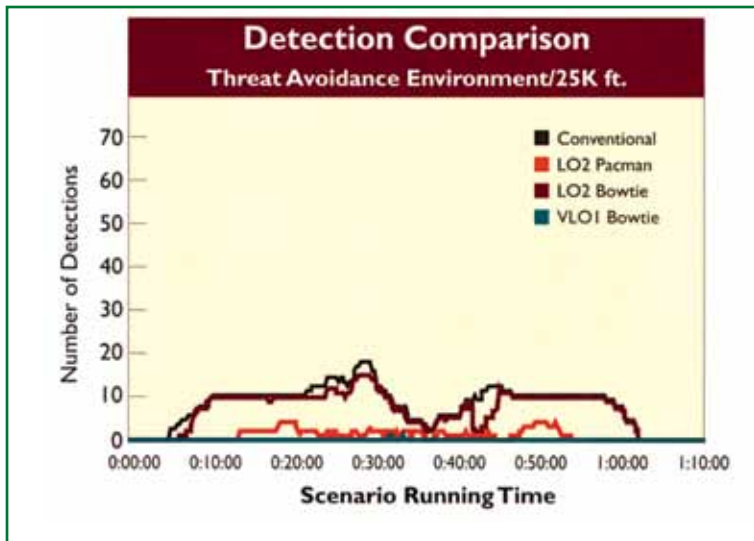
antiaircraft gun threats. In Vietnam, more than 85 percent of aircraft were lost to antiaircraft fire. In Desert Storm, aircraft in the KTO reported sporadic dense antiaircraft fire and shots from hand-held infrared SAMs, even after the IADS had been reduced to almost zero effectiveness. The survivability advantages of low altitude missions must be balanced against the level of threat from optically guided antiaircraft fire, small arms fire, and hand-held SAMs.

### Threat Avoidance

Similar results apply in another scenario where the aircraft attacks a point target along a flight path that deliberately minimizes exposure to the fire control radars. The threat avoidance scenario relies on maximum use of tactics through a carefully planned flight path where the aircraft skirts the edges of the anticipated radar coverage areas. Threat avoidance is similar to what the F-117 did on its opening night attack on the H-2 airfield, a Scud launch site. Because low observables reduce the range of detection, the SAM rings shrink, making the prospect of “threading the needle” that much better.



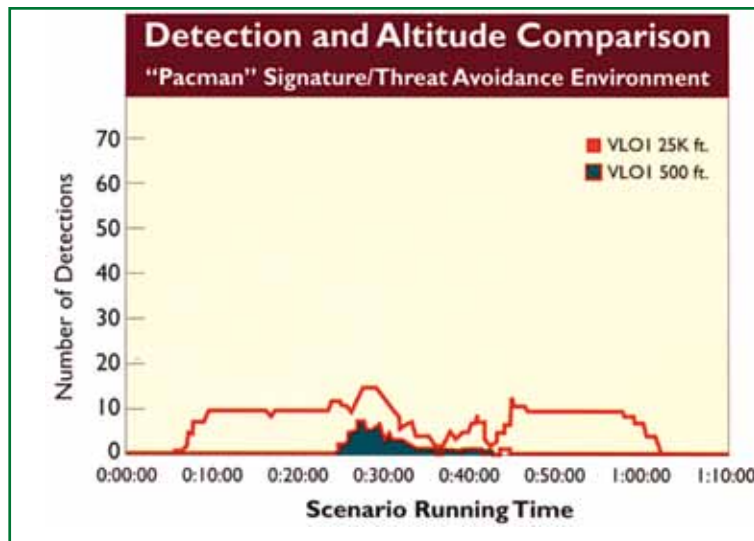
The threat avoidance scenario presents convincing evidence that balanced signature reduction is what makes tactics and planning most effective. The next chart illustrates that the shots taken against a conventional shape and the Pacman shape are still high in number even with route planning.



A real contrast emerges when the simulation sends in the Bowtie shapes. Even with only an LO2 level of signature reduction, the Bowtie nets enormous improvement in survivability. At the VLO1 level, the Bowtie experiences only a few valid trackings by the fire control radars.

For the Pacman shape, what helps most is lower altitude. As displayed in the chart below, the signature shape's run at low altitude minimizes time in jeopardy and decreases overall shots taken.

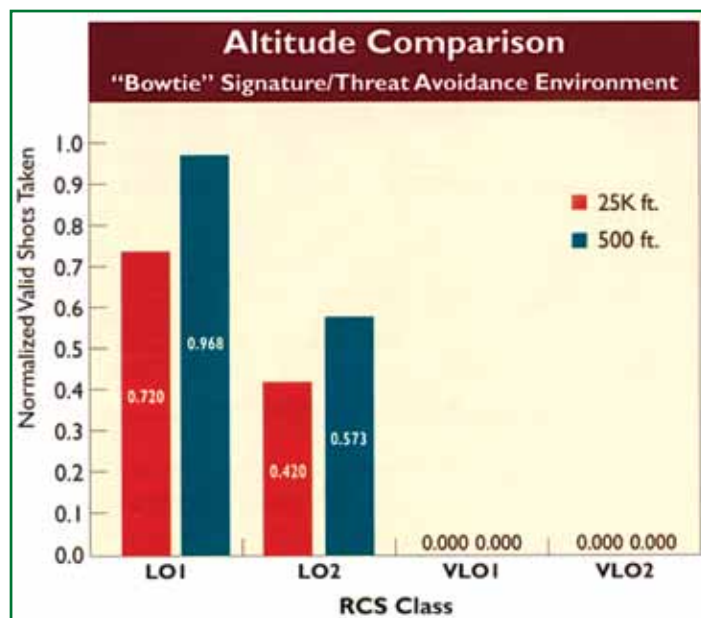
The threat avoidance scenario confirms that low observables are essential to assured mission success. In Desert Storm, there were some targets where the threat allowed low altitude attacks by conventional aircraft. However, anti-



aircraft fire was a factor and most attacks moved to medium altitudes as a result. For example, British Tornados flew low level attacks against Iraqi airfields and experienced some of the highest loss rates of the war.

As seen in the chart below, varying altitude is not nearly as effective for survivability as reducing the signature. The results of the simulation suggest that flying at high altitude draws the aircraft out of the range of some, but clearly not all, SAMs.

However, the real message of this chart is that signature reduction enables the aircraft to plan a route that greatly increases the chances of survivability. The variation from LO1 to LO2 is significant, while the VLO1 shape results in dramatic improvement to a very high chance of survival.



The tactical flexibility of low observables is indispensable to future mission planning. In future scenarios, highly survivable aircraft will draw the assignments to attack heavily defended hardened targets that can only be destroyed by direct weapons release of large penetrating bombs. Keeping attrition to a minimum will be important because it will ensure that the air component can continue to generate sorties and deliver ordnance at the rate demanded by the JFC's objectives. Another major payoff of highly survivable aircraft will be their ability to ensure that the air component can attack important targets from the outset and destroy those targets rapidly.

### Stealth and Electronic Countermeasures

The duels of the future may also draw on a combination of stealth and ECM to improve aircraft survivability in specific scenarios. A conventional aircraft cannot operate safely in a high threat environment until the integrated air defense system is nearly immobilized. In theory, an extremely

low observable shape could be survivable in almost any environment. However, planning for the majority of air operations falls somewhere in the middle of that spectrum. As threat radars expand their capabilities, stealth and ECM have a role to play in working together to increase aircraft survivability—especially when prompt attacks on key nodes have reduced the efficiency of the enemy IADS.

In some scenarios, ECM can also provide additional assurance for LO aircraft against certain types of threats. While analysts have established that the F-117s did not benefit from ECM support from EF-111s on the first night of the war, records suggest that the additional use of the EF-111 was welcomed by F-117 crews in subsequent missions.

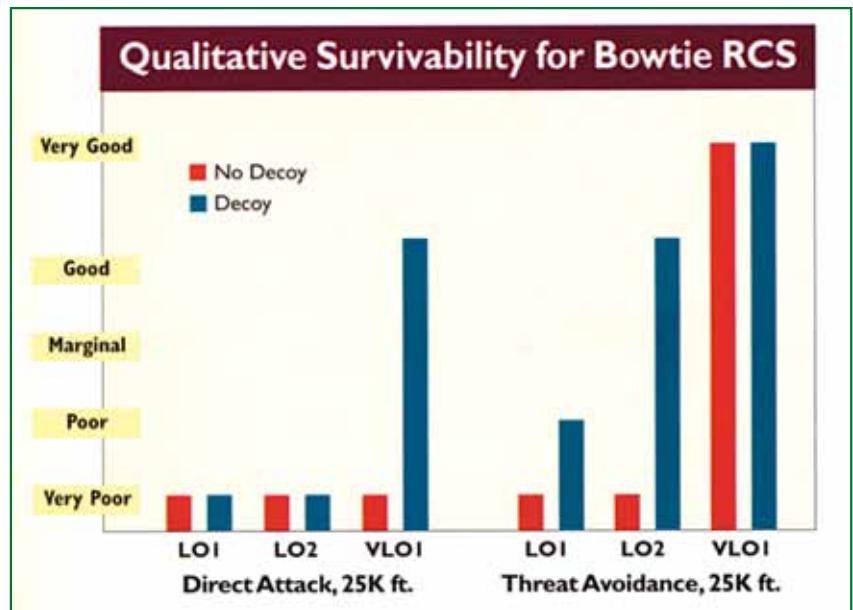
For aircraft without the F-117’s signature reduction, or for aircraft operating in different threat environments, ECM can contribute significantly to survivability. Conventional aircraft return much larger signatures. ECM is limited by the power of the airborne jammer. Therefore, a smaller aircraft RCS is easier to cloak because it requires less power from the jammer. An aircraft that reduces its front-aspect signature by a factor of 10 cuts the notional detection range by 44 percent. The power required in the ECM jammer also decreases in proportion. For the same amount of power, ECM can jam more effectively.

The next series of charts describes the results of a simulation that illustrates the interaction of reduced RCS and ECM. The simulation paired the Fuzzball, Bowtie, and Pacman signature reduction shapes with a towed decoy and assessed the results.

Towed decoys are a form of ECM that is carried outside the aircraft. A typical decoy is unreeled from the aircraft over the main threat area. Because the small pod is towed by the aircraft, the coverage of its transmitter is not blocked or impaired by the aircraft itself. Towed decoys provide a greater arc of coverage around the aircraft than would an ECM pod being carried on a weapons station.

The chart at top right plots the qualitative survivability for a Bowtie shape at three different signature levels. On the left, the scenario is direct attack, while on the right, the threat avoidance scenario is portrayed.

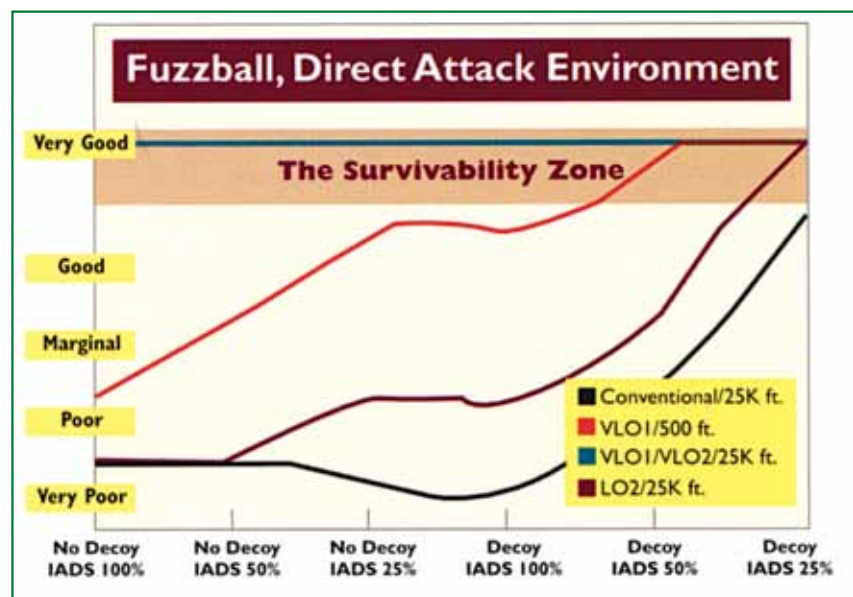
As the chart demonstrates, the VLO1 level of RCS reduction paired with a towed decoy produces only a “good” level of survivability in this conservative analysis. In this scenario, a weapon with limited or moderate standoff would probably improve survivability. When the threat is changed, a towed decoy can improve survivability significantly for the LO2 Bowtie. Still, only VLO RCS reduction produces desired results of “very good” survivability.



Towed decoys can be of even more benefit to moderately stealthy aircraft when earlier attacks have already degraded the air defenses. This scenario is important to explore because it represents planning for the use of a mix of VLO aircraft and aircraft with moderate stealth retrofits.

The chart below plots qualitative survivability as a function of LO shape, ECM, and the state of the air defense system. At the top of the chart is the survivability zone, where the probability of survival is rated very good. In the survivability zone, the probability of survival is high enough to keep attrition rates within acceptable levels for a sustained campaign.

In turn, reducing the efficiency of the air defense system or other high value targets opens up more options for the employment of other aircraft. For example, highly survivable aircraft can attack key nodes to degrade the IADS to 50 percent, 25 percent, or even near-zero levels of efficiency.



This does not mean that 50 percent or 25 percent of the early warning radars, fire control units, and antiaircraft guns are destroyed. Rather, it means that the flow of detection and tracking information is degraded to the point where the IADS can react to only about 50 percent of what is actually occurring in the battlespace it is supposed to protect.

The lines each represent one type of LO shape as simulated at a given altitude. The horizontal axis has six points. In the first three, no ECM decoy is deployed.

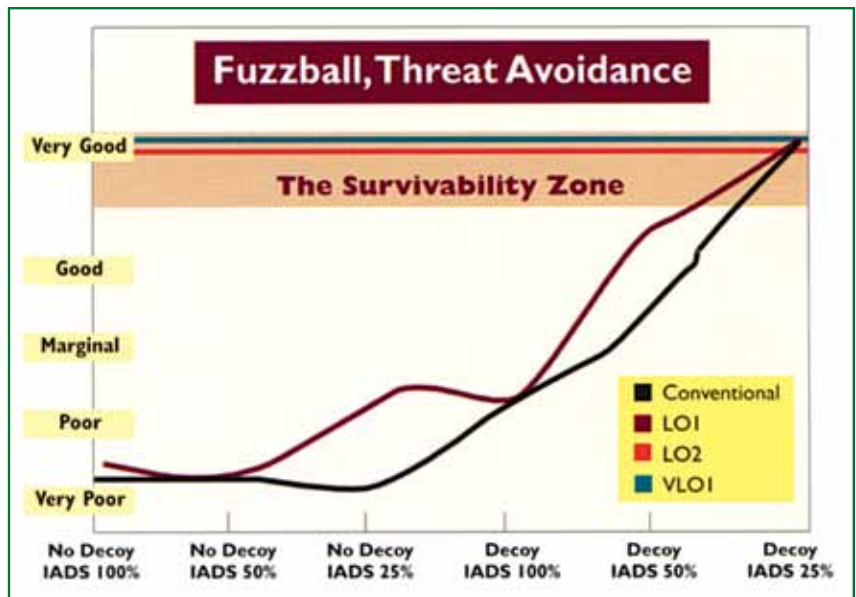
As the IADS becomes less efficient, ECM is better able to improve survivability rates. As the far right side of the chart suggests, a conventional aircraft, or one with some LO reduction, could begin to function efficiently when it employs a decoy and operates in areas where the IADS are at 25 percent efficiency. This, in fact, is exactly the type of tactical environment that air campaign planners set out to create by sending highly survivable aircraft to destroy selected air defense nodes.

The tactical options lie between these two extremes. A signature with some level of LO reduction, plus a towed decoy with ECM, improves its survivability somewhat. The VLO1 shape, which contains substantial low observables in its design, reaches the survivability zone in the highest threat environment only when a decoy is included and the air defenses are degraded.

In the threat avoidance environment (shown top right), the importance of campaign planning to degrade the air defenses stands out. The VLO1 shape achieves high survivability with or without the decoy because its small RCS enables it to thread its way between the threat rings.

However, the conventional shape and the moderately reduced LO1 shape operate most effectively when the IADS is degraded and a decoy is present. A Fuzzball achieves a very good probability of survival at the LO2 level whether the IADS are degraded or not.

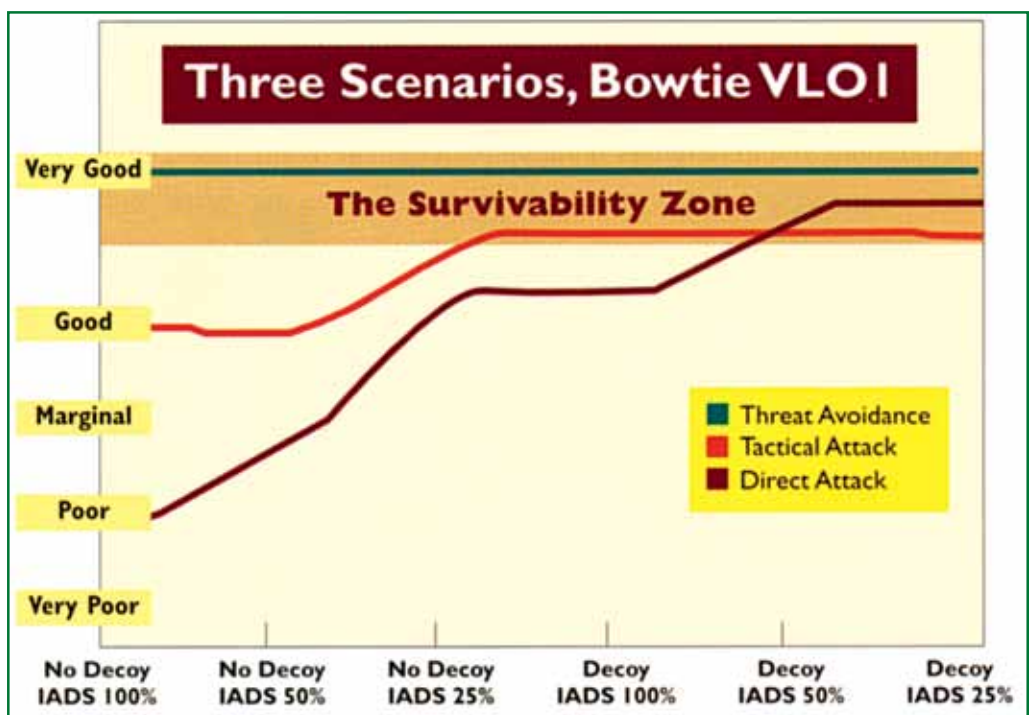
In practice, this analysis confirms what planners already know. Aircraft without significant RCS reduction would be scheduled to attack later in the campaign, and towed decoys will improve their survivability and effectiveness rates.



The scenario and the threat environment matter a great deal even when low observables and ECM are combined. In the chart below, the Bowtie at VLO1 runs through each scenario.

In the threat avoidance scenario, as shown earlier, ECM makes no difference. However, in a direct attack, ECM greatly increases the Bowtie's chances of surviving. ECM is also helpful in the tactical attack environment where sustained operations might otherwise produce unacceptable attrition over time.

The analysis of low observables and ECM underscores two important points. First, depending on the aircraft and the scenario threat environment, tactics will dictate different combinations of systems to ensure survivability. Many



scenarios in the future may feature a relatively moderate air defense threat. In those scenarios, aircraft with moderately reduced signatures (such as can be produced by retrofitted LO modifications) may be able to operate effectively in conjunction with towed decoys and other ECM support.

The second point, however, is that highly survivable aircraft are the air component commander's best tool to shape the environment for air operations. Other scenarios, with denser and more sophisticated air defense threats, will demand ever-improving results in signature reduction. The densest threats such as those presented by a capital region will still involve a measure of risk that is best mitigated by low observables.

For this reason, low observables are the "jewel in the crown" for aircraft survivability in the operational environment. Balanced, all-aspect signature reduction is the most important advantage an aircraft has in the duel with the defending IADS. Only aircraft with those special survivability attributes can attack the IADS with maximum efficiency. In turn, low observables also enhance other survivability measures. Electronic countermeasures are better able to mask an aircraft signature that has already been reduced by low observables.

Tactical survivability advantages add up to operational results. The options for employing airpower are regulated by the duel between attackers and defenders. Survivabil-

ity shapes the outcome that commanders can plan for as they construct the air campaign and determine what it will contribute to the JFC's operational-level plans. The number of highly survivable aircraft is the major variable that determines what can be done in the crucial early hours and days of a conflict against an adversary with air defenses.

In Desert Storm, for example, highly survivable F-117 stealth fighters allowed the JFACC to attack multiple target sets in the first hours of the air war instead of waiting until the integrated air defenses were completely suppressed almost a week later. Stand-off weapons such as TLAMs were important, but their inability to destroy hard targets or mobile targets limits their utility, especially in sustained operations over a large target set.

Campaigns of the future will depend on stealth to degrade enemy air defenses and destroy other high value targets through immediate attacks on key nodes in the system. It is this ability to shape the rest of the air component's operations that makes low observable's the jewel in the crown for airpower. Highly survivable aircraft are the instruments that ensure that even the most heavily defended targets in future threat environments will be within airpower's reach. They give the JFACC the ability to control the air and control what will be attacked from the air almost from the outset—a luxury imagined by World War II air commanders only in their dreams.

## CONCLUSION: THE FUTURE OF STEALTH

The radar game has defined and redefined the tactics for air combat since 1940. Aircraft survivability surfaced as a controlling variable in the effectiveness of air operations in World War I. The quest for survivability immediately influenced new aircraft designs, and contributed to the emergence of specialized combat aircraft. From the Spads and Fokkers honed for pursuit, to the Gotha bombers and the Salmson armored trench fighters laden with guns, the goal was increased survivability in the three-stage duel of detection, engagement, and probability of kill.

On the eve of World War II, the invention of radar changed the detection problem almost overnight by expanding detection ranges from the limits of the human eye to reaches of more than 100 miles. Over the next three decades, radar came to dominate each stage of the duel. Integrated air defenses with radar-guided missiles threatened the death of the flying air forces unless tactics and countermeasures could compensate. Research on electronic countermeasures and the packaging of aircraft for mutual support constituted the primary defenses against proliferating air defense capabilities.

By the 1970s, winning the radar game had become the central ingredient in dominating the skies. Developing and testing low observable features for aircraft offered a more certain way to break the cycle of constantly adjusting electronic countermeasures and counter-countermeasures. More than a decade after its initial testing, the F-117 proved the value and flexibility of stealth design by completing direct attacks on heavily defended targets during Desert Storm. The JFACC was able to use the highly survivable F-117 to destroy targets at a more rapid pace, and with much less risk, than could have been expected with conventional aircraft.

Low observables in aircraft design represent an achievement in bringing complex analysis and prediction of the causes of radar return together with aircraft design principles. The principles and the trade-offs required to achieve an LO aircraft design are complex. Low observables do not nullify radar or render aircraft invisible. Instead, LO design seeks to control and direct radar return, thereby diminishing the overall radar cross section of the aircraft. Much of the effect is achieved by curtailing specular reflection and diffraction.

As major sources of return are lessened, designs seek to control traveling waves, cavity diffraction, and to eliminate surface imperfections that could produce return. Balanced low observables include all-aspect signature reduction paired with attention to other sources of electromagnetic signature, from visual and acoustic to infrared. Advanced low observables also require striving for control of all electronic emissions from the aircraft.

Once achieved, aircraft signature reduction produces dramatic tactical results. Signatures vary according to the frequency of the search radar and the aspect from which it views the aircraft. However, reductions in RCS immediately begin to cut into the range at which radars can detect aircraft. A choice to optimize combat aircraft to be low observable to fire control radars breaks a crucial link in the air defense chain. LO aircraft are detected later and tracked with greater difficulty, allowing them to spend less time in jeopardy than would a conventional aircraft. In turn, this tactical flexibility produces enormous operational advantages for the air component.

As long as the radar game determines who controls the skies, low observables will deliver vital advantages. The Persian Gulf War, the most difficult air defense environment encountered in military operations in the 1990s, demonstrated that having highly survivable aircraft allowed the air component to achieve a variety of objectives quicker and with less risk. Future commanders will also count on the ability to keep the upper hand in the radar game.

## Counters to Stealth?

Because stealth is so important to current air operations and military strategy, it is reasonable to ask if and when it might be effectively countered. Historians contend that every military invention in history has been countered by new inventions or tactics, in due time. The radar game illustrates this principle, too. Radar changed the survivability duel during the Battle of Britain in 1940. Stealth changed it back 50 years later, in the Persian Gulf War of 1991. The most relevant question to ask is not “can stealth be countered?” but “how difficult is it to counter stealth with known technology?”

The radar range equation that demonstrates how lower RCS reduces the range of detection contains several variables. To counter stealth with a monostatic radar, the air defense radar would have to greatly increase its gain at the receiver. The way to do this would be to greatly increase the power of the system. If the target aircraft had an RCS reduction of 1,000, the radar power would have to increase by a factor of 1,000 to detect it at the same range as a non-stealthy aircraft. However, increasing power is easier at long wavelengths, not at the short, rapid frequencies commonly used for fire control. Ultra-wide band radar poses a similar problem. An ultra-wide band pulse could emit waves at several different frequencies hoping to catch the stealth

aircraft at a weak point in its RCS reduction. But transmitting over a wide band diminishes the power in each band, cutting the efficiency of the radar.

The second issue in discussions of counter-stealth is that stealth aircraft are designed against monostatic radars, the type used in nearly all military systems. Monostatic radar couples the transmitter and receiver at the same place, a process that simplifies the crucial function of distance tracking. In theory, a bistatic radar that placed the transmitter in one location and the receiver in another might be able to pick up what might be called the “craning” RCS that is directed away from the monostatic radar.

However, “bistatic radars, while simple in concept for the detection of stealthy vehicles, have many fundamental technical and operational issues to overcome,” according to John Shaeffer, RCS engineer at Marietta Scientific in Georgia. The receiver antenna beam must intercept its companion transmit beam and follow the transmit pulse which is moving at the speed of light. Unless the transmitter and receiver pulses are synchronized, distance measurement is impossible. Even a workable bistatic radar must then address the problem of how much volume of airspace it can scan at a given power setting in a given time. When the receiver, transmitter, and target are located on a straight line, the receiver can be overwhelmed by the transmitter pulse, which hides the target’s radar return. As Shaeffer put it, “This is similar to looking into the sun for light scattered from Venus.”<sup>64</sup>

The RCS reduction of stealth aircraft is difficult to counter. Improvements in radar must go a very long way to match the performance they were designed to achieve against non-stealthy aircraft. Concerns about countering stealth should pale in comparison to those about the known and increasing threats to conventional aircraft. The day will probably come when reusable hypersonic military space planes replace jets as the primary vehicles for ensuring aerospace dominance. Until then, for as long as jet aircraft offer the most reliable option for air superiority and air attack, stealth will be indispensable.

## Improving Future Survivability and Effectiveness

The first operational stealth aircraft, the F-117 and the B-2, demonstrated the feasibility of low observables and their importance to rapid and effective air operations. Like all combat aircraft, they rely on tactics to reach peak survivability, and they have limitations that must be recognized to ensure proper employment. For example, the F-117 and B-2 operate primarily at night. Indeed, many conventional aircraft do the same to maximize survivability under some conditions.

Several developments will make highly survivable aircraft even more effective. The F-117’s ability to deliver LGBs was a crucial component of its effectiveness. Recently, the B-2 has demonstrated great accuracy with the GPS-Aided

Targeting System (GATS) for the GPS-Aided Munition (GAM.) The ability to deliver 16 independently targeted weapons in any weather represents a formidable force. In the near future, the development of small munitions will enable all aircraft to carry more destructive power. Testing is under way on 250-pound, 500-pound, and 1,000-pound bombs that pack the explosive force of the 2,000-pound bombs in today's inventory. When stealth aircraft can deliver more munitions early in the campaign, they will take up an even greater share of the air component's tasks.

In the 21st century, the Air Force, Navy, and Marine Corps all plan to take delivery of new aircraft that incorporate low observables. With low observables as the centerpiece, a range of technologies helps extend mission planning options and creates the tactical edge that translates to greater effectiveness and flexibility in air operations for the Joint Force Commander.

The F-22, in particular, may fill multiple roles as survivability demands increase. It will be the first stealth aircraft that achieves a dominant air-to-air role. However, it will also find an expanding function as a highly survivable vehicle for delivering advanced air-to-ground munitions—munitions that could be used against SAMs or heavily defended targets. The trend toward development of smaller bombs will maximize the F-22's internal carriage capacity. As premier ground attack aircraft such as the F-15E and the F-117 age, an F-22 armed with small munitions now in development could take up the mantle of the survivable attack platform.

The F-22 will also have the distinction of being the first stealth aircraft capable of operating during the day. Of all the possible "counters" to stealth, perhaps the one that poses the greatest threat to aircraft survivability is the trade-off in speed and performance. The F-22 restores the aerodynamic

advantages of an air superiority fighter, while delivering the penetration and bomb-dropping capabilities of the F-117. The combination of these abilities will position the F-22 to become the backbone of air-to-air and air-to-ground operations ranging from first-night attack in major theater wars to air defense.

## Finis

The air operations of the early 20th century went from being a useful supporting force late in World War I to being "a determining factor" in the planning and execution of operations in World War II. It comes as no surprise, then, that when the radar game began to put the efficiency of air operations in jeopardy, scientists and airmen responded with vigor. The radar game is one that aircraft must play to maintain control of the skies and the freedom to attack and defend. The joint force has counted on their ability to win that game since World War II.

Winning the radar game has been and will remain central to future joint operations. As the US military moves away from decades of planning for a major war in Europe, the national military strategy still calls for the ability to intervene in regional conflicts that will vary in scope and intensity. Intervening on favorable terms will continue to require the air component to take direct and immediate action to control the air and the surface below. Air defense threats have increased throughout the 20th century and will continue to do so in the 21st century. Stealth is no magic panacea, but the edge it offers in the radar game is indispensable. Paired with other advantages from ECM to advanced munitions, the effects of low observables multiply, and will keep the edge of America's airpower sharp.

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The Air Force Association, founded in 1946, exists to promote Air Force airpower.

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