CSBA

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TRENDS IN AIR-TO-AIR COMBAT

IMPLICATIONS FOR FUTURE AIR SUPERIORITY

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2015

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

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Executive Summary

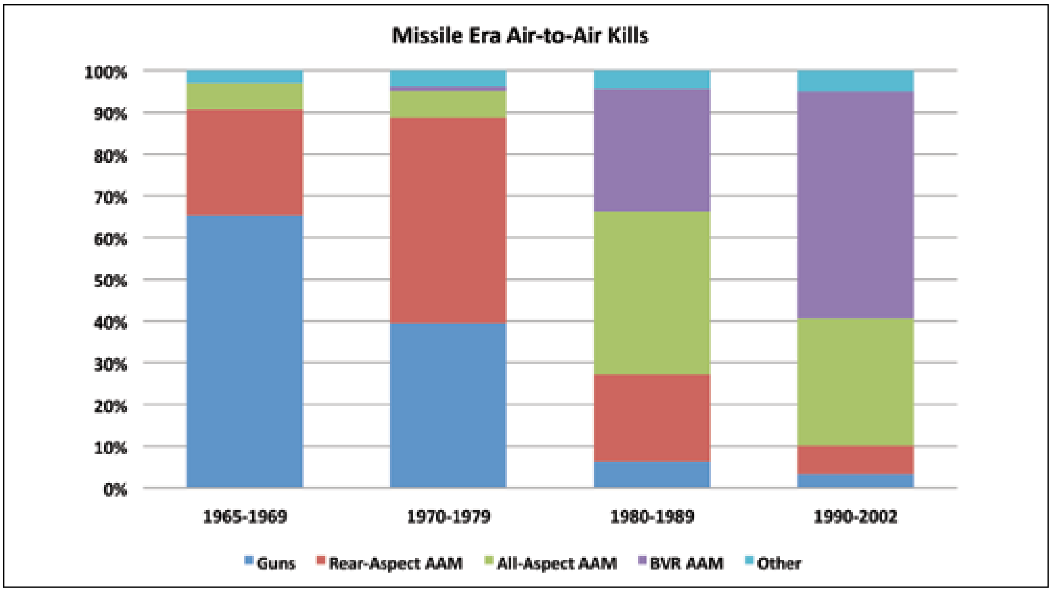
The Center for Strategic and Budgetary Assessments (CSBA) conducted a historical analysis of trends in air-to-air combat, evaluating air combat operations over the past century. The goal of this study was to assess how advances in sensor, weapon, and communication technologies have changed air combat and the implication of these trends for future combat aircraft designs and operational concepts.

The overall conclusion of this study was that over the past few decades, advances in electronic sensors, communications technology, and guided weapons may have fundamentally transformed the nature of air combat. Air-to-air combat developed rapidly after the operational implications of aerial reconnaissance became clear to all the major combatants early in World War I. Early aviators quickly learned the most effective techniques for achieving success in the air domain, and leading aces on both sides codified these techniques into rules and guidelines. The central purpose of these rules was to enable pilots to achieve what modern combat pilots call superior situational awareness (SA). This results when a pilot has a better understanding of the position of all relevant aircraft and their activities in the combat area than an opponent. The ultimate expression of SA is to move into position to attack an opponent without being detected, launch an attack, and escape before other enemies can take counteroffensive action.

For about fifty years, pilots relied on the human eye as the primary air-to-air sensor and machine guns and automatic cannon as their primary weapons. The physical limitations of human vision give it a relatively short effective range as an air-to-air sensor of about 2 nautical miles (nm). Aircraft can be seen farther away if the highly sensitive central vision is focused on them, but with central vision limited to a cone roughly 2 degrees wide, pilots searching for opposing aircraft without some sort of cue to limit their search are unlikely to detect them until the less acute peripheral vision is able to resolve them at about 2 nm. The effective range of aerial gunnery grew from about 50 meters (m) during World War I to about 500 m by the early 1960s, but pilots were still required to maneuver their aircraft in a small portion of the sky to ensure hits on an opponent. Against an un-alerted opponent, the attacker simply had to ensure he was within range and had the target “in his sight.” Against an alerted opponent, achieving hits required the attacker not only to be in range, but also to maneuver in the same plane as the target and to allow sufficient lead to account for the distance the target would travel during the bullet's time of flight. The difficulties and time required in attaining a good firing solution against a maneuvering target, combined with the decrease in SA due to the need to fully concentrate on the target, caused many of the great aces of World War II to shun maneuvering combat as a high-risk, low-payoff activity. Instead, they strove to achieve quick surprise attacks, break away, assess the situation, and attack again if possible.

By the mid-1960s, new aerial weapons and sensors appeared in conflicts in Southeast Asia, South Asia, and the Middle East. The new weapons included both infrared (IR) and radar-guided missiles, while the new sensors were largely air-to-air radars. IR missiles allowed attacks within a 30-degree cone behind the target at ranges approaching the 2 nm effective visual search radius. Radar-guided missiles, in theory, allowed attacks from any aspect (front, side, or rear) and beyond visual range (BVR). Air-to-air radars were capable of detecting and tracking targets at 15 nm or more. While the early missiles and radars had serious limitations and were unreliable, they offered substantial advantages over guns and the human eye. CSBA compiled a database of over 1,450 air-to-air victories from multiple conflicts from 1965 to the present. Advances in air-to-air sensor and weapon capabilities are illustrated in Figure 1. Guns were displaced by rear-aspect-only IR missiles, which were in turn replaced by all-aspect missiles, and finally, BVR missiles have come to make up the majority of modern air-to-air engagements.

FIGURE 1. MISSILE-ERA AIR-TO-AIR KILLS



These trends suggest that over the past five decades, advances in radar and other sensor technologies, missile capabilities, and communication technologies allowed pilots to search effectively much larger volumes of sky and engage targets at ever-increasing range. Most modern air combat engagements were initiated before the aircraft were within visual range with a commensurate decrease in the frequency of maneuvering combat. This means that aircrew SA is no longer primarily linked to what they can physically see through the cockpit canopy, but to what they glean from cockpit displays of sensor output and information passed from offboard sources such as nearby friendly aircraft.

This transformation may be steadily reducing the utility of some attributes traditionally associated with fighter aircraft (e.g., extreme speed and maneuverability) while increasing the value of attributes not usually associated with fighter aircraft (e.g., sensor and weapon payload as well as range). Aircraft performance attributes essential for success in air-to-air combat during the gun and early missile eras such as high speed, good acceleration, and maneuverability are much less useful now that aircraft can be detected and engaged from dozens of miles away. At the same time, nontraditional attributes such as minimal radar and IR signature; space, payload, and cooling capacity; power for large-aperture long-range sensors; and very-long-range weapons seem to be of increased importance. Both supersonic speed and high maneuverability place significant constraints on aircraft designers and force tradeoffs in aircraft design that limit the incorporation of many of the nontraditional, but increasingly important attributes listed above. The trends identified in this report suggest it may be appropriate to cast a much wider net in the development of future air combat operational concepts, sensors, weapons, and platforms, which would include examining “radical” departures from traditional fighter concepts that rely on enhanced sensor performance, signature control, networks to achieve superior SA, and very-long-range weapons to complete engagements before being detected or tracked by enemy aircraft.

Introduction

The U.S. military fields the largest and most sophisticated fleet of combat aircraft in the world. It relies on these aircraft to accomplish and enable a number of important combat missions including reconnaissance, strike, and air defense. Many missions conducted by maritime and land forces require security from enemy air attack as a precondition for success. Since World War II, U.S. forces have relied on superior capabilities in air-to-air combat to secure air superiority, and the nation has invested heavily in this area. The United States has not faced aerial opposition from a comparable power since World War II, yet there have been significant advances in aircraft propulsion, aerodynamics, weapons, and especially aircraft sensors and other electronic systems. It is difficult to assess just how these advances might shape the nature of future air-to-air combat. It is possible, however, to assess overarching trends in aerial combat over the past fifty years by examining changes in the types of weapons, sensors, and resulting operational concepts employed in conflicts around the world. To this end, CSBA developed a database of over 1,450 air-to-air victories claimed in various conflicts in Southeast Asia, Europe, the Middle East, and elsewhere from 1965 to the present day. This was then analyzed to identify and assess trends in air-to-air combat that can highlight aspects of aerial combat, aircraft systems, and attributes that seem to be growing in importance, and those that seem to be declining in importance. This information can then be used to inform future combat aircraft designs and concepts of operation. This is particularly timely as both the Air Force and Navy are in the process of developing requirements for future air combat aircraft.

This report is organized into the following chapters:

- The Genesis of Air Combat
- Analysis of “Missile-Era” Air Combat Trends
- The Evolving Importance of Traditional Fighter Aircraft Attributes
- An Alternate Vision of Future Aerial Combat
- Summary and Conclusion

CHAPTER 1

The Genesis of Air Combat

Aerial reconnaissance was the first, and remained the most important, mission of the combatant air forces during World War I. From the beginning of the war, aerial reconnaissance reports had a crucial impact on the flow of events. For example, on August 22, 1914, less than three weeks into the war, aerial reconnaissance reports revealed the British Expeditionary Force (BEF) was in danger of encirclement and annihilation by elements of the German First Army during the Battle of Mons.[1] BEF commander Gen. John French ordered a retreat, saving the BEF to play an important role in halting the German advance at the First Battle of the Marne and the subsequent "Race to the Sea" in September. Aerial reconnaissance reports also played a significant role in the French victory in the First Battle of the Marne and in the German defeat of the Russian army at Tannenburg early in World War I.

The establishment of a continuous line of field fortifications from the North Sea to the Alps on the Western Front in late 1914 made it impossible for cavalry on either side to perform their traditional reconnaissance tasks and greatly increased the reliance of ground commanders on aerial reconnaissance. This stimulated rapid advances in reconnaissance techniques and the use of aircraft dropping modified artillery shells to attack enemy troops and gun positions beyond the effective reach of artillery.[2] By mid-1915, reconnaissance aircraft crews were operating cameras that allowed both sides to produce up-to-date maps of opposing trench systems and were developing increasingly sophisticated techniques for cooperation with artillery.

The value of these activities was obvious to all sides, as was the importance of stopping, or at least disrupting, enemy aerial reconnaissance activities. Efforts along these lines first took the form of pilots and observers carrying aloft various pistols, rifles, and even shotguns. Early

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[1] Pamela Feltus, "Aerial Reconnaissance in World War I," *U.S. Centennial of Flight Commission*, 2008, available at http://webarchive.library.unt.edu/eot2008/20080920040830/http://centennialofflight.gov/essay/Air_Power/WWI-reconnaissance/AP2.htm, accessed August 21, 2013.

[2] John H. Morrow Jr., *The Great War in the Air: Military Aviation from 1909 to 1921* (Tuscaloosa, AL: University of Alabama Press, 1993), 64.

experiences with air-to-air combat revealed that hitting an aircraft was extremely difficult and that only a small percentage of hits resulted in critical damage.[3] Over time, this led to the adoption of machine gun armament. Early-on machine guns were usually mounted flexibly and wielded by the observer in two-seat reconnaissance aircraft. The restricted fields of fire, problems in aiming (especially to the sides), and difficulty of gaining and maintaining a firing position contributed to continued lack of success in countering enemy reconnaissance aircraft. A solution eventually emerged in the form of a light, agile, single-seat aircraft armed with a machine gun(s) mechanically linked to the engine to synchronize gunfire with propeller rotation.[4] This allowed pilots to aim their weapon by aiming the aircraft. In effect, the purpose of the new "pursuit" (fighter) aircraft was to carry their weapons to a particular part of the sky so that they could be employed effectively to shoot down or chase away enemy reconnaissance aircraft.

Of course, this remained easier said than done. Standard machine gun bullets of World War I had great ability to penetrate wooden aircraft structures of the time but generally passed through leaving small, clean holes that did not cause fatal damage unless they hit specific, critical items in the target aircraft including the crew, fuel tanks, and engine.[5] Moreover, opening fire at too great a range alerted the enemy to the danger of attack, resulting in immediate evasive action and possible return fire from two-seat aircraft. This greatly decreased the probability of scoring an air-to-air "kill" while simultaneously increasing the risk of being shot down. The preferred tactic of World War I fighter pilots was to approach a reconnaissance aircraft from the "blind spot" below and behind while the crew was fully occupied with precise navigation, photography, or artillery spotting tasks. Experienced pursuit pilots often closed to 15 m, but always to 50 m or less, before opening fire on their unsuspecting victims.[6] Why did they put so much effort into surprising their victims? The answer lies in the nature of maneuvering air combat, or what is often referred to as a "dogfight." An alert and maneuvering victim poses a series of problems for an attacking pilot. First, by turning into the attacker, the target aircraft, or defender, complicates the attacker's problem by forcing him to maneuver his aircraft to ensure he is in the same plane as the defender, is within range, and has the appropriate lead angle for a shot (see Figure 2).[7] Judging the correct lead angle requires accurate estimation of

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[3] Leon Bennett, *Gunning for the Red Baron* (College Station, TX: Texas A&M University Press, 2006), 22–46.

[4] Ibid., 105–06.

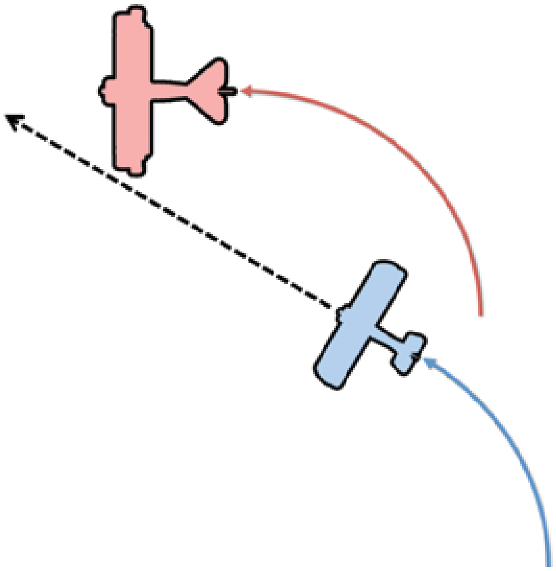
[5] Bennett relates the story of Capt. Albert Moris of the French Air Service, whose 1912 vintage Farman biplane received over 400 carefully recorded small-arms hits during 253 hours of combat flying in late 1914 without being shot down. Ibid., 24.

[6] Ibid., 104–06.

[7] Lead is required because even at a relatively short distance of 100 m, a typical machine gun bullet traveling at 900 m per second requires about 0.12 seconds to cover the distance between the gun and the target. Typical World War I combat speeds were about 150 km per hour, or about 41.5 m per second. So, during the bullet time of flight, a typical World War I aircraft would travel about 5 m. A typical fighter of the era was only about 6 m long, so if an attacker wanted to hit a vital part of the aircraft (like the engine) he would need to aim well in front of the target's nose. As aircraft speed and engagement range grew, the required lead grew dramatically. By the middle of World War II, engagement often took place at 470 km per hour at 200 m and lead distances of up to 30 m—two to three times the length of a typical World War II fighter. Jet combat in Korea and Vietnam could call for lead distances of 100 m or more.

range and rate of closure. All of these factors have to be considered while tracking a frantically maneuvering defender. Successfully solving the aiming problem requires full concentration for the duration of the engagement.

FIGURE 2. MANEUVERING AIR COMBAT



Attacker must be "In Plane, In Range, and In Lead" to successfully engage a maneuvering enemy with guns.

This leads to the second and most serious problem attackers face in maneuvering air combat. With his attention fully consumed with solving the aerial gunnery problem, an attacker is unable to scan the surrounding sky for any previously unnoticed friends of the defender. Sustained focused attention on the target aircraft causes the attacking pilot's mental picture of the relative position and direction of his aircraft and all others in the area to rapidly deteriorate. The longer a maneuvering fight lasts, the greater the probability the attacker will be attacked in turn by one of the defender's unseen friends.

Successful pilots on both sides rapidly developed sets of tactical rules for air combat, such as Oswald Boelcke's "Dicta Boelcke," that sought to implement Edward Mannock's main tactical principle:

> The enemy must be surprised and attacked at a disadvantage, if possible with superior numbers so the initiative was with the patrol.... The combat must continue until the enemy has admitted his inferiority, by being shot down or running away.[8]

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[8] Lt. Col. Thomas G. Bradbeer (Ret.), "Always above: Major Edward 'Mick' Mannock in World War I," March 22, 2006, available at http://www.thefreelibrary.com/%22Always+above%22%3A+Major+Edward+'Mick'+Mannock+in+World+War+I.-a0143215341, accessed August 22, 2013.

The advantages sought by Mannock, Boelcke, and other World War I fighter pilots include:

- Greater altitude, which can be converted into speed to attack or used to avoid combat with more numerous opponents at lower altitude;
- Approaching from "up sun" to delay or deny detection;
- Approaching from known "blind spots" of a defender (e.g., behind and below a two-seat aircraft); and
- Opening fire at short range to maximize hits while the defender is still suffering from surprise.

Surprise remained a key element of fighter tactics through the Vietnam War. During World War II, the great German aces Erich Hartmann (352 kills) and Gerd Barkhorn (302 kills) stressed what they referred to as "ambush tactics" in the skies over Europe at the same time American aces Richard Bong (40 kills) and Tommy McGuire (38 kills) perfected virtually identical "Boom and Zoom" tactics half a world away in the South Pacific. These tactical approaches shared most elements of Mannock's and Boelcke's rules including an emphasis on attacking unsuspecting targets from a position of advantage, usually from above, and avoiding maneuvering combat unless absolutely necessary. In postwar interviews, Barkhorn characterized maneuvering combat as a high-risk, low-payoff activity and estimated that between 80 and 90 percent of his victories were against unsuspecting targets. After the war, Hartmann stressed that his careful "See—Decide—Attack—Break" approach called for detecting the enemy first, achieving a tactical advantage, attacking from close range to maximize damage and surprise, and escaping to assess the attack.[9] Figure 3 illustrates these tactics.

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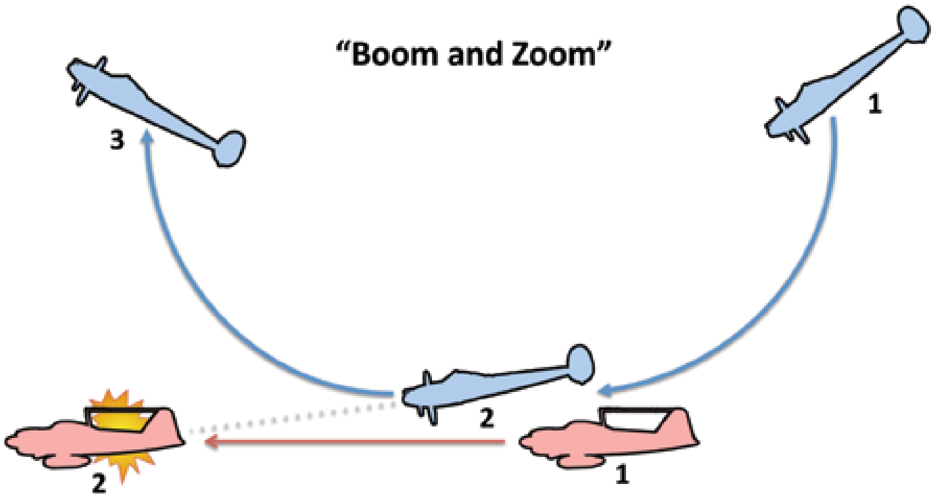
[9] Hartman's air combat procedure is strikingly similar to USAF Col. John Boyd's famous Observe, Orient, Decide, Act, or "OODA" loop.

FIGURE 3. BOOM AND ZOOM, OR AMBUSH TACTICS



Surprise usually results from one opponent having an immense advantage in SA. There are a number of definitions of SA, but one widely accepted definition summarizes SA as, "keeping track of the prioritized significant events and conditions in one's environment."[10] Therefore, aerial combat can be viewed as a competition, or battle, for superior SA. Aircrew obtain and maintain SA through the use of their own senses, training, and experience to interpret inputs from the surrounding physical environment, aircraft displays, and communications from friendly offboard sources.

More modern detailed analysis of 112 air combat engagements during the Vietnam War conducted by the U.S. Air Force (USAF) in the 1970s concluded that 80 percent of aircrew shot down were unaware of the impending attack. Surprise, the tactical outcome of superior SA, is so important to success in air combat that it is *assumed* in the modern USAF air combat mantra of "First Look, First Shot, First Kill." Despite vast changes in aircraft, sensor, communication, and weapon capabilities over the past century, the fundamental goal of air combat has remained constant: leverage superior SA to sneak into firing position, destroy the opposing aircraft, and depart before other enemy aircraft can react.

The Importance of Sensors and Communications as Situational Awareness Building Blocks

Early aces agreed that keeping a sharp lookout (sensing), frequently altering course to clear their own blind spots (never less than every 30 seconds, according to Mannock's rules), and turning to meet an enemy attack rather than attempting to dive away were essential defensive

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[10] Society of Automotive Engineers International, *Aerospace Glossary for Human Factors Engineers* (Warrendale, PA: SAE Press, 1988).

techniques. They also stressed the importance of teamwork and quickly developed communication techniques using visual signals, hand gestures, wing wags, rudder kicks, etc., to direct their formations. The combination of sensors (the human eye), weapons (rifle caliber machine guns), and rather rudimentary communications dictated not only the tactics of early air combat, but also stimulated pilots to demand certain key attributes from their aircraft such as:

- High speed to overtake or escape from an enemy;
- High service ceiling to maximize altitude advantage;
- High rate of climb to facilitate interception and/or outmaneuver an enemy in the vertical plane;
- Superior roll rate and turning ability to rapidly achieve firing position (or deny it) in a maneuvering fight;
- Heavy firepower to make the most of fleeting engagement opportunities; and
- Sufficient range to “take the fight to the enemy.”

This list of desired attributes continues to inform fighter design requirements to the present day. Unfortunately, many of these attributes are contradictory from an aircraft design perspective and require compromise. For example, increasing firepower generally requires aircraft designs that can carry more or larger weapons. These weapons add weight, which can reduce an aircraft’s rate of climb, speed, and maneuverability and lower its maximum operational altitude (or ceiling). Although these drawbacks could be addressed by adding a larger engine to restore speed and climb performance, a larger engine will also add weight, further degrading the aircraft’s maneuverability and likely burn more fuel per mile, reducing its range. This illustrates how the art of aircraft design involves numerous iterations to arrive at the best mix of attributes given the technology, time, and money available. It also underscores the interactive relationship between tactical demands, technological possibilities, and the nature of aerial combat.

CHAPTER 2

Analysis of “Missile-Era” Air Combat Trends

The first air-to-air missiles were designed during World War II by the Germans. As the scale of the Allied bomber offensive increased in 1943, it was clear to the German Luftwaffe that prospects of successful bomber interception required ever-increasing firepower. Initially the number and caliber of guns were increased, but this was quickly followed by the introduction of air-to-air rockets. Compared to guns that could deliver the same weight of explosive on target, rockets were much lighter and placed little recoil stress on the aircraft. However, they were inaccurate, and only a few could be carried at one time due to their bulk. The obvious solution was to develop a guided rocket to accurately carry a relatively large amount of explosive to destroy a bomber with a single shot. Late in the war, German engineers designed and tested the wire-guided Ruhrstahl X-4 air-to-air missile (AAM), but it did not reach service. Following the war, the United States, Great Britain, and Soviet Union all initiated AAM programs leveraging wartime German research. By the mid-1950s, all three countries had first-generation missiles in service. Figure 4 shows an example of the Ruhrstahl X-4 AAM (note the wooden fins).

FIGURE 4. GERMAN RUHRSTAHL X-4 WIRE-GUIDED AIR-TO-AIR MISSILE

Dawn of the Missile Era

The first use of guided missiles in air combat occurred in September 1958 when Taiwanese F-86 *Sabers* used AIM-9B Sidewinder missiles in a few engagements against People's Republic of China (PRC) MiG-17s.[11] The first sustained use of AAMs, however, did not occur until 1965 when the U.S. Air Force and Navy began the prolonged Rolling Thunder air campaign against North Vietnam. Unfortunately, early missiles did not live up to the expectations set for them during the late 1950s. The missiles were designed for use against large, nonmaneuverable targets, such as nuclear-armed bombers, flying at high altitude. Their limitations were first revealed when U.S. Air Force and Navy aircrew discovered that these early missiles, when used against small, rapidly maneuvering North Vietnamese MiG-17 fighters at relatively low altitude, often missed. Seeker, avionics, and missile reliability problems resulted in much lower success rates compared to successes achieved in pre-conflict testing. From 1965 through 1968, during Operation Rolling Thunder, AIM-7 Sparrow missiles succeeded in downing their targets only 8 percent of the time and AIM-9 Sidewinders only 15 percent of the time. Preconflict testing indicated expected success rates of 71 and 65 percent respectively.[12] Despite these problems, AAMs offered advantages over guns and accounted for the vast majority of U.S. air-to-air victories throughout the war.

Before proceeding to a discussion of early missile-era aerial victories, it is important to note that many fighters during the early missile era did not have air-to-air radar, and even for those that did, visual search and detection remained extremely important.

The region surrounding an aircraft where a pilot can reliably expect to detect approaching enemy aircraft extends to about 1.5 to 2.5 nm. Under conditions of good visibility, favorable lighting, minimal clutter, etc., it is possible to see modern fighter-size aircraft at ranges of 10 nm or more if they fall within the highly focused central vision. Aircraft are sometimes seen at these longer ranges, especially if the observer is cued and able to limit the search area to a few degrees, but uncued observers are extremely unlikely to detect enemy aircraft at anything approaching maximum theoretical range.[13]

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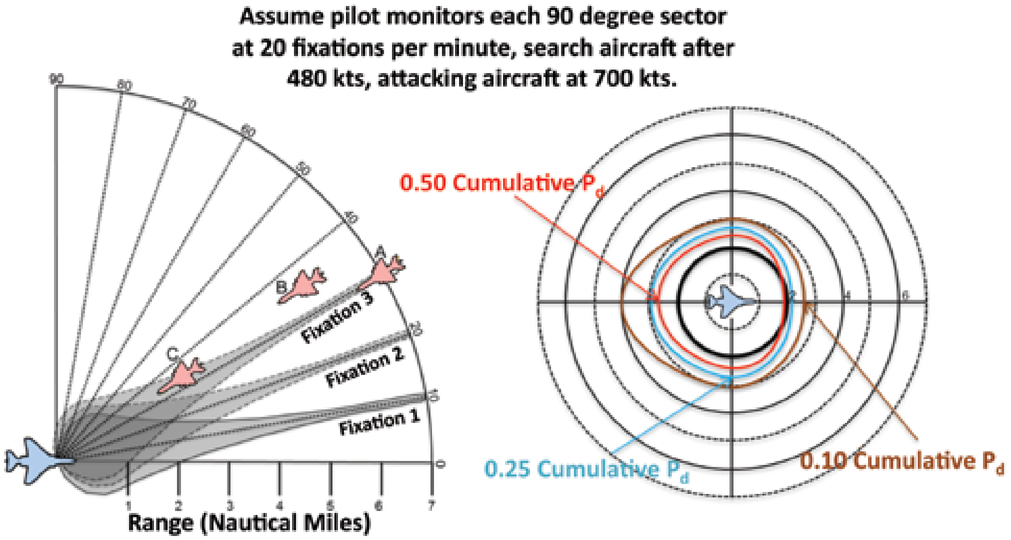
[11] Estrella WarBirds Museum, "Sidewinder AIM-9," 2003, available at http://www.ewarbirds.org/sidewinder.html, accessed August 23, 2013.

[12] Marshall Michel III presents a detailed discussion of the reasons for the large gap in U.S. AAM performance during preconflict testing and in combat during the Vietnam War. Marshall L. Michel III, *Clashes: Air Combat over North Vietnam 1965–1972* (Annapolis, MD: Naval Institute Press, 1997), 150–58.

[13] See S. Schallhorn et al., *Visual Search in Air Combat* (Pensacola, FL: Naval Aerospace Medical Research Laboratory, 1990), particularly 5–11, for the discussion on visual search and the practical use of the human eye as an air-to-air sensor.

FIGURE 5. VISUAL SEARCH LIMITS[14]


Assume pilot monitors each 90 degree sector at 20 fixations per minute, search aircraft after 480 kts, attacking aircraft at 700 kts.

Systematically searching an area of sky requires the observer to focus on a distant object such as the horizon to ensure proper focus.[15] The shaded area in the illustration on the left of Figure 5 represents the visual "lobe" thus formed where an opposing aircraft could physically be detected by the human eye in one "fixation." At extreme ranges, the lobe is only about 2 degrees wide, so aircraft A would only become visible on the third fixation, or deliberate shifting of the visual lobe. During fixation 3, aircraft B would not be detected, even though it is closer to the observer than aircraft A, because it lies outside the observer's central vision. Aircraft C would be detected on fixation 3, even though it is at the same angle to the observer as aircraft B, because it is close enough to be detected by the less sensitive peripheral vision. This explains why even when aircrew use disciplined search patterns and fly in formations where members are assigned different search sectors, the likelihood of detecting enemy aircraft beyond about 2 to 3 nm is low.[16] For example, a pilot searching a relatively small sector 90 degrees wide by 20 degrees high might be physically able to see a target at 7 nm range, but the probability it would fall within his 2 degree central vision on any given fixation is just 1/450 (0.002). This per-fixation probability increases to only about 1/110 (0.009) at 3 nm and is still only about 1/5 at 2 nm. The illustration on the right of Figure 5 shows the cumulative

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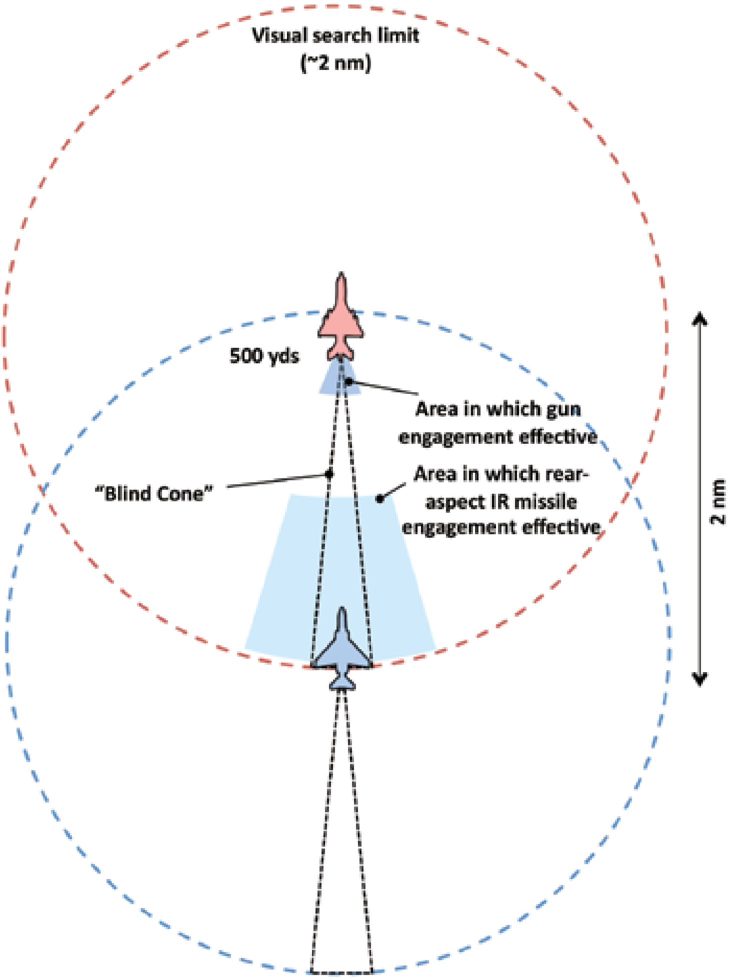
[14] This figure was adapted from S. Schallhorn et al., *Visual Search in Air Combat*.

[15] When not focused on a distant object, the eye muscles tend to relax, resulting in a focus distance of 10 feet or less. Ibid., 4.

[16] Disciplined search patterns consist of eight to twelve relatively widely spaced fixations per 90-degree horizontal sector. Aircrew in a formation are generally assigned to search a specific sector and do so in a systematic manner usually proceeding from the front to the rear of the sector slightly above the horizon, then from the rear to the front of the sector slightly below the horizon, or vice versa. The goal is to cover the sector in a reasonable amount of time with fixations spaced about 15 degrees apart. This maximizes the chances of detecting a target with peripheral vision while sacrificing little in terms of relatively low-probability long-range detections. Ibid., 13.

probability a pilot searching each 90-degree sector with 20 fixations per minute would detect an aircraft approaching from various directions by range.[17] The cumulative probability of detecting the approaching aircraft remains below 0.50 until it is between 1.9 and 2.8 nm. For simplicity, the series of figures that follow will use a circular 2 nm area to illustrate the region where visual search is likely to detect an approaching enemy aircraft.

FIGURE 6. ADVANTAGES OF REAR-ASPECT IR MISSILES OVER GUNS



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[17] Humans are generally capable of making two to three fixations per second, but aircrew must devote significant time and attention to tasks other than visual search such as maintaining formation, speed and altitude, navigation, monitoring other sensors (e.g., radar), and monitoring aircraft fuel status and other systems, so the calculations presented here assume only about 20 percent of the pilot's time is devoted to disciplined visual search. Ibid., 11.

Figure 6 illustrates several important aspects of air combat at the dawn of the missile era. The first is the effective uncued visual search limit, which is shown as a dashed circle centered on each aircraft. Note the dashed lines forming a wedge-shaped area directly behind the aircraft indicates an area difficult for pilots to visually scan. The extent of this blind spot varies with aircraft type. This reality is one of the main reasons that fighter aircraft fly in formations, which permit them to clear each other's blind spots and warn of impending attacks. As the preceding discussion of visual search showed, however, even in formations where aircrew execute disciplined visual search plans, the physical limitations of human vision still make it unlikely any aircraft in the formation will see an attacker that is still more than about 2.5 nm away.

The light blue wedge represents the area where the attacking aircraft could employ a typical first-generation IR homing missile. This area is about 30 degrees wide and extends from the missile's minimum range, typically about 2,500 feet, to its maximum range of about 2.3 nm at high altitudes to less than 1 nm at low altitudes. Early IR missile seekers were generally uncooled and tuned to detect IR radiation emitted by the hot metal of jet engine turbine blades and tailpipes. This limited them to "tail-only" attacks.[18]

The small, dark blue wedge behind the defending aircraft at the center of the red circle represents the attacking aircraft's maximum effective gun range. In the fifty years between the advent of air combat and the beginning of AAM combat, effective gun range increased by a factor of ten from 150 feet to about 1,500 feet thanks to the development of computing gunsights and the universal adoption of longer-range, harder-hitting automatic cannon in place of machine guns.[19]

Radar homing missiles had also been developed during the 1950s. They had several advantages over IR missiles, including the ability to engage aircraft from any aspect (front, sides, or rear), in bad weather, and at longer range. Exploiting these advantages in fast-moving combat between tactical aircraft proved much more difficult than anticipated due to the need to positively identify the target as an enemy aircraft before launching a missile. The unreliability of 1960s Identification, Friend or Foe (IFF) equipment resulted in extreme reluctance on the part of U.S. Air Force and Navy aircrews to actually employ their BVR weapons. This tendency was reinforced at some times and places by rules of engagement (ROE) requiring visual identification of the target aircraft. These factors resulted in only two confirmed BVR kills in Vietnam. The fact, however, that U.S. F-4 crews had the capability to engage targets BVR had a significant influence on North Vietnamese pilot tactics and reduced their effectiveness.

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[18] Don Hollway, "Fox Two!," March 2013, available at http://www.donhollway.com/foxtwo/, accessed August 29, 2013.

[19] Anthony G. Williams and Emannuel Gustin, *Flying Guns: The Modern Era* (Ramsbury Marlborough, UK: Crownwood Press, 2004).

The Missile-Era Aerial Victory Database

CSBA compiled a database of all confirmed aerial victories from 1965 through 2013. The primary source for the database is regional and national databases maintained by the Air Combat Information Group (ACIG).[20] Where possible, the ACIG air combat victories were cross-checked with official sources such as Project Red Baron accounts of U.S. victories and losses in Vietnam. The database contains information on 1,467 confirmed victories over fixed-wing combat aircraft.[21] In addition to the date and nationality of the victor, all database entries include information on the type of aircraft claimed shot down and the type of weapon used (e.g., AIM-9, AA-2 Atoll, gun). In many cases the name of the victorious pilot and his unit are available. In some cases, ACIG has been able to cross-reference claims with officially admitted losses and provide the victim aircraft pilot's name and/or aircraft tail number. The database contains victory claims for pilots from the United States, Vietnam, India, Pakistan, Israel, Egypt, Jordon, Syria, Iraq, Iran, the United Kingdom, Argentina, Venezuela, and Ecuador in achieving confirmed air-to-air victories.

While all of this data could be fabricated, the ACIG data is consistent with official sources and/or independent historical accounts for most of the nations listed. Post conflict analysis of victory claims and actual losses shows that aircrew tend to overstate actual damage done to the enemy in aerial combat. For instance, British fighter pilots claimed to have destroyed 499 German aircraft during the Battle of France in May 1940. Postwar examination of German Luftwaffe documents revealed a total of just 299 aircraft lost to enemy action, both British and French, during May 1940.[22] Another example is the claims by American F-86 and Russian MiG-15 pilots between December 1950 and July 1951. The release of official Russian MiG-15 losses after the fall of the Soviet Union allows a comparison of claims and losses for both sides during this period. It reveals that U.S. F-86 pilots claimed forty-five victories against nineteen actual Russian MiG losses in combat. Likewise, Russian pilots claimed thirty-seven victories against fourteen actual F-86 losses in air combat. This works out to the Americans over-claiming by a factor of 2.37 and the Russians by a factor of 2.64. Both sides sincerely believed they were soundly trouncing their opponents when in reality the exchange ratio was 1:1.36, with the Americans slightly in the lead.[23] While the actual number of aerial victories is likely less

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[20] The raw data files are available at http://www.acig.info/CMS/index.php?option=com_content&task=section&id=5&Itemid=47. CSBA combined them, reviewed them for duplications and inconsistencies, and reformatted the data to facilitate the analysis presented in the remainder of this section.

[21] Victories over helicopters and civilian aircraft were excluded, as were claims of "probable" kills and damaged aircraft.

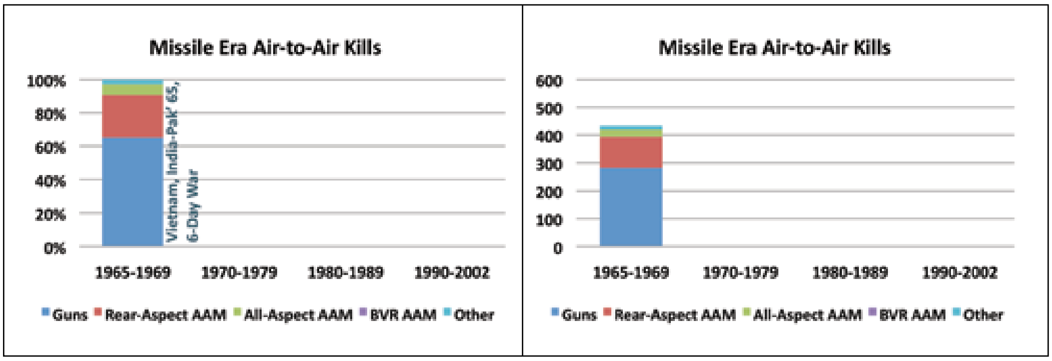
[22] Jon Lake, *The Battle of Britain* (London, UK: Amber Books, 2000), 22.

[23] The time-compressed nature of air combat and the imperative to resume scanning the area as soon as possible after a successful attack means that few "victors" actually watch their victims "all the way to the ground." Aircraft seemingly badly damaged on gun camera film and out of control often recovered, returned to base, and were repaired. In addition, in the confusion of an aerial melee, it was common for more than one attacker to shoot at and sincerely claim the same victim. This factor was even more pronounced in bomber formations, where many gunners might fire at an attacking fighter and claim a kill. Contemporary studies by the U.S. Army Air Corps estimated that during World War II, fighter crews overestimated victories by a factor of three and bomber crews by a factor of ten. Anthony G. Williams and Emmanuel Gustin, *Flying Guns: World War II—Development of Aircraft Guns, Ammunition and Installations 1933–45* (Shrewsbury, UK: Airlife Publishing, 2003), 223–24.

than half the 1,400+ credited to fighter pilots over the past fifty years, the focus of this report is on *trends* in aerial combat. The trends in the type and mix of weapons employed should still reflect the changing nature of air-to-air combat, even if the actual number of downed aircraft is significantly smaller than claimed.

Segregating the data into time slices, it is possible to further trace the dramatic changes in the dynamics of air combat over the past five decades. Figure 7 is the first of a series of similar figures throughout the remainder of this chapter. It shows a pair of charts summarizing the mix of weapons used in achieving confirmed aerial victories. The chart on the left shows the fraction of kills credited to each weapon type, and the chart on the right illustrates the total number of kills by weapon employed. Weapon types include guns, rear-aspect AAMs such as the early AIM-9 Sidewinder described above, all-aspect AAMs such as the AIM-7D/E employed by U.S. aircrew in Vietnam, and BVR AAMs such as the AIM-7M employed in Operation Desert Storm and the AIM-54 Phoenix and AIM-120 Advanced Medium-Range Air-to-Air Missile (AMRAAM). The "other" category includes kills resulting from a variety of factors including opposing aircraft flying into the ground during combat (sometimes called a "ground kill"), aircraft downed by collision with jettisoned drop tanks, and assorted other unusual means.

FIGURE 7. AERIAL VICTORY CLAIMS, 1965-1969



The 1965–1969 data indicates the continued dominance of the gun in late 1960s aerial combat. The majority of U.S. kills during this period were made with missiles (78 of 122 kills).[24] Most North Vietnamese victory claims during this period were credited to guns (40 of 73 kills). The other major scene of air combat during this period was the Six-Day War in the Middle East. Here, the gun was still the main weapon. The Israeli Air Force (IAF) did not have AAMs in widespread squadron service during the 1967 conflict and scored sixty-two of its sixty-six

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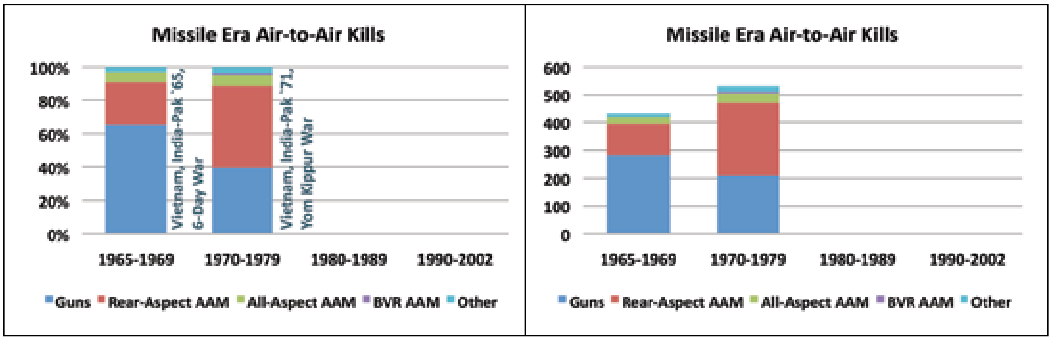
[24] One reason for this is the well-known lack of an internal gun on F-4B/C/D aircraft that formed the backbone of U.S. air combat capability during this period. However, eleven of the forty-one gun kills claimed by U.S. aircrew between 1965 and 1969 were achieved by USAF F-4C/D aircraft equipped with centerline 20 mm gun pods.

claimed victories with guns.[25] Most Arab victory claims are also attributed to guns. In the aerial sparring that continued through the end of the decade, the IAF claimed an additional ninety-two victories. Twelve were credited to first-generation IR-guided missiles and eighty to guns. All Indian and most Pakistani victory claims during the 1965 war were also attributed to guns. This was about to change.

Figure 8 illustrates the pace of change. With over five hundred claimed aerial kills, the 1970s saw the most intensive air combat of the past fifty years. Guns were still important, but improved versions of IR and radar-guided missiles began to make their presence felt.

FIGURE 8. AERIAL VICTORY CLAIMS, 1965–1979



The only significant aerial combat U.S. forces participated in during the 1970s was the continuing conflict in Vietnam. After the end of Operation Rolling Thunder in November 1968, U.S. air operations over North Vietnam did not resume until after the North Vietnamese Army (NVA) invaded South Vietnam in April 1972. During Operations Linebacker I and II in late 1972, U.S. aircrew were credited with sixty-eight air-to-air victories. Eight kills were achieved with guns, including victories by two B-52 tail gunners, whereas fifty-seven enemy aircraft were shot down by U.S. missiles. Meanwhile, in the Middle East, the IAF was engaged in an ongoing series of air engagements with Syrian and Egyptian air forces known as the "War of Attrition." Between January 1970 and the beginning of the Yom Kippur War in October 1973, the IAF claimed 112 victories. Forty of these were credited to missiles and sixty-five to guns. The thirteen Arab victory claims were all credited to missiles. The big shift came during the Yom Kippur War when the IAF scored seventy-nine of its 164 claimed victories with missiles and only eighty-three with guns. By the close of the decade, the IAF claimed an additional sixteen kills—eleven credited to missiles and only three to guns.

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[25] The remaining four victories were the result of maneuvering into the ground (2), fuel starvation (1), and a single AAM victory against a Tu-16 Badger bomber credited to an Israeli fighter armed with the quasi-experimental Shafrir I IR-guided missile. For more on the Shafrir I, see "Shafrir," *Global Security,* available at http://www.globalsecurity.org/military/world/israel/shafrir.htm, accessed September 11, 2014.

The Missile Comes of Age

One of the more frustrating aspects of aerial combat for U.S. aircrew in Vietnam was their inability to effectively employ several theoretical advantages of their sophisticated aircraft. These frustrations can be traced to key assumptions made by weapon and aircraft designers in the late 1950s. As previously mentioned, the missiles U.S. aircraft carried in Vietnam were designed under the assumption they would be used to defend U.S. cities or naval task forces from attack by Soviet bombers flying at high altitude. Designers assumed that in most cases U.S. fighters would be vectored toward incoming enemy bombers until the fighters could acquire them with their own onboard radars. They further assumed the position of other friendly aircraft and the incoming bombers would be sufficiently well understood to permit the fighters to shoot their radar-guided missiles at targets located at ranges of 10 nm or more. Engagements of this type, which are well beyond the range where humans can visually detect, let alone identify, an approaching aircraft, are referred to as BVR engagements.

The challenge for U.S. pilots in Vietnam as well as Israeli, Arab, Indian, Pakistani, and other pilots engaged in contemporary air combat operations was that their targets were rarely non-maneuverable bombers at high altitude approaching on expected routes. Instead, their targets were usually agile tactical aircraft operating at medium to low altitude. This made it hard for ground- and sea-based radar sites to support long-range missile targeting, because combat engagements often occurred beyond their effective range or at altitudes below their radar horizon.[26] Intermingling of friendly and enemy aircraft made it almost impossible for aircrew to reliably distinguish friend from foe until they were close enough to visually identify a potentially hostile aircraft.

Aircraft electronic IFF equipment was first introduced early in World War II and was carried on virtually all combat aircraft by the mid-1960s.[27] "Identification, friend or foe" is a bit of a misnomer. When this equipment receives a coded signal from friendly radar, it automatically replies with a coded signal of its own to positively identify the aircraft as friendly. Enemy aircraft will not give the proper coded reply, but neither will a friendly aircraft with malfunctioning equipment, battle damage, or an improperly inserted IFF code key. In other words, IFF systems can identify friendly aircraft with properly functioning IFF equipment, but the remaining radar returns could either be enemy aircraft or friendly aircraft with malfunctioning equipment. The high failure rate of 1960s-era electronics made IFF generally inadequate as a means of enabling BVR missile shots. This was especially true for U.S. aircrew operating over North Vietnam, where on any given day only a few North Vietnamese MiGs might be airborne among hundreds of U.S. aircraft. Under these conditions, odds were high that

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[26] A radar antenna 10 m high has line of sight (LoS) to targets at 33,000 feet of up to 220 nm (405 km). If the target aircraft is at 15,000 feet, it cannot be seen until it is within 150 nm (275 km) of the radar. Target aircraft at 5,000 and 500 feet must be within 85 nm (160 km) and 28 nm (50 km) respectively.

[27] During the Cold War, the Soviet Union/Warsaw Pact and United States/NATO developed unique, mutually incompatible IFF systems for their respective alliance blocks and supplied these systems along with combat aircraft sold on the international market.

an aircraft without a friendly IFF reply was *not* an enemy aircraft. In order to avoid incidents of fratricide, U.S. aircrew preferred to positively establish the identity of any aircraft they attacked, and for all practical purposes, this meant closing to within visual range of their targets where their superior radar and missile ranges were of little value.

By the late 1960s, U.S. forces were taking steps to solve the BVR IFF problem. The first was enabled by covert exploitation of Soviet SRO-2 IFF transponder equipment recovered by the Israelis from MiGs shot down during the 1967 Six-Day War. In 1968 the USAF started a program known as Combat Tree to build and incorporate a suitable SRO-02 interrogator into U.S. fighters. By 1971 a suitable system had been designed, tested, and fitted to a number of USAF F-4D aircraft. Known officially as the AN/APX-81, the system could be used in a passive mode where it received and processed IFF replies sent from MiGs in response to their own Ground Controlled Intercept (GCI) radar interrogations, or it could be used in active mode to trigger the MiGs response. A Combat Tree-equipped F-4 could positively identify enemy aircraft at up to 60 nm, three times farther than the F-4 could detect, but not identify, them with its radar alone.[28]

A second USAF initiative to enhance long-range target identification was the inclusion of the AN/ASX-1 Target Identification System Electro-Optical (TISEO) system on upgraded versions of the F-4E. TISEO was a stabilized telescope integrated with a TV camera attached to the inboard section of the F-4E's left wing (see Figure 9) that displayed images on the back-seater's radar scope. It had several operating modes, including one where the camera was slaved to the radar, allowing the crew to identify a target the radar was tracking, and another where the camera searched a volume of sky for possible targets. It could also automatically track targets once they were located. TISEO gave F-4E crews the ability to identify large aircraft at 50 to 80 nm and fighter-size aircraft at 10 nm or more.[29]

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[28] Peter E. Davies, *USAF F-4 Phantom II MiG Killers 1972–73* (Oxford, UK: Osprey Publishing, 2005), 16.

[29] Carlo Kopp, "Electro-Optical Systems," *Australian Aviation*, March 1984, available at *Air Power Australia*, http://www.ausairpower.net/TE-EO-Systems.html.

FIGURE 9. AN/ASX-1 TISEO IN PLACE ON F-14D NOSE AND F-4E WING[30]

F-4E crews equipped with Combat Tree and TISEO were much more likely to detect and identify enemy aircraft at long range where they could effectively employ their BVR weapons than were U.S. pilots through most of the Vietnam War. The USAF also incorporated a host of lessons from aerial combat over Vietnam into the requirements for their new dedicated, as opposed to the multirole F-4, air-to-air fighter: the F-15. One of the many innovations the F-15 introduced was Non-Cooperative Target Recognition (NCTR). NCTR compares prominent features from radar returns (e.g., engine compressor or turbine blades—if visible) with data on friendly and enemy aircraft features and automatically categorizes target returns.

These new sensors were paired with new weapons fielded in the 1970s and 1980s. Based on Vietnam combat experience, the U.S. military developed the AIM-7F. This new AAM had a dual-thrust rocket motor that offered more than double the effective range of the AIM-7Es used in Vietnam and used solid state electronics that were much more reliable than the vacuum tubes used in the AIM-7D/E. During the 1980s, follow-on missiles such as the AIM-7M introduced further improvements, including a programmable digital computer, a monopulse radar seeker for better jam-resistance and improved performance against targets at low altitude, an improved warhead, and an autopilot that increased the missile's range by allowing it to fly optimized trajectories.

The U.S. Navy went even further to improve BVR performance with its next-generation fighter. Not only did they include both the AN/ASX-1 and Combat Tree capability in the F-14 *Tomcat*, they also incorporated an exceptionally powerful and capable AN/AWG-9 radar/fire

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[30] For more detail, see Kopp, "Electro-Optical Systems;" J.P. Santiago, "Rivet Haste: Rebirth of the USAF at the End of Vietnam," *Tails through Time: Short Trips on the Long Road of Aviation History*, October 1, 2011, http://aviationtrivia.blogspot.com/2011/10/rivet-haste-rebirth-of-usaf-at-end-of.html, accessed September 11, 2014.

control system and the AIM-54 Phoenix missile.[31] The 1,000-pound Phoenix was twice the weight of the AIM-7 and was capable of engaging targets at ranges over 100 nm—about three times the maximum range of the AIM-7F/M and more than five times the maximum range of AIM-7D/Es used in Vietnam.[32]

The U.S. Navy and USAF did not put all of their air combat eggs into the BVR basket. They worked to improve short-range combat capability by launching a combined effort to improve the performance of the AIM-9 Sidewinder missile known as the AIM-9L.[33] The AIM-9L featured a completely new seeker design cooled by argon gas that was sensitive enough to lock onto the warm leading edges and other external parts of an aircraft rather than just hot engine parts. This gave the AIM-9L the ability to attack a target aircraft from any direction—front, sides, top, bottom, or rear. This "all-aspect" capability made the AIM-9L much more flexible than earlier AIM-9 versions. Pilots no longer had to maneuver their aircraft into a relatively small "launch cone" behind a target aircraft. Instead, if they could point their aircraft at the target and if they were within range (still relatively short for the ~200-pound Sidewinder), they could launch a missile. Other improvements incorporated in the AIM-9L were increased maneuverability and improved fuzing. Combined, these attributes made the AIM-9L one of the most successful air combat weapons of the 1980s.

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[31] The AN/AWG-9 and AIM-54 leveraged earlier Hughes Aircraft long-range radar and missile projects—the AN/ASG-18 and AIM-47 respectively. The latter were initiated in the mid-1950s as part of the Air Force F-108 Rapier program. This was canceled in 1959, but the AN/ASG-18 and AIM-47 made the jump to the YF-12 program, which was later canceled in 1968. By this time the AIM-47B had achieved six successful intercepts in seven test launches, weighed 800 pounds, and had a range in excess of 87 nm. See "Hughes GAR-9/AIM-47 Falcon," *Directory of U.S. Military Rockets and Missiles*, available at http://www.designation-systems.net/dusrm/m-47.html, accessed August 4, 2014.

[32] U.S. Navy, "AIM-54 Phoenix Missile," February 20, 2009, available at http://www.navy.mil/navydata/fact_display.asp?cid=2200&tid=700&ct=2, accessed September 17, 2013.

[33] While both services had used the AIM-9B in Vietnam, they developed a series of "service-specific" versions with various approaches to improving seeker performance, maneuverability, reliability, and range.

FIGURE 10. LATE 1980S AIR COMBAT SENSOR AND WEAPON CAPABILITIES

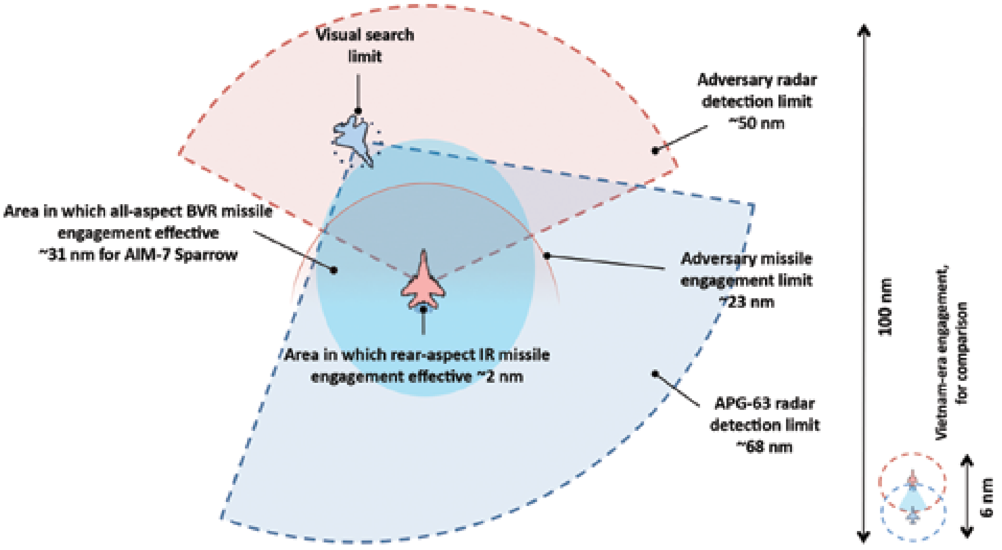
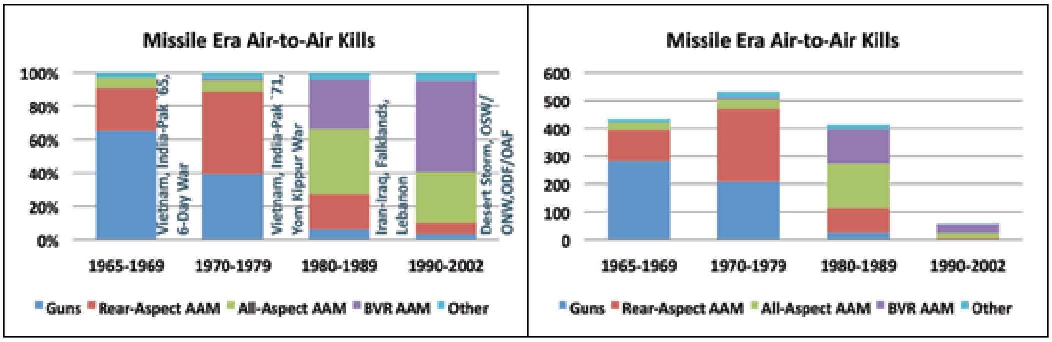


Figure 10 illustrates how sensor and weapon technologies in widespread service by the late 1980s had greatly expanded the potential engagement zone available to attacking aircraft.

FIGURE 11. AERIAL VICTORY CLAIMS, 1965–1989



As illustrated by Figure 11, improvements in fighter sensor and weapon capabilities had a dramatic effect on the nature of air combat during the 1980s.

The first thing to note is that aerial combat was still quite common during the 1980s. The ongoing conflict between Israel and Syria over Lebanon and the Falkland Islands War are widely known examples. The bulk of claimed victories, however, stem from the long and bitter Iran-Iraq War that raged for most of the decade.[34] There are relatively few good sources on the

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[34] During the Iran-Iraq War there were 290 confirmed aerial victories on both sides.

aerial dimension of this conflict, but those that exist indicate that the Islamic Republic of Iran Air Force (IRIAF) succeeded in maintaining a significant number of the F-4, F-5, and F-14 fighters it received from the United States during the 1970s in working order. Their crews, all trained in the United States, were credited with over two hundred aerial victories including sixty-two kills by F-14 crews using AIM-54 Phoenix missiles.[35] The second noteworthy aspect of 1980s aerial combat is the massive decline in gun use. During the 1970s over two hundred aerial victories were credited to guns, but during the 1980s the total declined to just twenty-six (an 87 percent decline). This was accompanied by a similarly large increase in the proportion of victories credited to all aspect missiles (including the AIM-9L) and true BVR missiles such as the AIM-54 and improved versions of the AIM-7.

1990s Aerial Combat and the Rise of Network Warfare

By the end of the Cold War, both NATO and Warsaw Pact air forces were equipped with air superiority fighters with pulse Doppler radar systems able to detect and target enemy aircraft at 40 nm or more, even when the target aircraft were flying in ground clutter at low altitude. This capability, often referred to as "look down/shoot down," was a significant improvement over fighter fire control radars fielded in the 1960s and 1970s and greatly expanded the potential utility of BVR engagements by eliminating the "low-altitude sanctuary" presented by earlier fighter radars.[36]

Figure 12 shows the vast increase in aerial sensor and weapon ranges available to fighter pilots of the 1990s compared to those of the 1960s.

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[35] Tom Cooper and Farzad Bishop interviewed IRIAF F-4 and F-14 aircrew and described their experiences in detail in *Iran-Iraq War in the Air 1980–1988* published by Schiffer Military History Press in 2000 and two Osprey Publishing books: *Iranian F-4 Phantom II Units in Combat* (2003) and *Iranian F-14 Tomcat Units in Combat* (2004). These books are not perfect—none are—and report some unlikely stories as fact, but most of the narratives are plausible and convincing, making these books among the best unclassified sources on the largest air war fought anywhere in the world in the past fifty years.

[36] From the late 1970s through the end of the Cold War, NATO air forces adopted and intensively trained in specialized low-altitude tactics designed to exploit limitations in air- and ground-based radar systems in widespread service during that time. By the end of the Cold War, both sides had begun to field more advanced radar systems with greatly enhanced capability against low-altitude targets, raising questions about the continued viability of this set of tactics. For more on the development of U.S. Air Force low-altitude tactics, see C. R. Anderegg, *Sierra Hotel: Flying Air Force Fighters in the Decade after Vietnam* (Washington, DC: Government Reprints Press, 2001).

FIGURE 12. 1990S AIR COMBAT SENSOR AND WEAPON CAPABILITIES

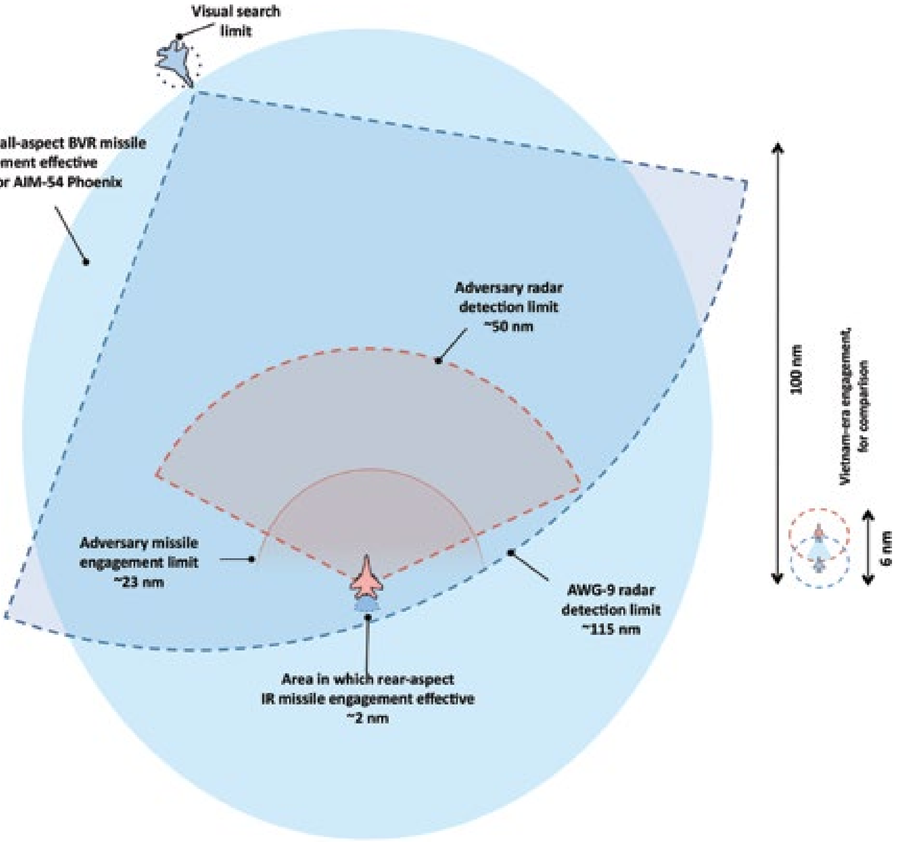

Figure 13 shows the continued changes in fighter weapon use spurred by these technological improvements. It also shows a dramatic decline in the frequency of aerial combat following the end of the Cold War. Over the past twenty-three years, the database holds just fifty-nine aerial victory claims.[37] The last two claimed kills occurred on September 14, 2001, and were credited to IAF F-15Cs; the victims were Syrian Air Force MiG-29s. There are multiple explanations put forward for the steep decline in the incidence of aerial combat engagements over the past two decades, including a lack of military conflicts between nations with modern air forces, the difficulty and expense of building and maintaining an air superiority capability centered on manned aircraft, and asymmetric responses, such as relying on cruise and ballistic missiles instead of manned aircraft for long-range strike missions in the face of a perceived overwhelming U.S. advantage in aerial combat capability. These are, however, beyond the scope of this report.

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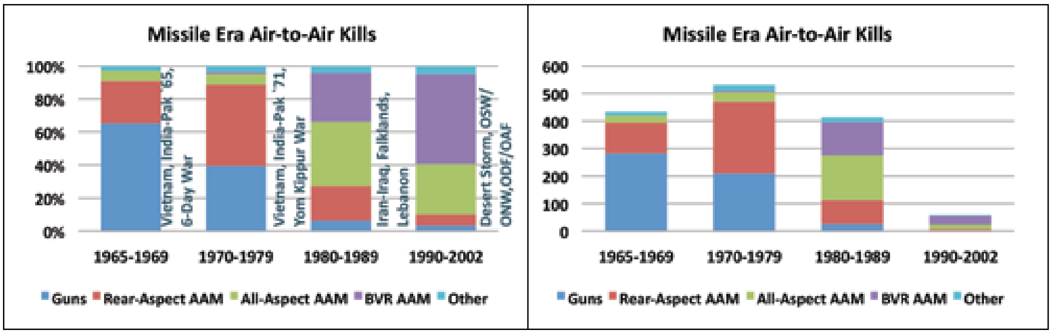
[37] The greatly reduced number of aerial victories has allowed more intense scrutiny of each claim with a correspondingly higher likelihood that post–1990 claims actually represent real victories. In other words, the decrease in numbers of claimed victories and the rise of global media over the past two decades have likely reduced the “overclaiming” problem discussed earlier.

FIGURE 13. AERIAL VICTORY CLAIMS, 1965–2002



While the frequency of aerial combat has declined greatly compared to the 1960s—1980s, the number of aerial victory claims registered since 1990 is sufficiently large to permit simple quantitative analysis of the kind presented throughout this chapter. The left-hand panel of Figure 13 reveals a continued shift in the mix of weapons employed in aerial combat during the post–Cold War era. The first thing to note is the virtual absence of victories credited to guns. The database includes two gun victories; the last was a Venezuelan AT-27 *Tucano* armed trainer shot down by a Venezuelan F-16 during a coup attempt in November 1992. Taking a longer perspective, the data shows the continued utility of guns in aerial combat through the 1970s and their rapid eclipse by missiles beginning in the 1980s.[38] In fact, the use of guns in aerial combat virtually ended after the Yom Kippur War in late 1973. Out of 498 victory claims since that time, 440 (88 percent) have been credited to AAMs and only thirty to guns.[39] The last gun kill of one jet combat aircraft by another occurred in May of 1988 when an Iranian F-4E downed an Iraqi Su-22M with 20 mm cannon fire.

Also of note is the near-disappearance of the rear-aspect-only IR missile victories and the reduction in proportion of victories achieved by all-aspect missiles such as the AIM-9L/M. Over the past two decades, the majority of aerial victories have been the result of BVR engagements where the victor almost always possessed advantages in sensor and weapon range and usually superior support from “offboard information sources” such as GCI radar operators or their airborne counterparts in Airborne Warning and Control Systems (AWACS) aircraft. This is significant, as it suggests the competition for SA is heavily influenced by the relative capabilities of the opponents’ electronic sensors, electronic countermeasures (ECM), and network links between sensor, command and control (C2), and combat aircraft nodes.

The next section examines the details of aerial victories achieved by coalition pilots during the First Gulf War in 1991 with the goal of illustrating the dramatic influence of more realistic

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[38] Gun utility seems to have diminished greatly following the 1973 Yom Kippur War. Of the 520 gun kills identified in the database, 490 (94.2 percent) occurred prior to November 1973.

[39] The remaining twenty-eight credited victories were attributed to other means—usually the opponent maneuvering the aircraft into the ground.

training combined with sensor, weapon, and offboard support (or network) improvements on coalition pilot SA and combat success.

Aerial Combat in the First Gulf War

The First Gulf War produced the largest number of aerial victory claims in a single operation since the end of the Cold War. Coalition aircrew destroyed thirty-three Iraqi fixed-wing aircraft during the war in exchange for the loss of a single F/A-18 to a BVR missile launched by an Iraqi MiG-25 on the opening night of the war. In contrast, U.S. aircrew achieved a kill ratio of only about 2:1 against the North Vietnamese Air Force. Moreover, the Iraqi Air Force in 1991 was probably better equipped relative to U.S. forces than the North Vietnamese had been twenty years before, and many Iraqi pilots had combat experience from the recently concluded Iran-Iraq War. It is true that U.S. aircrew had much improved air combat skills derived from training innovations such as Red Flag, Top Gun, and the USAF Fighter Weapons School and Aggressor programs. As previously mentioned, however, short-range maneuvering combat was rare during Desert Storm, and most engagements began with weapons fired before sighting enemy aircraft. If we limit ourselves to examining only instances of aerial combat that took place during the first three days of Desert Storm while Iraqi aircraft were still attempting defensive operations similar to those flown by the North Vietnamese two decades before, then the coalition victory margin declines to “just” 11:1.

Details of Coalition Aerial Victories

Why was there such a disparity in combat success between Iraqi and North Vietnamese pilots? Details of successful aerial engagements by allied aircrew during Operation Desert Storm, plus three that occurred several weeks after hostilities ended, were documented in detail by John Deur in a series of detailed interviews with all allied participants conducted post-conflict.[40] A review of these structured interviews reveals a wealth of details regarding the engagements summarized in Table 1.

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[40] John M. Deur, *Wall of Eagles: Aerial Engagements and Victories in Operation Desert Storm* (Unpublished Galley Proofs, 1994).

TABLE 1. SUMMARY OF FIRST GULF WAR AERIAL VICTORIES

Detection and Identification	In twenty-seven of thirty-three engagements against fixed wing aircraft (82%), AWACS provided target information *and* identification before U.S. fighters detected enemy aircraft.
	On average AWACS detected and identified enemy aircraft while they were still over 70 nm from U.S. fighters.
	In the four engagements where ACM occurred, U.S. pilots first detected enemy aircraft at 5 nm or more on radar.
Air Combat Maneuvering (ACM)	In only four of the thirteen visual range encounters did U.S. fighters engage in significant ACM to attain firing position.
	Only 15% of all engagements and 38% of visual range engagements involved ACM.
BVR Engagements	Sixteen of thirty-three engagements between fixed wing aircraft occurred BVR (48%).
	On average, U.S. pilots detected enemy aircraft on their own radars at 42 nm and launched missiles at 10 nm.
	U.S. pilots fired twenty-eight AIM-7s. Twenty-two of the AIM-7s hit their target or the debris (79%).
Speed	At no time did any U.S. aircraft exceed 650 knots (Mach 1.03 at 12,000 ft), even against targets moving at 700 knots or more.

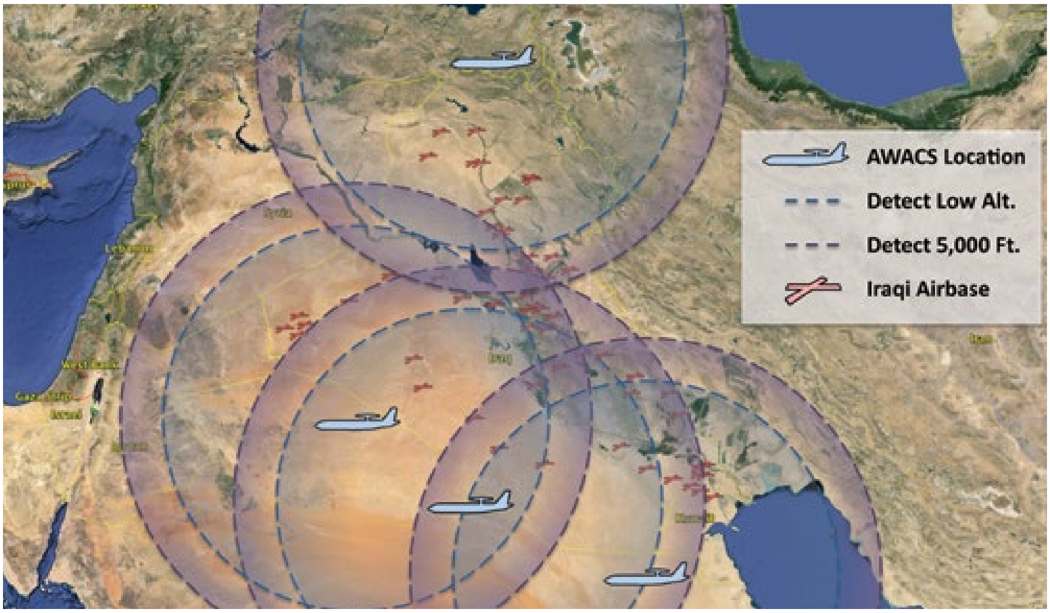
It is noteworthy that half of the BVR engagements occurred during the first three days of the conflict while the Iraqi Air Force was still attempting to maintain defensive patrols and *before* Iraqi fighter aircraft began to escape to Iran. What is striking about this is that the sheer numbers suggest the probability of coalition fratricide was quite high, yet none occurred. For example, on the first day of the air campaign, coalition aircraft flew more than 1,300 combat missions into Iraqi airspace, whereas the Iraqi Air Force flew just over one hundred fighter sorties. Four days later, the coalition flew almost eight hundred combat sorties over Iraq, whereas the Iraqi Air Force flew just twenty-five combat sorties. This disparity in the relative number of friendly and enemy aircraft operating over Iraq shows why simply relying on friendly IFF for target identification in BVR engagements is unadvisable. For example, if we assume coalition IFF systems have a 95 percent chance of functioning properly throughout a combat mission, then we could have expected about seventy-five IFF failures on the first day of Desert Storm and about forty on day four. These numbers are close to the number of Iraqi fighter sorties flown on those days. So, odds are about even that a target that fails to respond correctly to an IFF query is a friendly aircraft. This same numerical disparity in friendly and enemy aircraft existed over North Vietnam and was one of the primary reasons for the reluctance of U.S. aircrew to initiate BVR attacks and the rarity of BVR kills in that conflict.

By 1991 U.S. forces had much greater confidence in their ability to correctly identify enemy aircraft at BVR range, even in an environment where most aircraft, and many aircraft without proper IFF responses, were likely friendly. There were several factors that made this possible. By the late 1980s, the USAF and Navy had assimilated the lessons of missile-era aerial combat learned firsthand in Vietnam and through close monitoring of conflicts in the Middle East and elsewhere. They had also used significant defense spending increases during the “Reagan

Build-Up" to largely reequip their forces with aircraft, sensors, and weapons designed with missile combat in mind. Additionally, both services had instituted training programs geared toward providing realistic training in all aspects of air warfare (e.g., aggressor squadrons and Red Flag exercises in the USAF and Top Gun in the Navy). Finally, both services invested in significantly improved AWACS platforms. The most sophisticated and capable of these new AWACS was the E-3 Sentry, which was specifically designed as both a sensor and C2 platform to remedy crew workload, sensor, and communications problems the USAF experienced using EC-121 aircraft in a similar role throughout the Vietnam War.[41, 42]

During the First Gulf War, the E-3s proved their worth many times over. Their improved sensors and higher operating altitude allowed them to detect enemy aircraft that were flying at low altitudes at about 225 nm. Aircraft operating at higher altitudes could be detected even further away. Figure 14 shows how this allowed E-3 aircraft operating continuously at three orbit locations inside Saudi Arabia and a fourth in Turkey to detect Iraqi combat aircraft during their takeoff rolls at about three-quarters of Iraq's airbases. E-3 crews could detect and track aircraft operating at or above 5,000 feet virtually anywhere inside Iraq.

FIGURE 14. APPROXIMATE USAF E-3 SENTRY AWACS COVERAGE OF IRAQ, 1991



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[41] Michel, *Clashes: Air Combat over North Vietnam 1965–1972*, 100.

[42] The EC-121s were designed in the 1950s to detect Soviet nuclear-armed bombers approaching the United States over the ocean. When pressed into service to assist tactical aircrew over Vietnam, they initially lacked suitable sensors to detect and reliably track North Vietnamese MiGs over land. While this deficiency was eventually remedied with the addition of Combat Tree-like capabilities able to interrogate MiG IFF systems at ranges up to 175 miles, they still lacked a sufficiently large mission crew, generally only five, and suitable communications links to reliably relay the information to U.S. fighters over North Vietnam.

Watching Iraqi aircraft takeoff allowed E-3 crews to immediately identify them as hostile, while the E-3's comprehensive communications suite and large mission crews, between thirteen and nineteen air weapon controllers and other specialists, allowed them to communicate this information and provide dedicated support to multiple coalition fighter crews simultaneously via ultra-high frequency (UHF) voice radio links. Coalition ROE allowed combat pilots to engage any aircraft declared hostile by an E-3 crew without the need for further identification. But if the target was not declared hostile by an AWACS, then two independent sources were required, and only the F-15Cs with both NCTR and the AN/APX-76 IFF interrogator could meet the ROE on their own. This greatly increased the tactical freedom of action and confidence of coalition pilots.

Another important E-3 contribution, as outlined above, was providing coalition pilots with significant advanced knowledge of enemy aircraft position and heading long before the pilots' own radars could detect their opponents. Typically, E-3 crews detected, identified, and vectored coalition pilots toward Iraqi aircraft while they were about 70 nm away from the friendly fighters, whereas coalition pilots detected enemy aircraft at about 42 nm with their own radars. This effectively increased coalition fighter sensor range by about 65 percent and allowed coalition pilots significant extra time and space to position their formations to achieve a tactical advantage. This was the first consistently successful linking of offboard airborne sensors to fighter aircraft in combat. This network of airborne sensors, C2, weapons, and communications links greatly increased coalition fighter crew SA and gave them a commanding advantage in achieving surprise. Future U.S. fighter crews will be supported by both voice and data links that will allow them to build SA more rapidly, help eliminate uncertainty, and increase decision and engagement speeds.[43]

On those occasions where E-3 crews could not provide positive target identification, F-15 and F-18 aircrew could use NCTR features built into their digital pulse Doppler radars. Pulse Doppler radars are extremely adept at measuring and categorizing motion like those of rotating aircraft engine compressors or turbine blades. Known combat aircraft engine types have unique turbine and compressor blade characteristics that can be compared to radar measurements to determine the type of aircraft being tracked.[44]

Another significant factor in coalition air combat success was greatly increased weapon capabilities and reliability. Unreliable missiles had been one of the biggest frustrations of U.S. aircrew in Vietnam, but this was not the case in Desert Storm. Coalition fighters achieved every missile victory with evolved versions of the IR-guided AIM-9 Sidewinder and radar-guided AIM-7 Sparrow missiles. In addition to much improved range and increased capabilities against low-altitude and maneuvering targets as mentioned above, these weapons

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[43] A 2005 RAND study comparing pilot performance in simulated air-to-air combat found pilots with access to both voice and data networks more than doubled their kill ratio compared to pilots with access to voice networks only. See Daniel Gonzales et al., *Network-Centric Operations Case Study: Air-to-Air Combat with and without Link 16* (Santa Monica, CA: RAND Corporation, 2005).

[44] Deur, *Wall of Eagles*, p. 5.

were much more reliable than earlier versions used in Vietnam. One reason for this was the replacement of 1950s-era vacuum tube electronic components with solid-state electronics. The new electronics also brought increased seeker performance and resistance to radar and IR countermeasures.[45]

TABLE 2. U.S. MISSILE PERFORMANCE IN VIETNAM AND THE FIRST GULF WAR[46]

	Rolling Thunder			Linebacker			USAF First Gulf War		
	Total Expended	Hits	Successful	Total Expended	Hits	Successful	Total Expended	Hits	Successful
AIM-7	340	27	8%	272	29	11%	67	34	51%
AIM-9	187	29	16%	267	52	19%	18	12	67%
Total	527	56	11%	539	81	15%	85	46	54%

Table 2 illustrates the significant increase in the lethality and reliability of U.S. AAMs between 1973 and 1991. AIM-7 Sparrows fired by USAF aircrew were over six times more reliable in 1991 than they had been during Rolling Thunder in 1965–1968 and about five times more reliable than the "improved" AIM-7s used during Linebacker I and II in 1972 and 1973. Sidewinder reliability also improved by nearly a factor of four relative to its late Vietnam ancestors.[47] Overall, AAMs launched by USAF crews in the First Gulf War were about three times more likely to achieve a kill than missiles launched during the Vietnam War.

Prospects for Short-Range Combat

Chapter 2 discussed the significant advances in short-range IR missile capabilities during the 1970s and 1980s. These advances have continued over the past two decades. The most modern IR missiles are capable of being cued by Helmet Mounted Cueing Systems (HMCS) and turned toward the designated target and locked on after launch. Many also feature thrust vector control, which bestows extreme maneuverability, and imaging focal plane array IR seekers that recognize and home in on target aircraft images rather than simple heat sources. These missiles allow pilots to launch highly lethal IR missiles at any opponent they can see, even if that

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[45] Replacement of aircraft fire control systems with solid-state electronics helped improve missile reliability via improved launch envelope calculation capabilities and, in the case of the radar-guided AIM-7, more reliable and consistent target illumination.

[46] Vietnam missile data derived from Michel, *Clashes: Air Combat over North Vietnam 1965*–1972, 151, 154, and 287. Desert Storm data derived from author's analysis of Deur, *Wall of Eagles;* and Ellion A. Cohen, *Gulf War Airpower Survey Volume V: A Statistical Compendium and Chronology* (Washington, DC: Government Printing Office, 1993).

[47] Sidewinder expenditure figures for Desert Storm discount "about 30" launched by mistake by F-16 pilots rapidly switching between air-to-ground and air-to-air weapon modes early in the conflict. (Author conversation with Lt. Gen. Lloyd S. "Chip" Utterback, July 2008.) If these are discounted, the USAF AIM-9 success rate in Desert Storm increases to 65 percent. This is more in line with the reputation of late-model AIM-9s as reliable weapons, earned in British service in the Falklands and in Israeli service throughout the 1980s.

opponent is behind them.[48] With an increasing number of modern combat aircraft equipped with missile-approach warning systems, it is likely that a pilot under attack will have sufficient time to target an attacker and launch a missile in return. Once both aircraft have "launch and leave" missiles in the air, prospects are good that the short-range engagement will result in "mutual kills," with short-range combat kill ratios near 1:1. This suggests we may have reached a point in the development of short-range air combat technologies where serious, capable adversaries will attempt to avoid it and instead seek advantage in superior BVR capabilities.

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[48] See *Operational Test and Evaluation Annual 2012 Report* (DoD, 2012), 135, available at http://www.dote.osd.mil/pub/reports/FY2012/pdf/navy/2012aim9x.pdf, accessed December 10, 2013, for details on the most modern U.S. short-range IR missile, the AIM-9X.

CHAPTER 3

The Evolving Importance of Traditional Fighter Aircraft Attributes

Early in Chapter 2 aerial combat was described as a dynamic competition for SA. The side with superior SA usually wins and overwhelming victories suggest a lopsided outcome in the SA competition. The disparity in North Vietnamese and Iraqi Air Force aerial combat success against U.S. forces strongly suggests that by 1991 the United States had succeeded in creating an airborne battle network capable of bestowing on its well-trained aircrew an overwhelming advantage in SA. This is consistent with statistical analysis of results from extensive air-to-air combat testing conducted in the late 1970s and early 1980s. These tests, known as Air Combat Evaluation (ACEVAL), Air Intercept Missile Evaluation (AIMVAL), and the Advanced Medium-Range Air-to-Air Missile (AMRAAM) operational evaluation (OUE), consistently found that aircrew SA was the most important factor in determining combat outcomes.[49] Digging a bit deeper into the SA competition, the tests results suggested superior SA was a function of the technological enablers listed in Table 3.

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[49] ACEVAL examined the effectiveness of U.S. air combat tactics against less sophisticated opponents, AIMVAL was a series of tests designed to evaluate the impact of improved short-range IR missiles on combat outcomes, and the AMRAAM OUE used high-fidelity air combat simulations with humans in the loop to establish the utility of an AMRAAM.

TABLE 3. AIMVAL-ACEVAL-AMRAAM OUE: SA BUILDING BLOCKS AND ENABLERS[50]

Factor	SA "Building Blocks"	Enablers
Superior knowledge of enemy location and movements	Information acquisition	Superior sensors (radar), accurate Radar Warning Receivers (RWR), BVR ID, offboard support (e.g., AWACS), easily understood data presentations, and realistic training
Avoiding or delaying detection and tracking by enemy sensors	Information denial	Low radar, IR, and visual signatures—effective ECM

These studies also found that aircraft speed, maneuverability, range, and persistence were also important factors in combat outcomes. This chapter examines emerging tensions between two aircraft attributes most associated with fighter aircraft over the past one hundred years—speed and maneuverability—from the perspective of the constraints they impose on aircraft design and their potential impact on information acquisition and information denial in future aerial combat.

Advantages of Speed

This report has already examined the value of speed in achieving surprise and facilitating "ambush" or "boom and zoom" style tactics during the gun and early missile eras. While detection ranges were short and effectual weapon employment parameters restrictive, the pilot of a faster aircraft could often use his speed advantage to deny an adversary the ability to achieve an effective firing position or even to escape destruction.

Over the past fifty years, however, the advantage of speed in these traditional fighter engagements has declined significantly. For example, one of the major reasons speed was important in achieving surprise was that it allowed attacking aircraft to rapidly transit the distance between where a "victim" could detect the impending attack and effective weapon range. The less time spent in this region, the lower the probability a prospective victim would be able to detect and counter an attack. Visual detection range for a World War II fighter approaching another fighter head-on (i.e., coming in to attack) was about 1.5 nm. Typical piston-engine fighter aircraft of World War II cruised at approximately 240 knots,[51] had top speeds of approximately 380 knots, and had an effective weapons range of about 200 m. A fighter attacking an unsuspecting victim from behind could expect to cross the distance between likely detection range and weapon range at a relative speed of 140 knots in about 35 seconds. If our hypothetical attacking aircraft was a Me-262 jet fighter, its pilot could expect to transit

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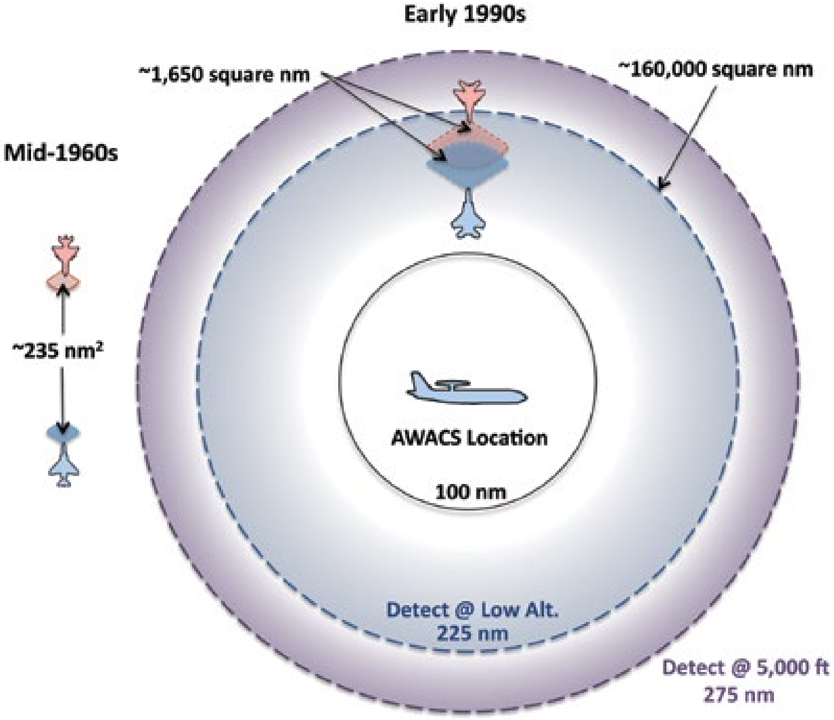
[50] R. E. Guild, *AIMVAL Analysis*, Briefing Slides (Washington, DC: Air Force Studies and Analysis, January 25, 1978); E. J. Griffith Jr., *ACEVAL: Origin, Description, Results, Applicability* (Undated); Capt. Pennington, *AMRAAM OUE Red Lessons Learned Briefing* (Dayton, OH: VEDA Inc., April 1, 1984).

[51] National Museum of the United States Air Force, "North American P-51D Factsheet," February 2011, available at http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=513, accessed September 26, 2013.

the detection to open-fire range in just 21 seconds, giving the victim pilot (or his wingman) 40 percent less time to detect the impending attack with a corresponding increase in the probability of a surprise attack.

Modern aerial combat seldom takes place in the visual arena, and guns are almost never employed against other combat aircraft. Instead, electronic sensors, typically radars, and guided missiles are the principal means used to detect and attack airborne targets. At the time AAMs first began to make an impact on aerial combat in the mid-1960s, the best fighter radars could typically detect targets at about 15 nm in a limited area approximating a 110-degree cone in front of the intercepting aircraft. In theory, weapons could be launched from about half this distance. By 1991, fighter radars were much more capable and could detect targets at 40 nm or more, even at low altitudes. Furthermore, the introduction of advanced long-range airborne radars on E-3 aircraft allowed their crews to provide friendly fighter crews with a form of electronic "overwatch" by constantly scanning areas the fighters' own radars could not scan due to sensor field of regard or range limitations. Figure 15 illustrates the increase in the "organic" and aerial network sensor footprints between the mid-1960s and early 1990s.

FIGURE 15. AERIAL SENSOR FOOTPRINT GROWTH, MID-1960S THROUGH EARLY 1990S



The decreased utility of speed for attacking aircraft under these circumstances is illustrated by the experiences of Navy Lt. Cdr. Mark Fox on the first day of the First Gulf War. Fox was flying an F/A-18C as part of a Navy strike package attacking an airfield in western Iraq. A pair of MiG-21 aircraft patrolling over an adjacent Iraqi airbase were vectored toward Fox and three other F/A-18s tasked with dropping 2,000-pound Mk-84 gravity bombs on the airfield. Fox and his companions were alerted by an E-2C *Hawkeye* AWACS crew while the MiGs were still 15 nm away. The MiGs were approaching head-on at supersonic speed, giving the two opposing formations a combined closing speed of 1,200 knots. At this speed, the MiGs and F/A-18s were only 45 seconds apart when Fox received his warning call. Within 20 seconds, Fox and one of his companions had each engaged and destroyed a MiG.[52]

Although the AWACS warning time/distance advantage Fox enjoyed on the first day of the First Gulf War was less than typically achieved in that conflict, it was large enough to give him a decisive edge. Even though his opponents were flying at supersonic speeds and closing from the front, the AWACS warning gave his flight more time to react than a World War II fighter pilot could typically have expected in the case of an attack from the rear. Had the MiGs been behind Fox instead, it would have taken them almost four minutes to catch him. More importantly, this incident illustrates how sensor and weapon performance had advanced even faster than fighter aircraft performance over the period between the end of World War II and the end of the Cold War. Over the past two decades, airborne sensor performance has continued to improve with the introduction of active electronically scanned array (AESA) radars, advanced Infra-Red Search and Track Systems (IRSTS), and the widespread adoption of electronic datalinks that eliminate the need for slow and easily misunderstood voice communications between aerial platforms. These developments are likely to provide even better SA and longer threat warning and set-up times in the future because sensor and network capabilities tend to advance much more quickly than raw platform performance measures like fighter top speed, which has improved little over the past fifty years.[53]

A continuing advantage that speed provides to modern fighters is giving a range “boost” to their missile weapons. All else equal, a missile launched from an aircraft traveling at 1,000 knots will travel much farther than the same missile launched from an aircraft traveling at 500 knots. This missile range extension is one of the most important benefits F-22s derive from their ability to cruise at supersonic speed without the use of fuel-gulping afterburners, known as supercruise. Superior speed is also useful in disengaging from combat after a successful attack. This advantage, however, is likely to diminish as weapon and sensor ranges continue to grow while aircraft top speed remains relatively fixed. Against an adversary armed with directed-energy (DE) weapons, it would likely be of little value in improving the prospects of successful disengagement.

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[52] Deur, *Wall of Eagles,* pp. 12–13.

[53] For example, the Navy’s fastest fighter in 1963 was the F-4B *Phantom II* with a top speed of 1,210 knots. The Navy’s fastest fighter today is the F/A-18E at about 1,050 knots.

Costs of Speed

If adding the ability to fly at supersonic speeds imposed little additional cost, there would be no need to question whether to retain it as an attribute of future combat aircraft. Supersonic speed requirements, however, impose significant constraints on aircraft performance characteristics and can significantly increase aircraft procurement and operating costs. In particular, supersonic aircraft are larger, more complex, and less fuel-efficient compared to subsonic aircraft with the same range-payload capabilities. The aerodynamic requirements of efficient supersonic flight and efficient subsonic flight conflict in several areas. For example, subsonic aerodynamic efficiency generally increases for aircraft with long, narrow (high aspect ratio) wings. Supersonic flight tends to be more efficient for aircraft with long, narrow bodies and short swept wings. Supersonic aircraft generally require higher thrust-to-weight ratios than subsonic aircraft with comparable range and payload characteristics. For any given level of engine technology, this requires larger engines with higher fuel consumption. This, in turn, requires additional fuel, which requires additional volume, which results in additional structural weight, which requires yet more powerful engines to maintain performance. Eventually this cycle subsides, but not until the final aircraft design is much larger and more expensive than a subsonic alternative.

Finally, there are some emerging tactical costs of supersonic flight. Over the past two decades, IRSTS have proliferated to the point where most current production combat aircraft have this capability. IRSTS were first developed during World War II, and early versions were fitted to U.S. fighters designed in the late 1950s including the F-106, F-101B, and early versions of the F-4. They fell out of favor with Western fighter designers as unnecessary during the 1970s and 1980s when the West enjoyed a commanding lead over the Soviet Union in fighter radar and electronic warfare technology. The Soviets incorporated them into both the MiG-29 and Su-27 fighters, which entered service in the early 1980s. The Europeans have incorporated them into the Eurofighter Typhoon and Rafale. The Russians continue to refine their IRSTS, and the Chinese have integrated them into their latest combat aircraft as well. Today, the Navy is developing an IRSTS built into the front of F/A-18E/F centerline fuel tanks, allowing it to be fitted to existing aircraft. Figure 16 shows the IRSTS sensor protruding from the nose of the centerline fuel tank.[54]

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[54] U.S. Navy, "NAVAIR News," June 28, 2011, available at http://www.navair.navy.mil/index.cfm?fuseaction=home.NAVAIRNewsStory&id=4663, accessed September 26, 2013.

FIGURE 16. F/A-18E/F LONG WAVE IRSTS UNDER TEST[55]

There are several reasons for the renewed interest in IRSTS. One is their immunity to Digital Radio Frequency Memory (DRFM) jamming techniques that can badly degrade radar performance.[56] Another is their ability to detect and track "stealth" aircraft with reduced radio frequency (RF) signatures.

IRSTS detection range is determined by a number of factors, including atmospheric attenuation, seeker sensitivity, sensor aperture size, target size, and the square of the difference in target temperature and the temperature of the surrounding environment.[57] The blue line in Figure 17 shows how aircraft leading-edge temperature increases with aircraft speed. Ambient temperature between 37,000 and 80,000 feet of altitude on a standard day is -70° F. The leading edges of an aircraft flying at Mach 0.8 are heated by friction to -21° F. As aircraft speed increases, skin temperatures rise rapidly. For example, a fighter aircraft traveling at Mach 1.8 would have leading edge temperatures of 182° F.[58] Increasing leading-edge temperatures by 200 degrees increases the probability of being detected by IR sensors.

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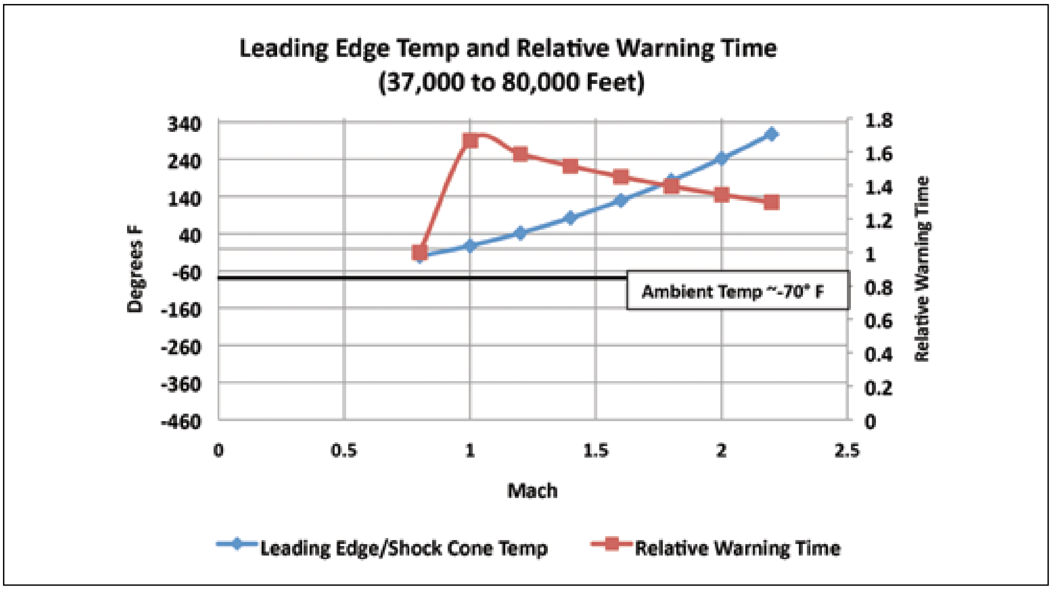
[55] For more detailed information, see, "Infrared Search and Track System Reaches Milestone B," *DC Military,* available at http://www.dcmilitary.com/article/20110630/NEWS14/706309921, accessed September 12, 2014.

[56] DRFM is an important element in modern ECM. DRFM digitizes incoming radar signals and stores an exact copy in digital memory. This signal can then form the basis of highly effective deceptive jamming techniques. Because it is essentially an exact copy of the original signal, retransmitting the signal can create large numbers of false targets that the transmitting radar will not be able to distinguish from other legitimate returns. The stored signal can also be subtlety altered to create errors in range, speed, and angle that defeat radar tracking and weapon guidance.

[57] "Infrared Propogation and Detection," January 20, 1998, available at http://www.fas.org/man/dod-101/navy/docs/es310/syllabus.htm, accessed September 26, 2013.

[58] NASA, "Stagnation Temperature," July 2008, available at http://www.grc.nasa.gov/WWW/K-12/airplane/atmosold.html, accessed September 27, 2013.

FIGURE 17. AIRCRAFT TEMPERATURE AND IR SENSOR WARNING TIME AS A FUNCTION OF SPEED



Aircraft flying at supersonic speeds also produce shock waves of highly compressed, and therefore heated, air. Figure 18 shows how large these "Mach cones" are relative to the aircraft creating them.

FIGURE 18. USAF F-22 WITH MACH CONE

The combination of a sudden increase in target area with the formation of the Mach cone and increase in temperature accounts for the "jump" in warning time shown on the red line in Figure 17.[59] As a target aircraft accelerates from Mach 0.8 to Mach 1, a Mach cone forms around the aircraft with a temperature of about 8° F. This rapidly heats the aircraft's leading edges to the same temperature while increasing the frontal target area presented to the sensor about ten times. IR range equation calculations show this more than doubles the range the aircraft can be detected. Warning time for the aircraft with the IR sensor is increased by only about 70 percent, because the aircraft at Mach 1 can cross the doubled detection range about 25 percent faster than an aircraft at Mach 0.8. Increased IR detection range has the additional disadvantage of dramatically increasing the size of the area a supersonic aircraft can be detected. Table 4 gives results of IR detection calculations for target aircraft speeds between Mach 0.8 and Mach 2.2.

TABLE 4. IR DETECTION RANGE, AREA, AND WARNING TIME AS A FUNCTION OF MACH

Temperature (°F)	Mach	Relative Detection Range	Relative Detection Area	Relative Speed	Relative Warning Time
-20	0.8	1.0	1.0	1.0	1.0
8	1.0	2.1	4.3	1.3	1.7
42	1.2	2.4	5.7	1.5	1.6
83	1.4	2.7	7.0	1.8	1.5
130	1.6	2.9	8.4	2.0	1.5
183	1.8	3.1	9.9	2.3	1.4
242	2.0	3.4	11.3	2.5	1.3
308	2.2	3.6	12.8	2.8	1.3

It is important to consider a final drawback associated with supersonic flight. Supersonic flight is much less fuel efficient than subsonic flight, even for aircraft with supercruise capability. In general, fighter aircraft burn about three to four times as much fuel in military power than at cruise power settings. Supercruise does not require the use of fuel-gulping afterburners, but it does require power settings at or near military power.[60] An aircraft with an 800 nm combat radius while cruising at Mach 0.8 would have only a 600 nm combat radius cruising in

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[59] The red line assumes that both the sensor and target aircraft are operating at 40,000 ft.

[60] Military power is the maximum amount of thrust a jet engine can produce under normal operating conditions where fuel is burned between the compressor and turbine sections of the engine. As the name implies, afterburners inject additional fuel behind (after) the turbine and ignite it. This produces significant additional thrust, but fuel efficiency is reduced even more. For example, the General Electric F110 engine that powers most F-16s produces about 17,000 pounds of thrust at sea level in military power and about 29,000 pounds of thrust in afterburner, an increase of 70 percent. However, fuel consumption goes up from about 12,000 pounds per hour to about 55,000 pounds per hour, more than 400 percent!

military power at Mach 1.8. This requires supercruise-capable aircraft crews to operate within range of an airbase or air refueling tanker if they believe they *might* need to use their supercruise capability.

Advantages of Maneuverability

Maneuverability has competed with speed as the most prized attribute of fighter aircraft since their creation. During the fighter gun and early missile era, maneuverability was important offensively to gain and maintain firing position against an alerted and maneuvering opponent and defensively in denying an attacker firing position or (later) outmaneuvering early AAMs. Most air combat training, at least through the early 1990s, focused on maneuvering fights within visual range where opponents sought to place themselves in a position of advantage, escape an attacker, or move a fight into a mode where their aircraft had an advantage over their opponents. Indeed, the image of swirling air combat is so tightly linked with fighter aircraft that it is difficult to think of one without the other.

An examination of First Gulf War aerial engagements, however, suggests that, even twenty years ago, advances in sensors, weapons, and networks had greatly decreased the prevalence of maneuvering air combat and with it the value of fighter maneuverability. The proliferation of highly agile "dogfight" missiles, such as the Russian AA-11 and the AIM-9X with thrust vector control and the ability to lock on to targets after launch, along with HMCS, has further reduced the need for maneuvering into firing position even in relatively rare visual range encounters.

Costs of Maneuverability

Just as with speed, there would be no need to reduce the maneuverability of combat aircraft designs if it could be incorporated for "free." Just as with speed, however, adding features necessary for high maneuverability to a combat aircraft imposes constraints that force aircraft designers to make tradeoffs in other areas of performance and add weight and cost to the aircraft. For example, maneuverability is enhanced by a relatively low wing aspect ratio and a high thrust-to-weight ratio to allow for tight turns and sustain energy at high G-loads. Low wing aspect ratio tends to reduce aerodynamic efficiency, and, as previously mentioned, high thrust-to-weight ratios result in inefficient engine cruise performance.[61] High maneuverability also requires strong aircraft structures, and these add significant weight. The load-bearing structure of an aircraft with a design goal of maintaining 9-G turns must be three times

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[61] Wing aspect ratio is the ratio of the square of an aircraft's wing span to the area of the wing. For a given wing area, the longer the span, the higher the aspect ratio. Higher aspect ratio wings allow for lower induced drag and greater cruise efficiency, but have higher bending stress for a given load requiring greater structural weight, assuming similar materials, and generally lower roll rates because they have a higher moment of inertia to overcome than a lower aspect ratio wing of the same area. Lower-aspect ratio wings offer higher roll rates and produce more lift at high angles of attack than high-aspect ratio wings. Both of these factors have received high priority in fighter designs resulting in relatively stubby wings compared to aircraft designed for efficient cruise flight like airliners.

as strong as one designed to sustain only 3-Gs. For any given level of aircraft structure technology, this will make the 9-G structure significantly heavier than the 3-G structure if both aircraft are to have the same range and payload. Since aircraft cost is closely correlated with empty weight, adding maneuverability contributes directly to aircraft cost.

Another potential drawback to high-maneuverability designs is that they require significant vertical tail area to facilitate high-angle-of-attack maneuvering. This was not much of an issue before the advent of stealth technology. However, large vertical tail surfaces add significantly to the side radar cross-section of aircraft.[62] So, while increased maneuverability certainly contributed to the combat effectiveness and survivability of fighter designs in the past, it is much less clear that its future value will outweigh its costs.

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[62] Three-dimensional thrust vector control has been suggested as an alternative to vertical tails to provide the necessary yaw control without the radar cross-section drawback. However, this solution carries penalties of its own in terms of weight, complexity, and cost.

CHAPTER 4

An Alternate Vision of Future Aerial Combat

If the analysis and arguments presented in the preceding chapters are valid, it is possible that a fundamental change in the nature of aerial combat with equally fundamental implications for the relevancy of specific attributes of air combat aircraft design are already underway. This chapter describes a future air combat concept designed to fully leverage trends that benefit superior sensors, weapons, and networks. This concept emphasizes aircraft attributes such as signature control and payload that differ from those of traditional fighter designs. The majority of the chapter presents a series of illustrations showing how such a concept might be implemented.

Maximizing the Most Useful Attributes

The goal of aerial combat is still to achieve a victory, then get or remain outside the effective reach of a potential counterattack. Given the increased importance of sensor, weapon, and network capabilities to success in aerial combat relative to speed and maneuverability, what attributes should a future combat aircraft possess to maximize these factors?

For most of the twentieth century, the primary air-to-air sensor was the human eye. In most cases, large combat aircraft such as bombers could be seen by enemy interceptors long before the bomber crews could see the fighters. During the gun and early missile era, large combat aircraft could not employ forward-firing weapons effectively against smaller and more agile aircraft, and instead they were forced to rely on rotating gun turrets that lacked the accuracy and hitting power of rigidly mounted forward-firing weapons carried by fighters. Defending fighters also enjoyed the advantage of using early-warning networks of ground observers and radars linked to control centers that could direct them to the vicinity of the bombers, whereas bombers operating deep in enemy territory lacked any comparable capability.

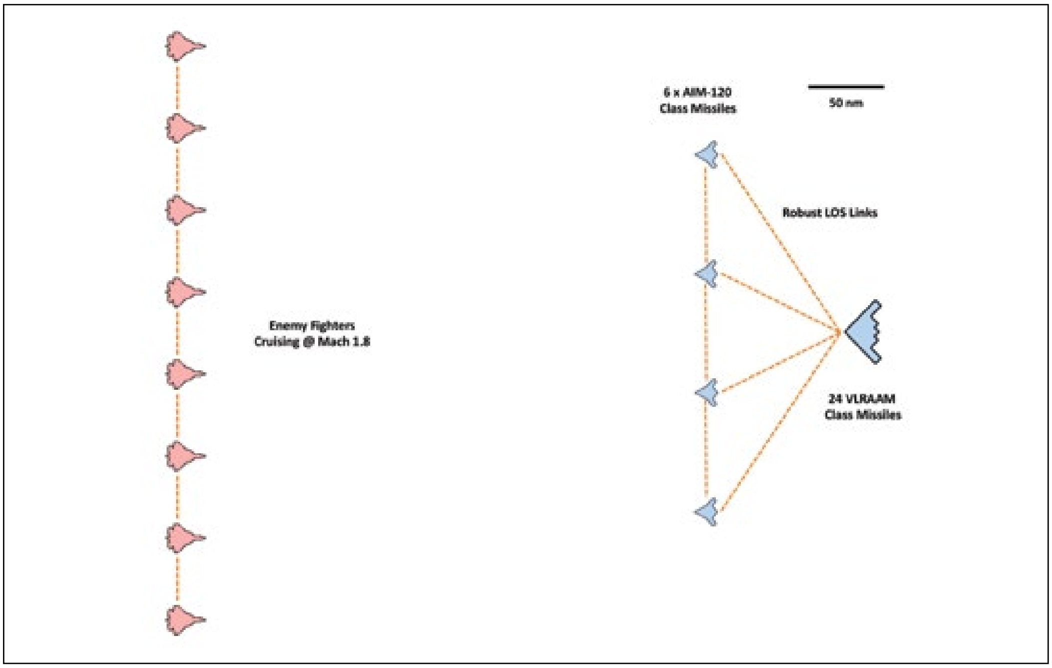
If the future air combat environment consists almost exclusively of BVR missile duels or, eventually, directed-energy weapons engagements, achieving a decisive SA advantage will increasingly depend on the relative ability of the opposing sides to acquire and process long-range sensor data and rapidly integrate it with offboard information provided via data networks. This suggests future SA "building blocks" may differ from those defined in the late 1970s and early 1980s as outlined in Table 5.

TABLE 5. FUTURE SA BUILDING BLOCKS AND ENABLERS

SA "Building Blocks"	Enablers
Information acquisition	Long-range, multi-phenomenology sensors. These will require large apertures and plenty of cooling capacity to maximize performance and should be able to detect and track targets at any aspect, not just in front of the aircraft. IRSTS probably increasingly preferred, as they are passive and immune to DRFM jamming. The same applies to passive RF sensors. Radars will still be important for determining range, NCTR, midcourse missile updates, etc. Offboard information sharing will continue to grow in importance, making robust network connectivity important. Fusing data from multiple sources (active and passive, onboard and offboard) will be vital for early detection and identification of adversary aircraft.
Information denial	The lowest possible radar signature across a wide range of frequencies and from all aspects, known as broad-band/all-aspect (B2/A2) low observability, to reduce the effectiveness of adversary fighter, AWACS, and ground-based radars. Low IR signature to minimize enemy IRSTS detections, which argues against operating aircraft at supersonic speeds. Advanced RF electronic attack systems and IR countermeasures. IR countermeasures are likely to be laser-based systems. Initially these will primarily deceive seekers and sensors, but as laser power improves they will likely be capable of destroying sensor and seeker elements.

The ability to carry a deep magazine of long-range air-to-air weapons with multiple seeker options will almost certainly be vital to success in future air combat. Many of these attributes are much easier to integrate into large aircraft that have greater space and payload available for sensors, cooling, electrical power, and large, long-range weapons compared to small aircraft the size of traditional fighters. The prospect that supersonic speed and high maneuverability have much reduced tactical utility suggests it could be possible to build effective combat aircraft with no large vertical tails to facilitate B2/A2 radar low observability. The increased importance of electronic sensors, signature reduction, RF and IR countermeasures and robust LOS networks in building dominant SA, and the potential reduced tactical utility of high speed and maneuverability could mean that, for the first time, the aerial combat lethality of large combat aircraft may be competitive or even superior to more traditional fighter aircraft designs emphasizing speed and maneuverability. The next section presents a series of illustrations depicting how an appropriately equipped large aircraft could form the centerpiece of a survivable, highly effective aerial combat network.

FIGURE 19. FUTURE AERIAL COMBAT STAGE 1



A Future Vision

This section consists of several illustrations of an imaginary future aerial encounter between a network of U.S. aircraft and a group of stealthy enemy fighters that have supercruise capability. The U.S. network consists of several long-range Unmanned Combat Air Systems (UCAS) optimized to perform as sensor platforms with modest aerial weapon payloads that are coordinated by a human crew on board a stealthy bomber-size aircraft with a robust sensor suite. They are linked by robust LoS datalinks and have the ability to fuse information from offboard sources and their own sensor outputs, as illustrated by Figure 19. Tactically this concept is a marked departure from past and current practice in aerial combat, but seems worthy of further investigation as it extends the trends identified earlier in this report into the future.

As mentioned earlier, radar will remain important, but in this instance, we assume our adversaries are equipped with fighters such as the Russian PAK-FA with greatly reduced radar signature and supercruise capability. Forward hemisphere radar signatures of future fighter threats need not be as small as those attributed to U.S. aircraft in unclassified sources (-30 to -40 dB square meter range) to greatly reduce the range and therefore the utility of radar in future air combat.[63] For example, adversary fighters with radar cross sections of -20 dB (sm) would

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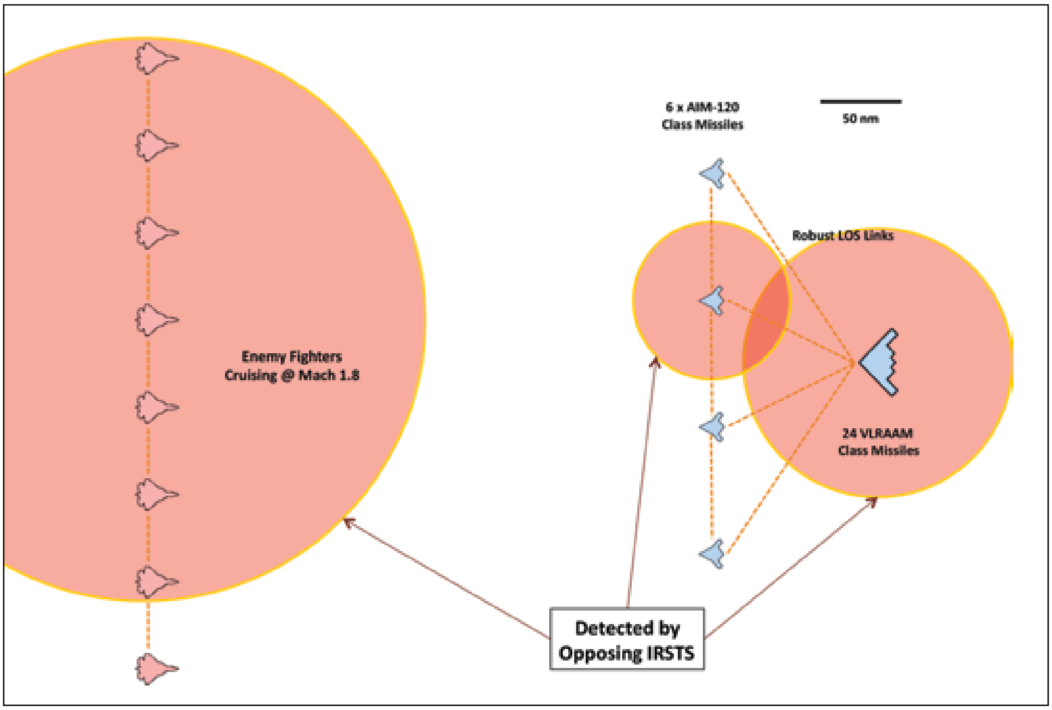
[63] The most widely cited unclassified source gives F-35 RCS as “equal to a metal golf ball” and the F-22 as the same as “a metal marble.” Using standard values for marbles and golf balls these figures equate to about -29 and -37 dB (sm) respectively. See “Warplanes: F-22 Stealth Ability Revealed by USAF,” *Strategy Page,* available at http://www.strategypage.com/htmw/htairfo/articles/20051125.aspx, accessed August 1, 2014.

reduce the effective range of U.S. radars by about 70 percent relative to a modern "fourth-generation" fighter such as the French Rafale.[64]

FIGURE 20. FUTURE AERIAL COMBAT STAGE 2



In this example, all aircraft are assumed to be equipped with an IRSTS that has capabilities similar to the PIRATE sensor currently installed on the Eurofighter Typhoon.[65] Figure 20 shows the relative IR detectability of the three types of aircraft involved in an air-to-air engagement. The shaded circles represent the region where each aircraft can be detected by its opponents. The subsonic manned aircraft is armed with twenty-four 1,500-pound class AAMs with a range of approximately 170 nm.[66]

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[64] Range reduction based on the radar range equation and typical fighter radar cross-section is from "Radar Cross Section (RCS)," *Global Security*, available at http://www.globalsecurity.org/military/world/stealth-aircraft-rcs.htm, accessed August 1, 2014.

[65] "Eurofighter Typhoon," *Starstreak.net*, available at http://typhoon.starstreak.net/Eurofighter/sensors.html, accessed September 30, 2013.

[66] Parametric analysis of BVR missiles fielded since 1990 indicates a 1,500-pound weapon would be capable of achieving 170 nm range. Several missiles in this weight/range class exist, including the Russian/Indian K-100 (160–215 nm range/1,650 lbs) and R-37M [NATO AA-13 Arrow] (160+ nm/1,320 lbs). For comparison, the U.S. Navy's now-retired AIM-54 Phoenix missile had a maximum range of about 100 nm and weighed just over 1,000 pounds. The total weight of twenty-four such weapons and launchers should be within the 40,000-pound payload of the B-2, but might require new rotary launchers.

FIGURE 21. FUTURE AERIAL COMBAT STAGE 3

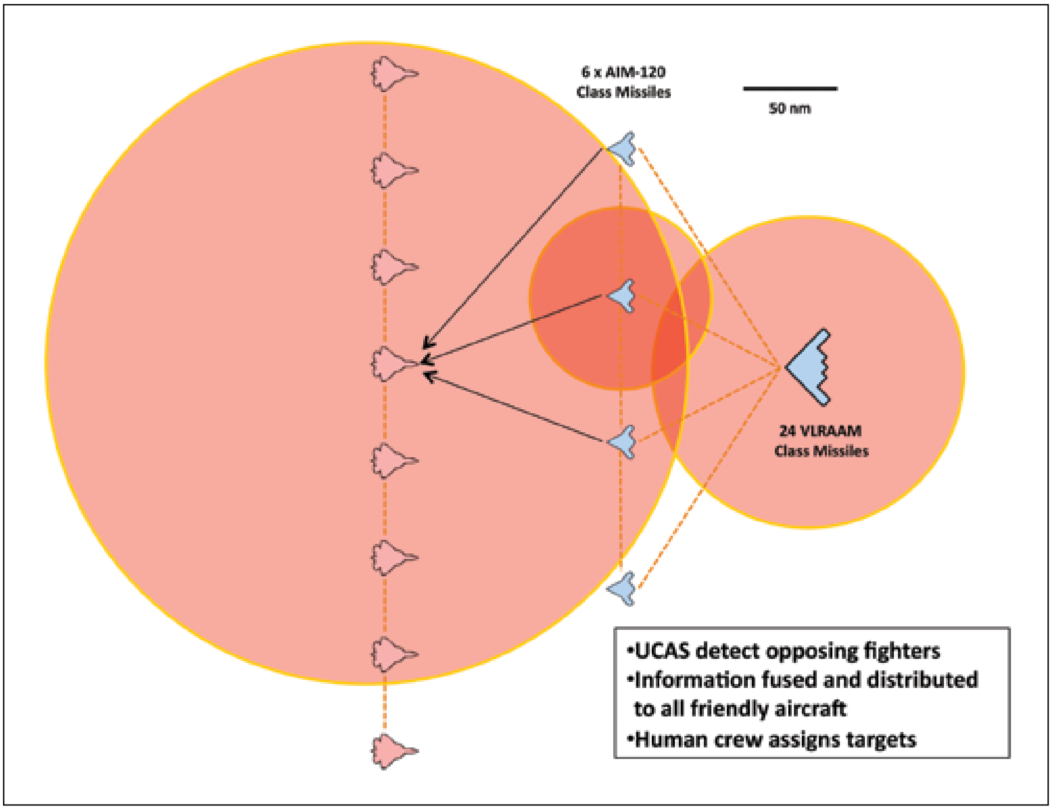
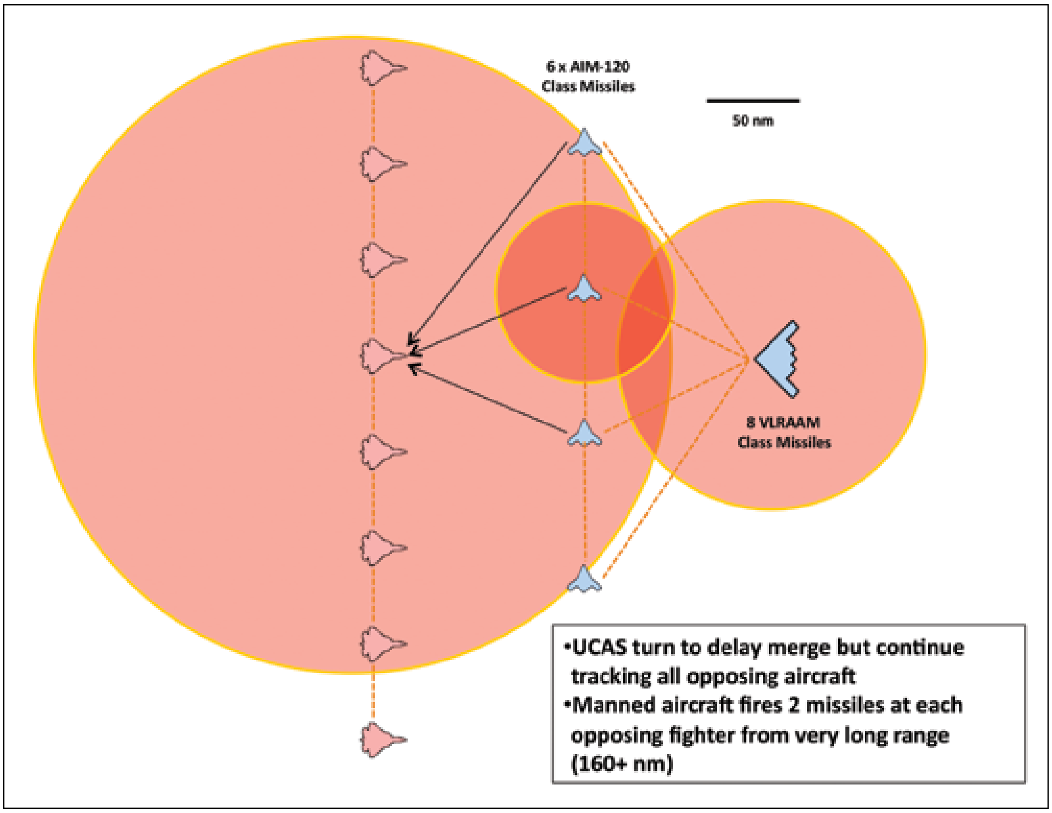


Figure 21 illustrates how networked UCAS and manned aircraft work together to achieve weapon-quality tracks on opposing fighters and assign weapons to targets. Fusing sensor data from multiple widely spaced sources allows onboard systems to rapidly appraise the location, heading, altitude, and speed of supercruising target aircraft or conduct short, highly focused searches with low-probability of intercept/detection radars to generate sufficiently accurate targeting data.

FIGURE 22. FUTURE AERIAL COMBAT STAGE 4



- UCAS turn to delay merge but continue tracking all opposing aircraft
- Manned aircraft fires 2 missiles at each opposing fighter from very long range (160+ nm)

In Figure 22, the UCAS turn to reduce the closure rate and allow time for the very long-range BVR missiles fired by the manned aircraft to reach opposing fighters with time and space left for follow-up BVR engagements if necessary. Positive identification of opposing aircraft will require a combination of measures, but the reduced utility of radar in this regard will likely require a different mix of ID sources. Blue Force Tracker combined with advanced IFF systems, including a completely new encrypted Mode 5, will positively identify most friendly aircraft.[67]

Contextual information will also be important. As discussed below, U.S. aircraft facing significant enemy fighter opposition will often be deep inside enemy-controlled territory and well beyond the effective combat radius of friendly fighters. In some cases they may be able to detect opposing fighters taking off from their bases as E-3s did in Desert Storm. In other cases they may need to rely on other measures. For example, any aircraft cruising supersonically and beyond friendly fighter range can safely be assumed to be an enemy fighter. Modern information networks should also allow each friendly aircraft's assigned mission be kept "up to

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[67] DoD, Operational Test and Evaluation, "Navy Programs," 2009, available at http://www.dote.osd.mil/pub/reports/FY2009/pdf/navy/2009markxiiaiff.pdf, accessed September 30, 2013.

date." This will enable further automatic contextual sorting by assessing whether any friendly aircraft has an assigned mission that would require it to be where an unknown contact is. Finally, U.S. aircraft operating deep in enemy airspace will likely be outnumbered by defending fighters. This turns the "numbers problem" experienced by U.S. fighter pilots during and following Vietnam on its head. If most aircraft aloft are enemy aircraft, odds are high that any aircraft without a friendly IFF and no Blue Force Tracker file is an enemy.

FIGURE 23. FUTURE AERIAL COMBAT STAGE 5

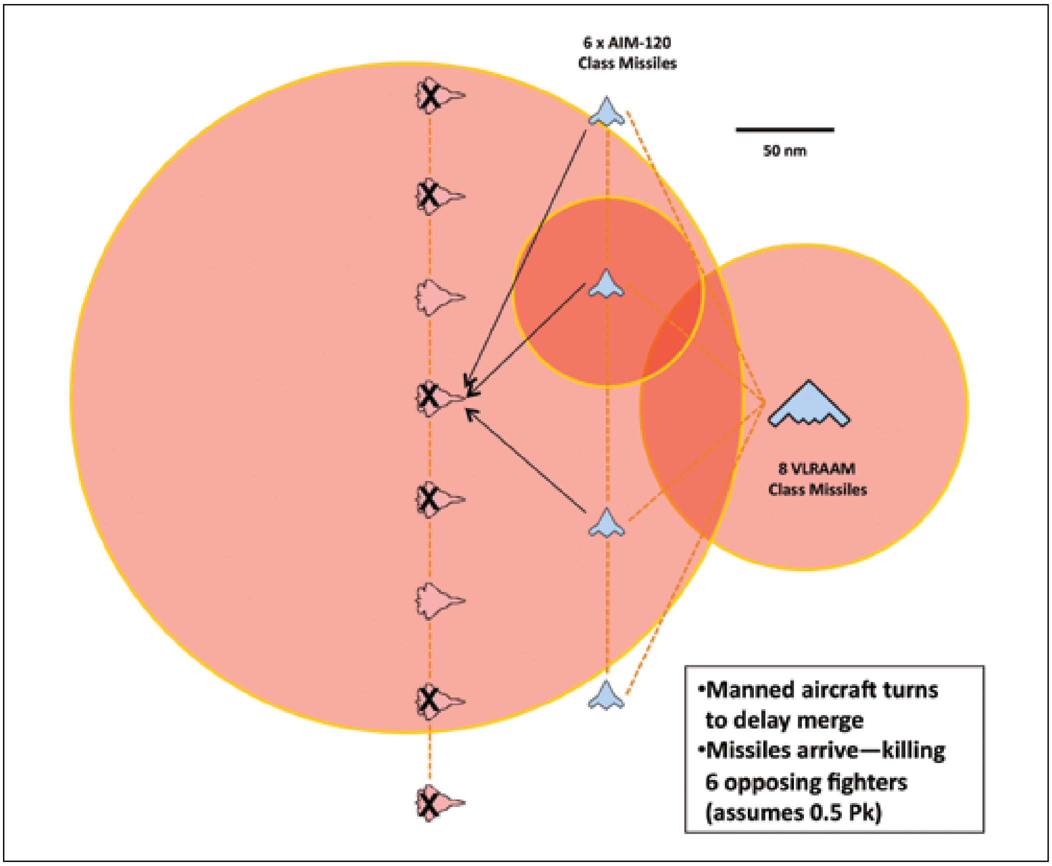

Figure 23 shows the average result of engaging eight enemy aircraft with two missiles each, where the missiles each have a probability of kill (Pk) of 0.5.[68] For this engagement, a Pk of 0.5 would result in six of eight enemy aircraft killed before the opposing fighter formation is able to detect any friendly aircraft.

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[68] Probability of kill, or Pk, is the likelihood a single missile fired at a target will result in its destruction. In this example, a Pk of 0.50 means there is a 50 percent chance each missile fired at a target will destroy it. Firing two missiles at each fighter results in half (4) being hit by the first missile fired at them and of the surviving four fighters, half (2) being hit by the second missile fired at each one.

FIGURE 24. FUTURE AERIAL COMBAT STAGE 6

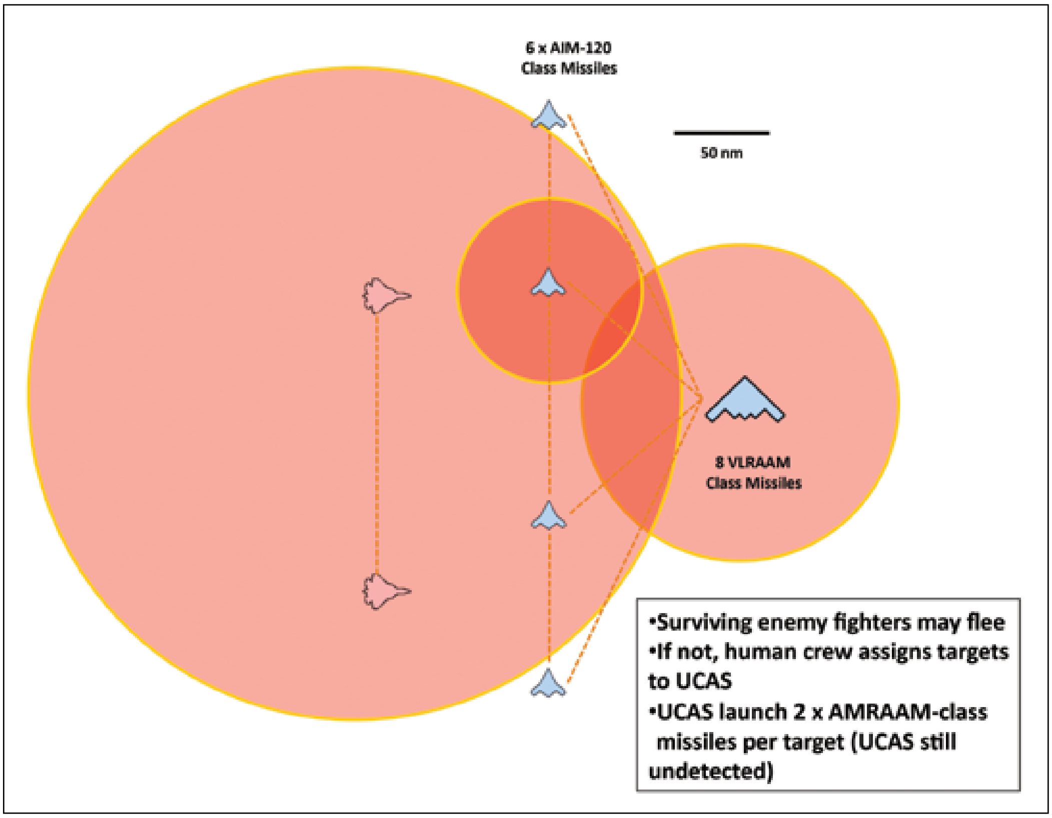

Figure 24 shows the conclusion of the engagement. If the opposing fighters continue to close on the friendly formation after taking 75 percent losses, they could be engaged by additional very long-range missiles launched by the U.S. manned aircraft or by AMRAAM-class shorter-range weapons carried by the still-undetected UCAS. In this illustration, we assume the human crew elects to engage the remaining fighters with two AMRAAM-class weapons each. Again assuming a missile Pk of 0.5, both remaining fighters would likely be shot down. At the conclusion of this example engagement, eight enemy aircraft have been shot down, while friendly aircraft are undetected and have twenty AMRAMM-class weapons and eight very long-range BVR weapons.

The unmanned "picket" aircraft were included to showcase the possibilities of future aerial battle networks and can be thought of as something of a substitute for the sensor (but not C2) capability currently resident in AWACS aircraft, as they extend the "eyes" of the human crew beyond the range of their organic sensors.[69] This will be an important factor in future conflicts that will require U.S. ISR and strike aircraft to operate effectively against enemy fighter aircraft in threat environments that will preclude the presence of non-stealthy assets such as E-3 *Sentry* and other high-value asset (HVA) sensors, C2, and air refueling

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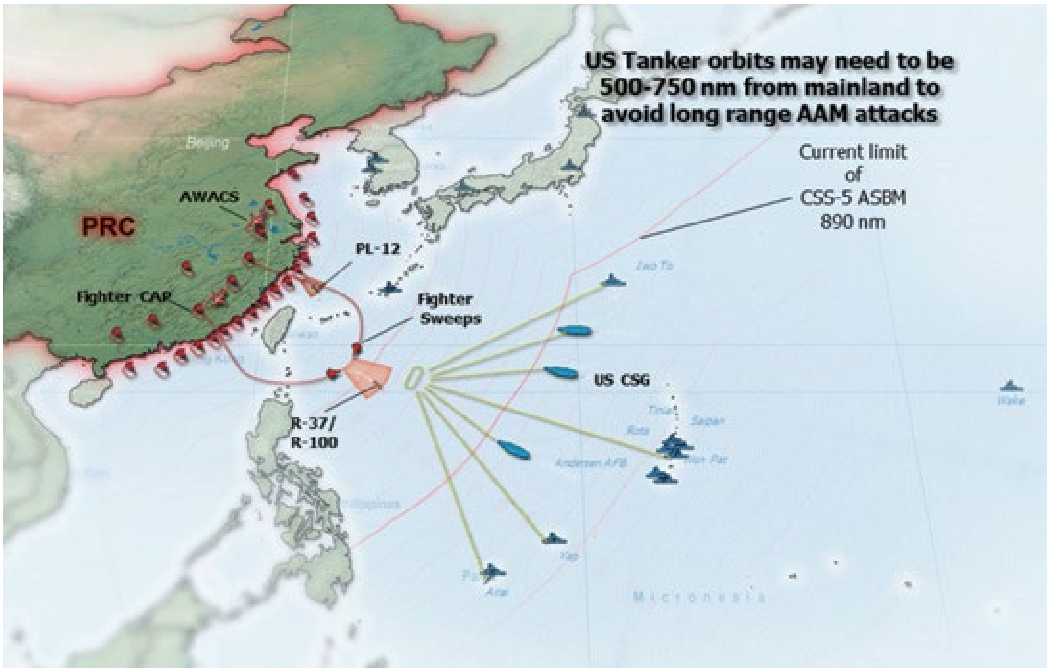
[69] With a smaller overall payload, these aircraft could have unrefueled range sufficient to accompany bombers 1,000 to 1,500 nm into contested airspace.

tanker platforms based on modified commercial transport aircraft (e.g., E-8 JSTARS, RC-135, KC-46A). These large, non-stealthy aircraft will need to remain at least 200 nm from enemy territory to avoid engagements by advanced surface-to-air missile (SAM) systems such as the SA-21 Growler.[70]

Figure 25 illustrates a second class of threats to U.S. HVAs. Until the enemy fighter threat is substantially reduced, refueling operations and HVA orbits could be threatened by enemy fighter sweeps 500–750 nm from enemy territory. The ability of opposing forces to concentrate their anti-HVA attacks in time and space makes protecting HVAs costly in terms of the number of friendly fighters required, and the possibility such an attack might succeed, at least to the point of forcing HVAs to "retrograde," makes persistent HVA operations within the effective reach of opposing fighters unattractive. This is particularly true in cases where the disruption of air refueling operations could greatly decrease the effective range of U.S. fighters.

FIGURE 25. FIGHTER THREAT TO U.S. HIGH-VALUE ASSETS IN THE WESTERN PACIFIC



This suggests that in the future, U.S. combat aircraft needing to operate hundreds of miles inside contested airspace may be at least 1,000 nm or more from friendly HVA support. Without offboard support from AWACS aircraft that proved so helpful to Coalition aircrew in Desert Storm, future U.S. combat aircraft may need to provide wide-area surveillance for themselves by operating as a large "distributed weapon system" with sensors, weapons, and

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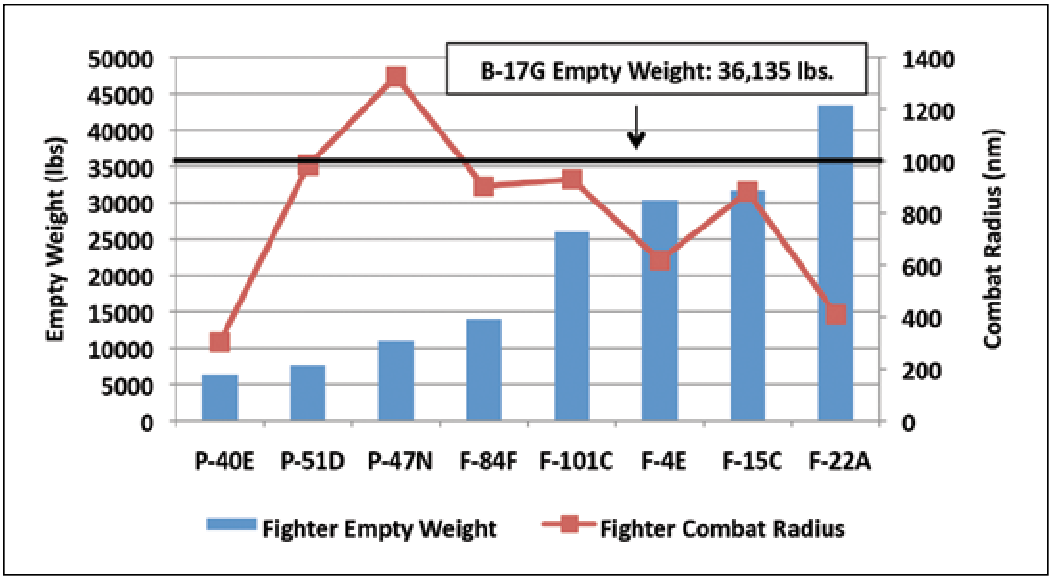
[70] "S-300PMU3/S-400 Triumf/SA-21 Growler," *Global Security,* available at http://www.globalsecurity.org/military/world/russia/s-400.htm, accessed September 12, 2014.

C2 linked by robust line-of-sight communication links. In other words, just as ground forces in the early twentieth century learned that advances in weapon ranges and communications made it both unnecessary and unwise to concentrate their troops in order to concentrate fire, air forces in the early twenty-first century may find advances in sensor, weapon, and network technology make it unnecessary to "concentrate" their aircraft to achieve mutual support.

The requirement to operate against targets and forces 1,000 nm or more beyond friendly tanker support provides additional stimulus for integrating air-to-air combat capability into future long-range ISR and strike systems. U.S. air superiority fighters have grown tremendously in capability over the past seventy years. As new propulsion, structural, and aerodynamic concepts were integrated into designs, their speed, ceiling, and maneuverability increased. Advances in avionics and sensors have vastly improved their ability to search for and destroy enemy aircraft as well as to seamlessly transition from air-to-air to air-to-ground missions. This increased capability, however, has come at some expense. The first is the well-known increase in aircraft unit cost. Closely related is an almost unbroken trend toward ever-higher aircraft empty weight, as illustrated by the columns in Figure 26.

FIGURE 26. U.S. AIR SUPERIORITY FIGHTER EMPTY WEIGHT AND COMBAT RADIUS OVER TIME



The Lockheed-Martin F-22A *Raptor*, the premier air superiority fighter in U.S. service, weighs 43,340 pounds when empty.[71] This is over 35 percent greater than its two immediate predecessors, the F-15C *Eagle* and F-4E *Phantom II*, more than 20 percent greater than a B-17G "heavy

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[71] U.S. Air Force, "F-22 Raptor Fact Sheet," May 8, 2012, available at http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104506/f-22-raptor.aspx, accessed October 2, 2013.

bomber" of World War II, and almost seven times the empty weight of the P-40E fighter used by the United States for air superiority missions when it entered World War II.

The point here is not that the U.S. military needs smaller, less capable fighters in the future, but that adding capabilities traditionally considered as "necessary" for success in aerial combat has steadily increased the empty weight and cost of fighter aircraft. A final "cost" has been a dramatic decrease in the unrefueled combat radius of U.S. air superiority fighters.[72] The availability of aerial refueling capabilities has allowed U.S. air campaign planners to minimize the operational impact of this cost since the mid-1960s. As discussed above, however, should U.S. forces be called on to confront an adversary with a capable and competent fighter force in the future, the distance between locations safe for aerial refueling operations and enemy territory may significantly exceed the combat radius of modern U.S. fighters.

While this situation is bad enough, as it limits the ability of modern U.S. fighters to perform precision attacks against enemy ground targets, it carries an additional operational penalty. Currently, U.S. bombers lack the ability to carry and employ air-to-air weapons. This has not been a significant hindrance to U.S. air campaigns waged over the past two decades against opponents with limited air defense resources. Nevertheless, they would face significant operational limitations if called upon to attack targets guarded by a capable, competent enemy fighter fleet that lay beyond the effective combat radius of modern fighter aircraft. In other words, there is a severe deficiency in the ability of U.S. air superiority fighters to accompany bombers deep into enemy territory to enable sustainable bomber operations in the face of a significant fighter threat. This deficiency is likely to be most acute in the Western Pacific, where the paucity of land bases combined with the serious and growing anti-access/area-denial (A2/AD) threat to both airbases and aircraft carriers makes the ability of U.S. bombers to operate from distant theater bases extremely valuable. Even if, however, the United States never actually faces a conflict in the Western Pacific region, it is likely to face the same dynamic of growing A2/AD threats and the increased need for effective operations well beyond the effective unrefueled combat radius of existing and planned fighters.

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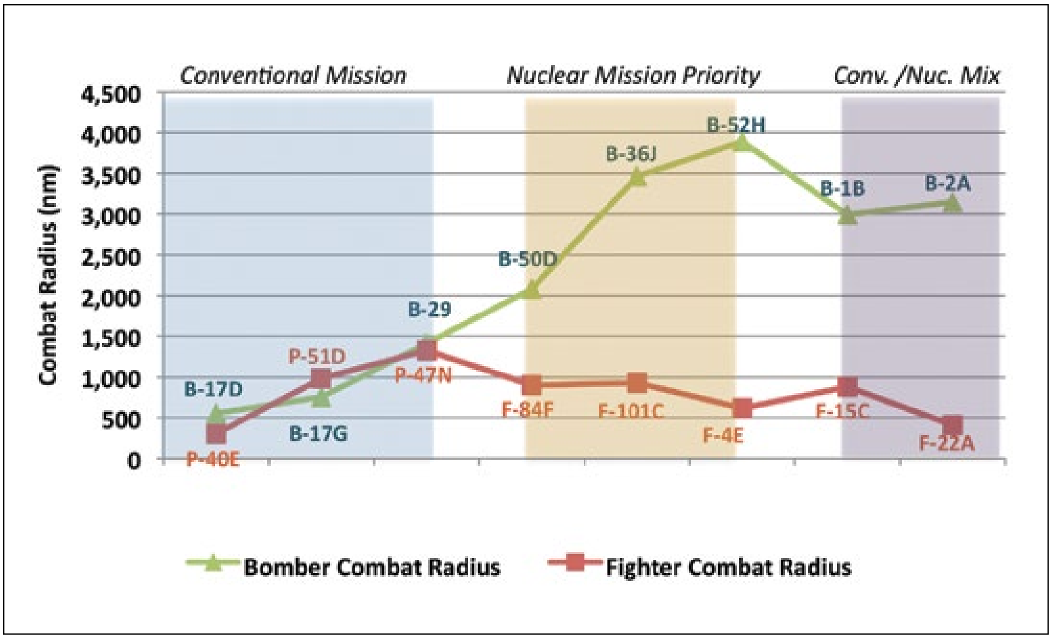
[72] Fighter combat radius assumes a high-high-high profile with two minutes of combat at maximum power for all aircraft except the F-22. The F-22 combat radius assumes a high-high-high profile and a 100 nm supercruise segment. See "Flight Test Data," *F-22 Raptor,* available at http://www.f22-raptor.com/technology/data.html, accessed August 1, 2014. All profiles assume a 10 percent fuel reserve.

FIGURE 27. DIVERGENCE OF U.S. FIGHTER AND BOMBER COMBAT RADIUS POST–WORLD WAR II



How did this state of affairs arise? As Figure 27 shows, the combat radius of late World War II fighters and bombers were well matched. This was no accident, as initial attempts to operate bombers on deep penetration missions into Germany without adequate fighter protection proved unsustainable due to enemy fighters imposing heavy losses. The U.S. response was to field modified versions of the P-51 and P-47 that were specifically tailored to the bomber escort mission. In addition to carrying sizable quantities of fuel in external tanks to extend range, the P-51D and P-47N both had significantly increased internal fuel capacity compared to their earlier variants.[73] Neither of these approaches seems attractive for modern stealthy fighters. The internal spaces of contemporary fighters are already fully utilized for avionics, sensors, internal weapons, and fuel. Adding external fuel tanks could increase fighter range, but because they would significantly increase radar cross sections, they would need to be jettisoned before entering the effective range of enemy air defenses. Modern ground-based air defense systems such as the Russian S-400 (SA-21) can engage targets at up to 200 nm. A stealthy fighter carrying external tanks would probably need to discard them before entering the engagement envelope of such a threat. If the fighter refueled from a tanker operating 400 nm from enemy

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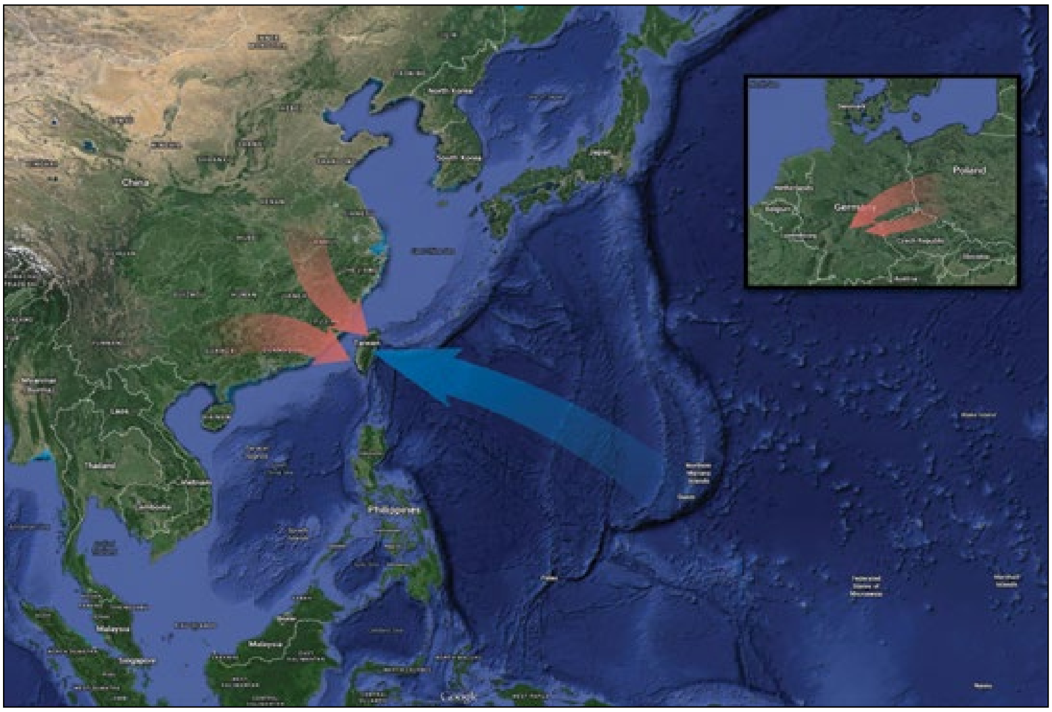
[73] The P-51B/C/D carried an 85-gallon fuel tank in the aft fuselage not included in earlier versions. When full, aircraft center of gravity was very close to the aft limit for stability, and maneuver restrictions were imposed when this tank contained 25 gallons of fuel or more. The same was true of the P-47N. WWIIAircraftPerformance.Org, "P-51 Mustang Performance, P-47N Performance Test," 2006–2013, available at http://www.wwiiaircraftperformance.org, accessed October 2, 2013.

territory and discarded its external tanks 200 nm from enemy territory, then using external fuel tanks would extend its combat radius by just 100 nm.[74]

During the Cold War era, bombers were designed primarily for delivering nuclear weapons against targets at intercontinental ranges. This mission precluded fighter escort, and it would probably not be necessary, as many of the enemy air defense systems and bases would be destroyed by nuclear-tipped missiles long before the bombers arrived to attack their targets. With no requirement to escort bombers, fighters evolved along a path focused on dealing with conventional threats posed by Soviet air and ground forces facing NATO with range and payload attributes optimized for the relatively short ranges along the "Central Front" in Europe. Figure 28 illustrates the vast difference in size between the potential operating area U.S. power projection forces confront in the Western Pacific and the geography of NATO's Cold War-era Central Front.

FIGURE 28. GEOGRAPHICAL COMPARISON OF NATO'S COLD WAR CENTRAL FRONT TO THE WESTERN PACIFIC



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[74] For example, if a stealthy fighter's combat radius on internal fuel alone is 600 nm, and it flew from a tanker 400 nm from enemy territory to a point 200 nm from enemy territory using external fuel, then it could fly a total distance from that point of 1,200 nm. Flying 500 nm from the point it dropped its external tanks would put the aircraft 700 nm from the tanker with 700 nm of fuel left, so it must turn around. Had the fighter not used external tanks it could have reached a point 600 nm from the tanker.

With the reemergence of conventional bomber missions in the post–Cold War era, and especially with the need to retain power projection options in the face of growing A2/AD threats, the need to provide bombers protection from enemy fighters may have returned. Existing fighter designs, however, do not even come close to the combat radius required to effectively enable bomber operations in the face of significant enemy fighter forces. What would it take to build a modern escort fighter?

Based on the Breguet Range Equation, the alternatives available to modern combat aircraft designers for increasing fighter range are improved engine fuel efficiency, improved structural efficiency to allow for increased internal fuel volume, improved aerodynamic efficiency, or some combination of the three. If we postulate a "bare minimum" unrefueled combat radius of 1,200 nm for our future escort fighter and use unclassified performance data for the F-22 as a point of departure for our new design, we get some interesting first-order results.

- Increasing estimated F-22 unrefueled combat radius to 1,200 nm through improved engine efficiency alone would require engines about 62 percent more efficient than the F-119s currently installed. In the sixty-five-plus years since the J-33 was installed in the F-80, America's first production jet fighter, to the F-110 engines of the latest F-15s and F-16s, U.S. fighter engine efficiency improved 39 percent. This makes near-term prospects for a leap in fighter engine efficiency of the magnitude required appear rather dim.[75]

- Increasing F-22 combat radius to 1,200 nm by increasing the fuel/empty weight fraction through improved structural efficiency alone is impossible. With no improvement in engine or aerodynamic efficiency, we would need to find some way to reduce F-22 empty weight enough to accommodate an additional 46,800 pounds of fuel. Since the aircraft only weighs 43,340 pounds empty, this is clearly not possible without increasing maximum takeoff weight.

- Increasing range through increased aerodynamic efficiency alone would require more than doubling the lift over drag (L/D) ratio of the aircraft. This could be done but would require a fundamentally different aircraft shape—one that is more like a commercial jet transport than a stealthy supersonic fighter.[76]

Clearly, a mix of all three approaches would be required to significantly extend the range of a modern fighter aircraft. Initial Breguet Range equation analysis indicates improving all three main components of aircraft efficiency (propulsion, aerodynamic, and structural) by about 33 percent would be required to allow an aircraft with the same empty weight as an F-22 to achieve a combat radius of 1,200 nm. Efficiency gains of this magnitude generally

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[75] "Military Turbojet/Turbofan Specifications," *Jet-Engine,* March 21, 2005, available at http://www.jet-engine.net, accessed October 2, 2013.

[76] Typical fighter aircraft subsonic cruise L/D is between six and eight, whereas modern airliners are in the high teens.

require several decades or more to achieve, suggesting that no aircraft even close to the size and weight of current fighter aircraft will be able to perform even "bare minimum" escort missions. If U.S. tankers must remain 750 nm from adversary territory for safety, then an air superiority aircraft with a 1,200 nm combat radius could penetrate 450 nm into enemy territory at most. A number of potential adversaries with significant strategic depth (China, Iran, Russia, etc.) could leverage this limitation to place important forces and facilities beyond the reach of U.S. strike aircraft by locating them more than 450 nm from their borders. Furthermore, any requirement to arrive before the strike aircraft and remain in the area until they are safely clear would reduce the effective range of the escorts. Finally, as the unrefueled bomber combat radii in Figure 27 show, even tripling the unrefueled combat radius of the F-22 would still not allow it to enable bomber operations at the full extent of their combat radii.

With extremely limited prospects for designing an effective and affordable escort fighter over the next several decades, it seems prudent to seriously examine the possibilities of adding air-to-air combat functionality to future long-range ISR/strike aircraft as an alternative. The potential that large aircraft with the appropriate attributes incorporated in their designs could be effective in aerial combat against traditional fighter designs as discussed above opens the prospect that "self-defending" bombers could fulfill both future ISR/strike missions and some aerial combat requirements as well.

Summary and Conclusion

Since World War I, the goal of aerial combat has been to shoot down enemy aircraft without being detected and engaged. This accomplishment is usually the result of a pilot having superior SA relative to an opponent. Initially, this required attacking fighter pilots to close to very short range, often 50 m or less, either without being seen by their potential victims or being seen too late to avoid being shot down. Aces in both World Wars stressed the importance of superior SA and of surprising the enemy as well as achieving decisive results without being dragged into "low-payoff/high-risk" maneuvering fights. Many of the great aces of World War II, including Gerd Barkhorn, estimated that 80–90 percent of their victims did not realize they were under attack until after being hit. These estimates were validated by extensive USAF analysis of aerial combat during the Vietnam War. The modern embodiment of these time-honored principles is "First Look, First Shot, First Kill."

By the mid-1960s, AAMs opened the possibility of achieving aerial victories without the need to close within visual range of a potential victim or the necessity of maneuvering into tight gun parameters. U.S. pilots quickly found that missiles designed to attack nonmaneuvering bombers at high altitude were much less effective than anticipated against maneuvering fighters at low altitude. These missile performance limitations were compounded by the lack of trustworthy means of positively identifying enemy aircraft BVR and the unreliability of early missile vacuum tube electronics. Despite these limitations, about 75 percent of U.S. aerial victories in Vietnam were achieved with missiles.[77]

Accordingly, the USAF and Navy set about addressing the challenges of employing missiles against maneuvering targets, improving missile reliability, and, perhaps most importantly, developing robust means of identifying enemy aircraft at long range to fully leverage the ongoing improvements in sensor and weapon range. These efforts bore fruit during Operation Desert Storm, where a large fraction of coalition aerial victories were achieved BVR without a single incidence of fratricide. One of the key enablers of this performance was the advent of

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[77] This was partly due to the lack of an internal gun in the primary U.S. air superiority fighter of the day, the F-4 Phantom II. Most of the missile kills were achieved with AIM-9 IR missiles.

AWACS aircraft able to track both friendly and enemy aircraft as well as assist U.S. pilots in identifying their targets and positioning themselves for BVR kills.

Aerial combat over the past two decades, though relatively rare, continues to demonstrate the importance of superior SA. The building blocks, however, of superior SA, information acquisition and information denial, seem to be increasingly associated with sensors, signature reduction, and networks. Looking forward, these changes have greatly increased the proportion of BVR engagements and likely reduced the utility of traditional fighter aircraft attributes, such as speed and maneuverability, in aerial combat. At the same time, they seem to have increased the importance of other attributes, shown in Table 6.

TABLE 6. EMERGING COMBAT AIRCRAFT ATTRIBUTES

Aircraft Attributes of Growing Import	Rationale	Implications for Aircraft Design
Long-range sensors	Information Acquisition	All else being equal, bigger aircraft with their larger available space, weight, cooling capacity, and power allow for larger, more powerful RF and IR sensors with longest possible range.
Good all-aspect signature control across RF and IR regimes and effective RF and IR countermeasures	Information Denial	Subsonic tailless aircraft have significant advantages in achieving these goals. Just as with sensors, larger aircraft are able to carry larger and/or more RF and IR countermeasure systems.
Long-range air-to-air weapons	Kill adversaries before they reach their own sensor weapons employment range.	Larger aircraft enjoy significant payload advantages over smaller aircraft with the same range and should therefore be able to carry more and larger (longer-range) weapons. This applies both to missiles and eventually to directed-energy weapons.
Robust network connectivity	Shared information maximizes SA and leverages all available sensors in the battlespace.	Could be implemented on “fighter-size” or larger aircraft.

If the analysis presented above is correct, it is possible that the desirable attributes of future air-to-air platforms may be converging with those of long-range ISR/strike platforms, or that at least large aircraft with good low observable (LO) characteristics may be able to give a good account of themselves in aerial combat. If this is true, then a sixth-generation “fighter” may have a planform that is similar to a future “bomber” and may even be a modified version of a bomber airframe or the same aircraft with its payload optimized for the air-to-air mission. If this is correct, then the United States may be in position to save tens of billions of dollars in nonrecurring development costs by combining USAF and Navy future fighter development programs with each service’s long-range ISR/strike programs.

Finally, it is important to acknowledge that all of the foregoing discussion is based on certain assumptions plus analysis of past trends, and the future of aerial combat might continue to belong to fast, agile aircraft. The alternative vision of future aerial combat presented in Chapter 5 relies heavily on robust LoS data links to enable widely distributed aircraft to efficiently share information and act in concert to achieve superior SA and combat effectiveness. Should the links be degraded or denied, the concept put forward here would be difficult or impossible to implement. If this is the case, one could argue that the United States would be wise to continue to acquire stealthy fighters in any event. Current program of record plans ensure that both the USAF and Navy will acquire hundreds of stealthy fighters over the next fifteen to twenty years. These will remain in service for several decades more and constitute an automatic hedge against unforeseen technical developments that would render BVR combat less pervasive or the failure of other assumptions underlying this analysis. There are currently no relatively large, stealthy, tailless, subsonic aircraft in production for either service, so combat aircraft force structures will continue to be dominated by fighter-class aircraft for decades to come. Indeed, the serious investigation of the implications of this analysis would seem to be only the first step in a series that could lead to a true discontinuity in aerial combat, which could come to represent an important hedge against the possibility that the analysis presented in this paper is correct.

LIST OF ACRONYMS

A2/AD	anti-access/area denial
AAM	air-to-air missile
ACEVAL	Air Combat Evaluation
ACIG	Air Combat Information Group
AESA	active electronically scanned array
AIMVAL	Air Intercept Missile Evaluation
AMRAAM	Advanced Medium-Range Air-to-Air Missile
AWACS	Airborne Warning and Control System
B2/A2	broad-band/all-aspect
BEF	British Expeditionary Force
BVR	beyond visual range
C2	command and control
CSBA	Center for Strategic and Budgetary Assessments
DoD	Department of Defense
DRFM	Digital Radio Frequency Memory
ECM	electronic countermeasures
GCI	Ground Controlled Intercept
HVA	high-value asset
HMCS	Helmet Mounted Cueing Systems
IAF	Israeli Air Force
IFF	Identification, Friend or Foe
IR	infrared
IRSTS	Infrared Search and Track System
IRIAF	Islamic Republic of Iran Air Force
JSTARS	Joint Surveillance and Target Attack Radar System
L/D	lift over drag
LO	low observable
LoS	line of sight
NCTR	Non-Cooperative Target Recognition
nm	nautical mile
NVA	North Vietnamese Army
ODS	Operation Desert Storm
Pk	probability of kill
PRC	People’s Republic of China

LIST OF ACRONYMS

RF	radio frequency
ROE	rules of engagement
RWR	Radar Warning Receiver
SA	situational awareness
SAM	surface-to-air missile
TISEO	Target Identification System Electro-Optical
UCAS	Unmanned Combat Air System
UHF	ultra-high frequency
USAF	United States Air Force

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