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RF STEALTH (OR LOW OBSERVABLE) AND COUNTER-RF STEALTH TECHNOLOGIES: IMPLICATIONS OF COUNTER- RF STEALTH SOLUTIONS FOR TURKISH AIR FORCE

by

Serdar Cadirci

March 2009

Thesis Advisor: Edward Fisher
Second Reader: Michael Herrera

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This thesis will examine the evolution of stealth, with a focus on RF low observables, and the counter technologies to detect RF stealth or low observable aircraft, the reasons why an air force needs such technologies, advantages and disadvantages of these assets, and the latest developments in the area.

While low observable technologies have been around for nearly half a century, they are still secretive in nature and sensitive. This poses problems when conducting unclassified research in this field; nevertheless, this thesis will address technological details that enable the operational use of stealth assets by examining open sources.

Counter-stealth technologies are increasingly relevant, and research in this field is ongoing around the world. This thesis will give information about these efforts and will also discuss the possible solutions that can be applied to a complex air defense network.

Finally the thesis will focus on the Turkish Air Force's possible counter- RF stealth requirements and the evaluation for the desired solution.

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RF STEALTH (OR LOW OBSERVABLE) AND COUNTER- RF STEALTH TECHNOLOGIES: IMPLICATIONS OF COUNTER- RF STEALTH SOLUTIONS FOR TURKISH AIR FORCE

Serdar Cadirci
First Lieutenant, Turkish Air Force
B.S., Turkish Air Force Academy, 2001

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NAVAL POSTGRADUATE SCHOOL
March 2009

Author: Serdar Cadirci

Approved by: Edward Fisher
Thesis Advisor

Michael Herrera
Second Reader

Dan Boger
Chairman, Department of Information Sciences

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DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Turkish Republic, the Turkish Armed Forces, the Turkish Land Forces, the Turkish Naval Forces or the Turkish Air Force.

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I. INTRODUCTION

The future is bright, the future is stealth [1]*…*

Stealth technology is considered modern and sophisticated, but there are several examples of stealth found in nature. Visual stealth is demonstrated in nature by camouflage. One of the simplest and best examples is the change in color of insects as they blend into their backgrounds. Without a doubt, humans were inspired to use stealth in order to deal with dangers found in nature from defeating wild animals while hunting, to fighting in wars, evolving this capability into the combat arena.

At the beginning of the twentieth century, rapid advancements in aviation made it possible to use aircraft in combat. There were several advantages to this; but aircraft were vulnerable to attack from the ground, sea and air. Many technologies were introduced to overcome this vulnerability. One of the most promising focused on reducing the visibility of aircraft and was referred to as visual stealth. Germany pioneered the construction of less visible (ideally invisible) planes before and during World War I (WWI). They developed a synthetic material, called cellon, which was used to make aircraft transparent; however, this resulted in limited success because in some cases the aircraft were more visible than desired. During World War II (WWII), visual stealth was employed by the United States on Project Yehudi. In this case, bright lights were deployed along the leading surfaces of the TBM-3D Avenger aircraft. The brightness of these lights could be adjusted to deceive an opponent by disguising an aircraft against the background sky, thus reducing the aircraft's visual detection range from twelve to two miles. Later during the war, the B-24 Liberator bomber was adapted with "Yehudi lights" for submarine attack missions. During the Vietnam War, counter-illumination technology was again employed in the Compass Ghost project, where F-4 Phantom fighters were modified with lights, apparently resulting in some success [2].

After its invention, radar became the most accurate method for detection of aircraft, and countries developed new tactics and projects to defeat it and hence increase survivability. Bomber Command's de Havilland Mosquitos (Figure 1) had the lowest loss rate of any WWII bomber. This was attributable to its high speed, high altitude and to some extent its low radar reflectivity, a result of the bomber's wooden sandwich construction. Germany's Horten HoIX V2 (Figure 2) design achieved lower detectability by a combination of its external shape and the use of integral radar absorbent materials (RAM). The Horten design was the origin of all flying wing, RAM and radar cross section (RCS) based designs [3].

Figure 1. Bomber Command's de Havilland Mosquitos (From [4])

Figure 2. German's Horten HoIX V2 (From [5])

Later, more developed low observable technologies are used in U-2R, SR-71 (and CIA's A-12), B-1, F-117, B-2 and finally F-22. Today stealth is an indispensable technology, not only for modern military aircraft, but also for other military assets, such as ships (Visby), helicopters (RAH-66 Comanche), and unmanned air vehicles (UAVs), (X-45).

A. AREA OF RESEARCH

This thesis will examine the evolution of stealth, focusing on radio frequency (RF) signature reduction methods and RF low observable aircraft counter detection technologies. Furthermore, this thesis will examine an air force's requirements for such technologies, the advantages and disadvantages of these low observable or counter stealth technologies, and the latest developments in these areas.

While low observable technologies have been around for nearly half a century, they are still secretive in nature and sensitive. This poses problems when conducting unclassified research in this field; nevertheless, this thesis attempts to address technological details that enable the operational use of stealth assets by examining open sources.

Counter-stealth technologies are increasingly relevant, and research in this field is ongoing around the world. This thesis will provide information about these efforts and will also discuss possible solutions that can be applied to a complex air defense network.

Finally the thesis will focus on the Turkish Air Force's possible counter-RF stealth requirements and an evaluation of potential solutions.

B. MAJOR RESEARCH QUESTIONS

This study seeks to answers the following questions:

1. Primary Question

a. What objectives should the Turkish Air Force pursue in the area of counter RF stealth?

2. Subsidiary Questions

a. What is stealth and what is meant by low observable?

(**1**) What is the historical background of stealth?

(**2**) What are the capabilities of stealth?

b. Why does an air force need stealth technology?

c. What are the technical details of RF stealth?

(1) How is the radar cross section (RCS) of an object decreased?

(2) What is meant by the RCS shape factor?

(3) What are the technical details of a non-metallic air frame and RAM?

(4) What are passive and active cancellation systems and how are they employed?

d. What are other signature reduction methods?

e. What are the challenges involved in building a stealth aircraft and are there any operational disadvantages?

(1) What is the cost impact?

(2) What are the operational and maintenance difficulties?

f. What counter-stealth technologies can be used to detect low observable aircraft?

(1) What are the most promising technologies and techniques to detect RF low observable systems?

(2) What are the advantages and disadvantages of these counter stealth technologies and techniques?

C. LITERATURE REVIEW

Stealth technology, or more correctly, low observable technology, includes various methods to hide or make assets less detectable (ideally less visible) from radar, infrared or other sensors. This technology provides the user a significant advantage over his adversary by making it more difficult for an adversary to detect an opponent. This enables the user to conduct surprise military missions and ultimately results in an increase in his survivability.

When stealth is implemented effectively, aircraft can dominate in combat; however, there are technologies and techniques that defenders can invoke to detect and counter attack stealth aircraft. Early on, the only aircraft detection methods were either based on visual or acoustic technologies. The reduction of detection range was important to increase aircraft survivability and for mission success. Military aircraft operators concentrated their early counter detection efforts on making aircraft less visually detectable, because visual detection was likely to occur before acoustic detection. Camouflaging and illuminating techniques were the most useful of these methods.

Later, defenders significantly increased their detection capabilities with the invention of radar. Radar gave users awareness of an opponent's incoming air assault much earlier than before. Radar not only provided users the ability to implement an effective defense, but also enhanced their ability to conduct counter attacks, both of which resulted in a decrease in the success of enemy air operations. However, there were some vulnerabilities of radar. Aircraft developers implemented new production methods and techniques to exploit limitations of radar. These resulted in "low observability" against radars. Further advancements in low observability technologies resulted in "stealth" capabilities, allowing aircraft to fly into enemy territory with immunity versus the radar threat.

Stealth technology has been refined and evaluated for nearly half a century. It has been used operationally for more than twenty years. However, stealth technology is still a sensitive subject. Due to its secrecy, this technology is typically protected under "black" programs [6]. This is done, first, to protect the technology from exploitation by other countries and to ensure dominance and sole possession of the technology, and secondly, to hinder the development of counter tactics against low observable technologies. However, the science and physics which underpin stealth technology are not secret, and are openly discussed in literature.

Currently, stealth technology is one of the main electronic countermeasures used to make aircraft, ships, helicopters, UAVs, missiles and other military vehicles less detectable. It is a military research and development priority. Any missions which can be served well by incorporating low observable technology are being driven in that direction. Table 1 provides examples of operational and demonstration projects based on low observable technology for aircraft, UAV and surface vessels.

All military platforms have visual, radar, thermal (infrared), and acoustic signatures. Stealth reduces these signatures and there are several methods used to accomplish this reduction [7]. This thesis discusses all of these but focuses primarily on radar (RF) signatures.

Operational and Project Aircraft/UAVs	**Ships**
F-22A Raptor (USA Fighter Aircraft)	Swedish Visby Class Corvette
F-35 Lightening II (USA Fighter Aircraft Project)	Dutch Zeven Provinciën Class Frigate
Sukhoi PAK FA (Russian Fighter Aircraft Project)	Norwegian Skjold Class Patrol Boat
Sukhoi S-37 Berkut (Russian Fighter Aircraft)	French La Fayette Class Frigate
J-XX (China’s Fifth Generation Fighter Aircraft Project)	German MEKO Ships Braunschweig Class Corvette And Sachsen Class Frigates
Medium Combat Aircraft (MCA-India’s Fifth Generation Aircraft Project)	Indian Shivalik Class Frigate
Mitsubishi ATD-X Shinshin (Japanese Fighter Aircraft Project)	Singaporean Formidable Class Frigate
Boeing X-45 (UAV Variants)	The U.S. Navy's Zumwalt-Class Destroyer
The BAE Systems Taranis (UAV)	British Type 45 Destroyer
The Dassault Neuron (UAV)	Finnish Hamina Class Missile Boats

Table 1. Examples of Operational and Demonstration Projects Based on Low Observable Technology for Aircraft, UAV and Surface Vessels

In the physical world, platforms that implement RF stealth technology are not invisible to radar. This technology reduces the detection range analogous to camouflage tactics. When applied to aircraft, this method is referred to as radar cross section (RCS) reduction. Using this method, the return signal from a target to the radar is so small (on the order of a bird's radar signature or smaller) that it is not detected as a threat.

To achieve RCS reduction, four approaches are used. The first one applies shaping features. In a conventional radar configuration, the transmitter and receiver are collocated, so the stealth platform is shaped to reflect the incoming radar signal in a direction other than directly back to the radar. The second approach seeks to absorb, cancel or scatter the incoming radar transmitter signals so as not to reflect them to the radar receiver(s). This is accomplished by the application of special coatings to the platform's body or using special composites or materials in platform construction. The third technique implements passive cancellation. Cancellation is achieved by adding a skin to the surface of the platform which acts as a secondary scatterer and cancels the reflected field from the primary target [8]. The fourth technique implements active cancellation of incoming radar signals. Technologies, including the use of platform-mounted active transmitters, are employed that mask and cancel out these signals. One additional approach involves the absorption of RF signals using a plasma layer, formed with ionized and conductive gas particles. There are not many applications of this technique; however, some scientists consider it promising for future low observable designs.

Various countermeasures can be used to detect high technology RF low observables. Bistatic, multistatic or low frequency radars are possible solutions. Furthermore, with their look-down ability, high altitude airborne and spaced based radar systems have some geometrical advantages over stealth assets. Networked detection systems are also promising new solutions to countering stealth. Processing data from multiple nodes would improve signal to noise ratio by means of effective quantity of transmitter or receiver, together with variability of types and deployment geometry. Each technique has some capability for detecting low observables.

Another solution to counter stealth is based on using passive receivers. A cell phone network can be used, conceptually, in a fashion similar to a multistatic radar network. This method involves using cell phone transmitter nodes, spread out widely in a defended area, for gathering the different RF signals scattered from a low observable vehicle's surface. Using high speed computers and processors within an air defense system, the data from the various cell phone base stations can be processed to gain positional and tracking information on the stealth targets [9].

As stealth technology evolves and new approaches are developed to maintain stealth's "ghost-like" advantage, the counter stealth world will have to counter. This will require an in-depth understanding of stealth technologies, radar knowledge and electronic warfare principles.

D. IMPORTANCE AND THE BENEFITS OF THE STUDY

Although this subject is very scientific and electronic warfare-focused, this thesis explains concepts simply and clearly with figures, graphs and tables, so readers with little knowledge of the basic science will have little trouble understanding the principles behind stealth technologies. The reason for this approach is that the study is intended to be easily understood by non-engineers and other non-technical individuals with little or no electronic warfare (EW) training, education, or background. By adopting this approach, the author hopes to broaden the number of targeted readers.

The results of this thesis may be used to support ongoing and future efforts by the Turkish Armed Forces to apply electronic warfare methods against modern threats. This study should enhance the perspective and knowledge of electronic warfare officers, related project officers and technical personnel. Furthermore, research and results will assist the Turkish Armed Forces in evaluating future needs and requirements of electronic warfare systems.

E. ORGANIZATION OF THE THESIS

This thesis is composed of five chapters. Chapter I provides an introduction and overview of stealth technology by literature review.

Chapter II presents the historical background and evolution of stealth technology and provides information about the requirement of stealth technology in modern military forces.

Chapter III explains the fundamentals of low observable technology. The design processes for reducing the detection range of radars will be the main focus. Other stealth research and application areas concerned with making assets less detectable (ideally non observable) to the eye (visible world), acoustic sensors and infrared detectors will be explained. Some modern assets which use these technologies will be reviewed with a presentation of their specifications and pictorial representations. Lastly, both limitations and complications of producing and operating stealth assets will be examined and a report of their effectiveness will be provided.

Chapter IV details counter RF stealth technology. Primary counter stealth radar applications and their advantages together with limitations over stealth, such as accuracy problem of radars for tracking systems, will be explained. Furthermore, a table will be presented that outlines these technologies.

Chapter V is the conclusion chapter. This chapter addresses the question of "which counter RF solutions should be recommended to the Turkish Air Force to defend its home land and improve its combat capabilities in the twenty-first century?" This is done by analyzing the information provided in Chapter III and IV.

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II. STEALTH IN MILITARY AVIATION

It was not possible to create an aircraft invisible to early warning or missile guidance radars, but in combination with high speed, high altitude, maneuvering, and electronic countermeasures, a very high degree of survivability has been obtained in service [10].

A. HISTORICAL BACKGROUND OF STEALTH TECHNOLOGY

When stealth is used in military terminology, it describes a quality that gives someone or something the characteristic of being undetectable. In military aviation, stealth refers to an asset aided with novel technologies to improve its mission survivability by elimination of adversary detection capability from all possible sensors. The term low observability, which is preferred in technical and formal jargon, is defined as a degree of achieving the total stealth ability. Various classes of stealthiness are used to indicate the degree of undetectability an asset possesses. These classes increase in stealthiness in the following order: low observables, very low observables and stealth. Sometimes low observability refers to the steps taken to achieve the total goal of stealth. However, because it is impossible to reach complete undetectability, many publications use the terms of low observable and stealth interchangeably. This approach is sound if it is considered that, in practice the degree of low observability always changes, especially with the advances of counter stealth technologies. Thus, in an attempt to simplify the subject and to avoid confusion, the terms low observable and stealth are used synonymously in this study.

Aircraft survivability is based on successful accomplishment of the mission and return to base. It is significantly increased with the aid of stealth technology and many efforts have been made to develop and improve these technologies. The challenge in these developments is competing with the continuous improvement of detection capabilities. The sensors involved in detection cover methods and production of visual, acoustic, magnetic, infrared (IR) and radio frequency (RF) baselines. Because radar, since its first deployment, still remains as the most powerful way to make the earliest and most accurate detection, measures to improve low observability are more focused on RF signal reduction. Therefore, this study will focus on RF stealth and counter stealth, although other signal reduction techniques are introduced. Likewise, historical background discussions will be concerned with methods of defeating radar signals. It should not be forgotten that the reality of an effective stealth aircraft requires the reduction of all sensor signatures (visual, acoustic, magnetic, IR, and RF).

From a historical perspective, the first attempt at applying stealth principles was the use of visual camouflage to conceal aircraft against airborne or surface forces. WWI and II designs presented many ingenious visual camouflage capabilities which also proved operational successes. However, after the invention of radar, aircraft could be detected from a distance, negating much of the effectiveness of visual camouflage. After WWII, political tensions required that the U.S. develop new aircraft which could penetrate deeply into the Warsaw Pact’s territory for reconnaissance missions. The low observable capabilities of these spy planes or remotely piloted vehicles (RPVs) proved to be one of the most indispensable capabilities to ensure survival against a growing surface-to-air missile (SAM) threat. Later, stealth technology was designed into strategic bombers and tactical fighters, because penetrating with surprise gave the attacker more time to perform the mission and exit before the defending force’s counter-attack. Currently, new aircraft, such as the F-22 Raptor, are being developed for air superiority to dominate all airspace.

As mentioned, the requirement for low observable aircraft to avoid any type of sensors in the military aviation world came about nearly with the use of the first aircraft in war. However, discussing the entire stealth history is not intended. In this context, some remarkable examples in the RF stealth world will put forward in this study to present the brief historical background of this technology. These examples are the most significant attempts to achieve low observability goals together with contribution to future designs.

1. Horten IX Flying Wing (1944-1945)

It has never been completely proven that the Horten IX Flying Wing's (Figure 3) unusual shape and airframe characteristics reduced its RCS, even to less advanced radar sensors during the WWII era. However, it is certain that there were many ingenious design specifications of the Horten brothers' 0.92 mach, 620 nm., combat-radius, 1930s' bomber that would inform subsequent low observables' design priorities [11]. Radical flying-wing airframes with no vertical surfaces, extensions of trailing edges, solid plywood wing skins, steel engines and steel-tube substructures concealed under the absorbent skin of the fuselage and engine exhausts on top of the wing were some of these specifications [3]. Although designed and tested, it never flew operationally. The HO-IX V2 was the only powered aircraft to fly and it was destroyed during testing [3]. The HO-IX V3 was completed but never flew. However, when the prototypes and design schemes were captured by U.S. Forces in 1945, it was discovered that future production aircraft would have a wood/plastic laminate structure [12] and "…sandwich skin with a material derived from charcoal, sawdust and glue matrix (early RAM) to be used in the core to absorb radar energy [13]."

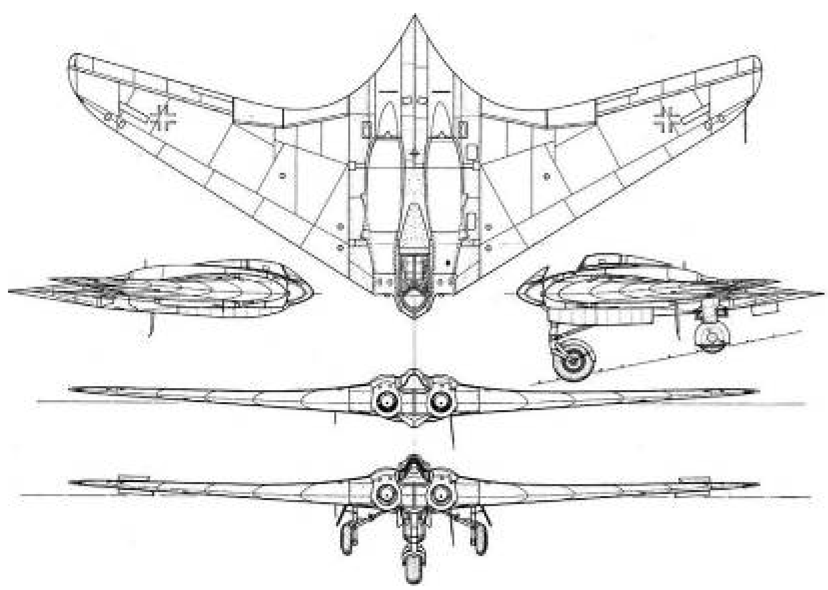

Figure 3. Horten IX Flying Wing
(From [14])

2. Lockheed U-2 Dragon Lady (1958-1960)

When the Central Intelligence Agency’s (CIA) U-2 (Figure 4) strategic reconnaissance aircraft was designed in the 1950s, the specifications required an aircraft that could fly over Soviet airfield with some operational capabilities to provide minimum risk of being shot down [13]. Low RCS was never proposed as a chief design factor. The main purpose of the program was to build a plane which could fly at an extremely high operational altitude, on the order of 70,000 to 90,000 ft. Soviet radars and weapons systems were considered incapable of reaching such high altitudes. Although particular U-2 models had different service ceilings, aircraft achieved flight at high altitudes with cruise speeds of around 460 mph and a maximum range of 2,200 to 3,500 nm. Furthermore, flying radius could be increased with external fuel [15].

Figure 4. U-2 Spyplane
(From [16])

When deployed operationally over Soviet Union airspace, it was discovered that Soviet radars could detect the U-2 and development of a missile which could also reach the aircraft’s service altitude was just a matter of time [13]. As a result, radar absorbent materials were placed on the surface of the aircraft and printed circuits were used to counter S-band radars. Moreover, in order to defeat low frequency (70 MHz) radar signals by cancellation methods, the leading and trailing edges of the wing and tail surfaces of the aircraft (Figure 5) were fitted with wires at a distance of quarter-wavelength away [13].

These upgrades did not give the desired results since they were effective at only specific frequencies and other frequencies could still be used to detect the aircraft. Even worse, some of these modifications reduced the aircraft's operating altitude to less than 60,000 ft., which increased the risk of threat missiles. Later U-2 models, such as the U-2R and TR-1 variants, were more successful at RCS reduction by employing flat-black iron ball RAM coatings and small, red, low visibility markings [15]. These efforts taught manufacturers that if an effective low RCS design was desired, the asset should be designed with this purpose from the very beginning of the project [13].

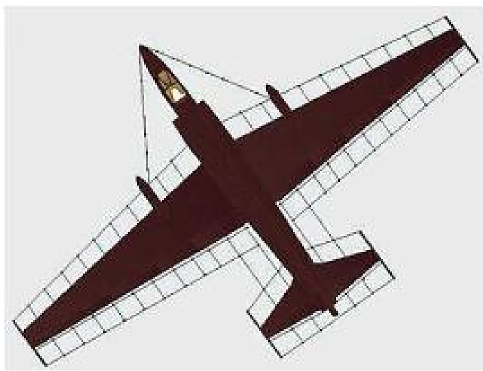

Figure 5. Trapeze Modification of U-2s (From [17])

3. Teledyne Ryan's RPV Designs (BQM-34A (1960), AQM-91A Compass Arrow (1969), Low RCS Vehicle (1973-1974 Design Study), Mini-RPV (1974-1975))

One of the best known attempts by the Soviet's to counter U.S. reconnaissance operations was the successful shoot down of a U-2 over Russia on May 1, 1960. This event caused the U.S. to make a very important political and diplomatic decision; abandon manned overflight of foreign territory. However, the need for intelligence gathered by U-2s or later A-12s was still indispensable. The solution was reconnaissance satellites which were operated very far from enemy fire and did not risk the capture of an aircraft pilot. However, satellites exhibited a number of operational disadvantages. They were expensive and slow to fill the desired deployment, had limited mission life, and ineffective operation conditions with the technology of those times. Furthermore, relocating satellites to monitor desired targets at specific times was either prohibitively expensive or impossible during certain time, and satellite sensors were not able to collect certain types of desired data [3]. These disadvantages made another solution more suitable; remotely piloted vehicles, the earlier form of unmanned air vehicles, UAVs (or unmanned air systems, UAS) [3].

This new approach provided Ryan Aeronautical, the producer of several types of Ryan Firebee RPVs, the opportunity to offer the U.S. Air Force (USAF) a new version of its designs which would have low RCS capabilities to accomplish reconnaissance missions. The Ryan Firebee RPVs were air-launched or ground-launched and were used as target drones or unmanned air vehicles from the 1950s to 2000. A wire mesh screen over the inlet and RAM [13] in some parts of the body were used in the BQM-34A (Figure 6), the later version of the Firebee (Q-2A and other versions (Figure 7)). By incorporating these design modifications, coupled with the advantage of being smaller than a manned aircraft, the model achieved some RCS reduction. However, it was again demonstrated that significant RCS reduction could not be achieved by manufacturing upgrades, but was only feasible when considered from the base design [13].

Figure 6. The BQM-34A
(From [18])

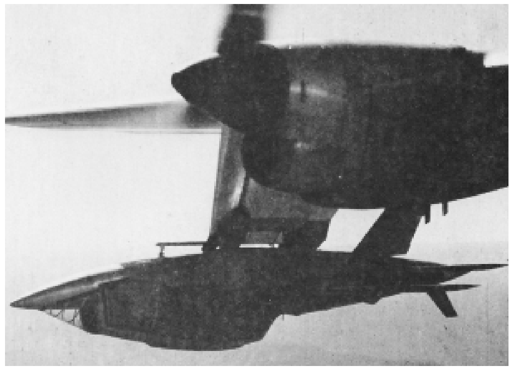

Figure 7. Q-2C, a Variant of BQM-34, with Kind of RAM Blankets and Wire-mesh Fairing
(From [6])

The U.S. concern with Chinese nuclear development and testing facilities in the mid-1960s gave a new motive for designers to work on high altitude, long range reconnaissance RPVs. This was driven by the inadequate quality of existing satellite data. Furthermore, U.S. U-2s, some of which were operated by the Nationalist Chinese Air Force (CAF, Taiwan), were very vulnerable to Chinese SAMs [19].

After several unsuccessful attempts by the Lockheed D-21 (D-21 will be discussed in following sections), the Teledyne Ryan AQM-91A Compass Arrow (Figure 8), high flying, unmanned, photo reconnaissance aircraft, was selected to fulfill the mission. Some new approaches to stealth design were considered while manufacturing this RPV. To ensure a small RF signal return back to SAM and other tracking radars, vertical surfaces of Compass Arrow were canted inward, and its lower surface was designed flat. Additionally, RAM and plastic composites, which had less radar reflectivity than metal, were used effectively in many skin parts as in earlier designs. Moreover; the engine was fitted on the upper side of the fuselage and the engine exhaust was mixed with cool air, both of which helped to reduce its IR signature from ground threats. The aircraft also carried electronic countermeasures for anti-radar purposes.

The AQM-91A was designed to be carried by and air-launched from a DC-130E Hercules aircraft. After separation, it would fly to around 78,000 ft altitude and self navigate with its internal Doppler guidance system. If desired, it could also be piloted manually by an operator in the mother-ship. Completing the mission, the vehicle would fly into a safe area by a microwave command system, and be grasped in mid-air by a helicopter after deploying its parachute for recovering. With its conventional design and some newly produced low observable concepts, the Compass Arrow achieved test successes. An improved relationship with China made deployment of this asset unnecessary, and it was never used for its design objectives. Despite a significant investment, the money spent would not be wasted and helped very much in the creation of later stealth designs [20], [21], [22].

Figure 8. Teledyne Ryan AQM-91A Compass Arrow (From [23])

The demands of the Cold War provided an impetus to make drones stealthier. Success in this area was not achieved until the 1970s. However, counter designs and advancements in the Warsaw Pacts' SAM and radar technology required assets to have extended stealth capability which covered wider frequency bands of interest.

Teledyne Ryan's low RCS vehicle design of 1973-1974 (Figure 9) attempted to address these issues. Because conventional wing-body-tail surfaces, up to that date, did not have very low RCS, the new design required flying delta wings with two inward-canted vertical tails and "a small metal center body surrounded by a large amount of lossy dielectric material [13]" with RAM. Model tests of the design achieved very low RCS results, but the frequency coverage was unsatisfactory. Moreover, the useful load volume of the vehicle was very small and technically it was very hard to manufacture the radar transparent components.

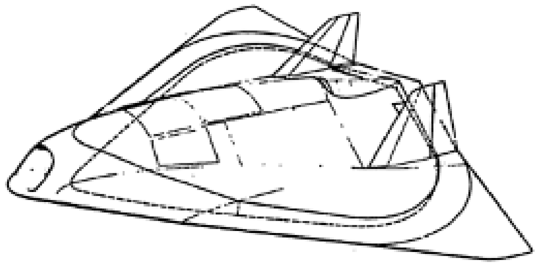

Figure 9. 1973-1974 Design of Teledyne Ryan, Unproduced RPV (From [13])

In 1974-1975 another design (Figure 10), having a similar shape but without any reliance on RAM, was introduced. Several versions were designed, each of which represented "tradeoffs between radar treatment, countermeasures and overall system cost [13]". To reduce radar signature, the vehicles had a ducted propeller on the top of the fuselage and wire screens were used at the end sides of this duct and also at the sensor radome beneath the drone. Unfortunately, these designs could not achieve adequate RCS reduction levels to evade detection while operating in a military mission [13].

Figure 10. 1974-1975 RPV Design of Teledyne Ryan (From [24])

4. North American Hound Dog Air-to-Surface Weapon (1962) and Boeing AGM-69A SRAM (Short Range Attack Missile) (First Flight 1969)

Besides using drones for reconnaissance missions, new systems to destroy enemy targets with remotely controlled conventional or nuclear bombs were developed during the Cold War. Short range attack missiles (SRAM), or more clearly, flying bombs, had already been manufactured and employed by using technologies and designs derived from RPV developments. The critical mission of SRAM, amplifying the importance of a low observable capability, was to deliver its warhead to a selected strategic target without the need for the penetrating bomber to directly overfly the risky or defended enemy zone. In fact, remote - inertial - or auto-controlled bombs were not a new idea. Some earlier designs, such as the U.S. aerial torpedo Kettering Bug of the WWI era, Germany's Henschel Hs 293 anti-shipping guided missile and the V-1 (primitive) cruise missile deployed in WWII, had similar missions. Although these missiles had much less RCS relative to manned fighters, low observable characteristics were still very important to engage a target without being detected by enemy defense systems [25], [26].

During this developmental period, when attempts to reduce the RCS of RPVs were being made, another force multiplier, the AGM-28 Hound Dog (Figure 11), air-to-surface missile, underwent a retrofit that included covering the inlet spike and duct with radar absorbent structure. The main RCS reduction required on the structure was treatment of the inlet. "All other flying surfaces had highly swept leading edges for supersonic flight [13]" that already provided a small RF signal back to the hostile radar. Moreover there was no internal radar system included to fulfill the mission (the missile was inertially guided) which was another factor in augmenting the low observable characteristics of the system. Although the system's RCS reduction was never tested in a combat, the endeavor was considered to provide remarkable RCS reduction in the forward aspect [13].

Figure 11. The AGM-28 Hound Dog
(From [27])

The Boeing AGM-69 (Figure 12) was another early SRAM which was designed to replace the older AGM-28 Hound Dog stand-off missile. The shape and design characteristics of the missile, which included no wings, no canopy and no engine inlet (it was rocket powered), made it easier to get a low RCS on the frontal sector. Small amounts of lossy magnetic material, with 2 cm of soft rubber, were utilized for purposes of absorbing radar energy and reducing IR signature. Moreover, some tail fin parts were made of a phenolic material to reduce the scattering energy back to the radar. It was reported that the AGM-69 had nearly the same radar signature as a machine-gun bullet [13], [28].

Figure 12. AGM-69
(From [29])

5. Lockheed A-12 (First Flight 1962) and Lockheed D-21 Drone (First Flight 1966)

Because the U-2 was vulnerable to Soviet radar tracking, the U.S. decided to develop a new high supersonic and extreme service altitude reconnaissance aircraft with the lowest possible RCS that could be achieved [30]. Among two available options, the U.S. government chose Lockheed's A-12 design (Figure 13) rather than General Dynamics' proposal, although it had a smaller RCS.

The A-12 was the earlier CIA-funded operational version of the SR-71 Blackbird, with a maximum speed of 3.35 mach, service ceiling of 95,000 ft, and range of 2,200 nm. It was the first aircraft known that was designed with RCS reduction methods from the beginning of the project. Internal construction methods, which included structures behind the skin of the aircraft, such as re-entrant triangles (Figure 14, 15 and 16) that trapped or absorbed radar energy, were first used on the A-12. Furthermore, design concepts such as inward canted vertical fins, a slender oval section fuselage blended with a thin delta wing, and special iron ball infrared and radar absorbent paints all combined to reduce its nose-on and side radar signature. This made possible this aircraft's survivability against state of the art (especially Soviet) radar and guided missiles [13].

Figure 13. A-12, the Winner of the Skunk Projects after the Demand of U.S. Intelligence Agency to Replace the U-2 Spy Plane (From [31])

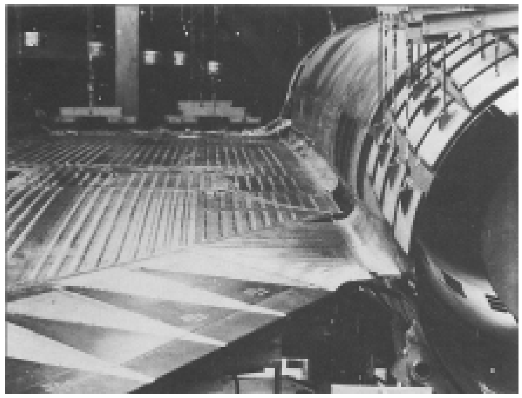

Figure 14. SR-71's RAM that was Placed in Triangle Shape
(From [32])

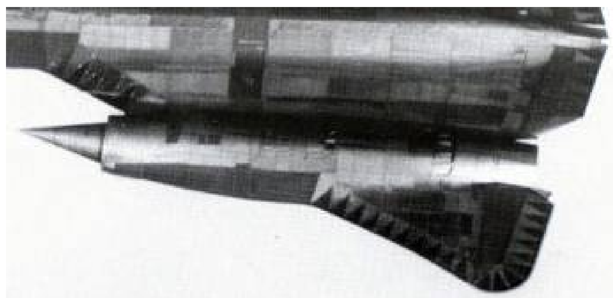

Figure 15. The RAM on the Leading Edges of the SR-71 Wings
(From [33])

Figure 16. The RAM on the Fuselage of the SR-71
(From [33])

However, there were still some unwanted elements that did not benefit stealth. One of these was the inlet lips of the A-12 which caused diffraction toward the receiver. This design element was necessary to enable the aircraft to reach extremely high altitude and mach numbers. Therefore, some compromise to stealth was accepted with the idea that "It was not possible to create an aircraft invisible to early warning or missile guidance radars, but in combination with high speed, high altitude, maneuvering, and electronic countermeasures, a very high degree of survivability has been obtained in service [13]."

Although the A-12 was a successful spy plane, the political tensions of the period required the U.S. to sustain its deep penetrating missions with unmanned vehicles. The plan was to carry a drone as far as possible on an M-21 (specially designed A-12 mother ship), and then to launch the drone at an extremely high speed, boosting it to nearly mach 4 and around a 100,000 ft altitude (Figure 17). After taking pictures of the target area in the enemy zone, the drone would come back to a safe zone, eject a capsule that contained the data, and terminate itself, while the capsule, gliding with a parachute would be snatched in mid-air by a C-130 plane.

Figure 17. A D-21 Drone on the M-21 Mother-ship (From [34])

The drone, which flew its first test mission in 1966, had a shape very similar to its ancestor the A-12, with and (Figure18) nacelle and two outer wings [3], and fuselage composite. Moreover, the ramjet tailpipe was extended to increase the IR low observable capability of the drone. Low RCS, speed and altitude goals were achieved; however, it was very hard to deploy this drone from the mother ship at the required high speeds. Thus, the configuration was changed to carry the drone under the wings of a B-52 H, by modifying both assets, but the project was cancelled after four operational flights failed to achieve success and the Teledyne Ryan AQM-91A Compass Arrow, high flying, unmanned, photo reconnaissance aircraft, was selected to fulfill the mission.

Figure 18. The D-21 Drones, very Similar Shape with SR-71 (From [34])

6. Mc Donnell Douglas Quiet Attack Aircraft (1972-1973 Design Study)

There were also some design studies which never resulted in an operational system, but were delivered as technology demonstrators which were successful in promoting the evolution of sophisticated low observable technologies. In 1972-1973 McDonnell Douglas designed the Quiet Attack Aircraft Project (Figure 19), which attempted to achieve lower radar, infrared and acoustic signatures than former attack aircraft, increasing survivability in high threat environments. The design included hidden inlets and a blended shape which avoided all vertical surfaces and contained no straight, leading, or trailing edges. However, the edge returns resulted in a contradiction. Entire curved platform edges produced a flare spot, which resulted in a relatively strong diffracted return from part of the edge, perpendicular to the line-of-sight [13] at nearly every viewing aspect.

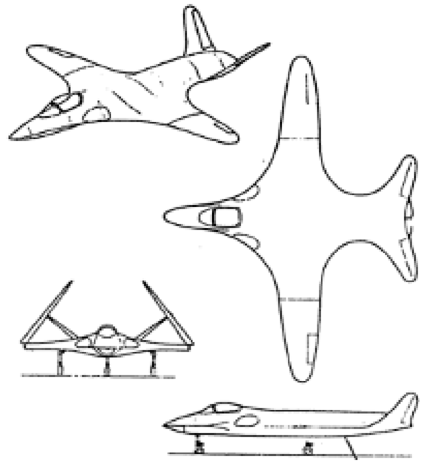

Figure 19. Quiet Attack Aircraft Project
(From [13])

7. Rockwell International B-1B (First Flight 1984)

At the beginning of the 1970s, the U.S. realized that its B-52 squadrons would be vulnerable to advanced Soviet defense radars. Therefore, a faster bomber with more capability to conceal itself from enemy tracking missile systems was vital. The B-1 bombers (Figure 20) were designed to meet these requirements with their low altitude, high speed, penetrating bomber capabilities. Its careful design with rounded fuselage shape and RAM applied to key areas, gave it a RCS which was much less than a small fighter [7].

Figure 20. B-1B Lancer
(From [35])

Although its curved engine nacelle upgrade (Figure 21) reduced the flight performance and top speed of the B-1B as compared to the B-1A, this design change resulted in a great RCS reduction by means of eliminating and trapping incident radar signals [7]. If illuminated by radar, rotating fan stages on the front surface of the engine were very big RCS contributors. Today, it is even possible to identify aircraft in some cases by means of processing returned radar signals from these fan stages.

Figure 21. The Engine Nacelles of B-1 (From [7])

Furthermore, removing the fuselage dorsal spine of the earlier B-1A model, which was designed to cover ALQ-153 tail-warning system, provided further RCS reduction. In later upgrades, “some adhesive tape was also applied to seams [7]” on the surface. These electrically conductive tapes prevented discontinuities, thus travelling waves, which contribute to RCS, were eliminated. The aircraft's AN/ALQ 161A defensive avionics also improved survivability by means of its comprehensive electronic counter-measures, such as electronic jamming, dispensing expendable chaff and flares (or towed decoys), in-flight re-programmable design, detecting-countering enemy radar threats and missiles even when attacking from the rear [7], [36].

B. THE REASONS WHY AN AIR FORCE NEEDS "STEALTH" TECHNOLOGY

Air operations have provided many advantages in warfare, resulting in the extensive use of aircraft to dominate the battlefield. The mission benefits of aircraft include flexibility, mobility and speed, and have given users rapid, massive, effective and surprise attack opportunities on remote territories. However if an aircraft does not employ tactics and technologies that improve its survivability it will be vulnerable to counter attack. In general, survivability, which improves with these tactics and technologies, "depends on a complex mix of design features, performance, mission planning and tactics [37]."

Stealth aircraft are specifically designed with the aforementioned features and performance qualities to increase survivability, which means accomplishing the mission objectives and returning home safely. Thus, stealth capability has a very high importance in the battlefield. Further, stealth aircraft are able to accomplish and survive missions where other assets cannot. Their operational flexibility provides users the ability to penetrate even the most well defended zones with relatively little risk.

In warfare, detection of enemy forces is vital for counter attack and defenders are made aware of an attacker's air operations by means of several types of detectors, especially radars. For instance, in air operations, defenders have more time to deploy interceptors and other ground forces after early detection by radars. Defensive forces attempt to defeat an opponent's attacks by using counter weapon systems. Further, defenders may have sufficient time to take precautions in the targeted zone to reduce or eliminate the effectiveness of a campaign. On the other hand, low observable technology enhances air superiority and the freedom to attack surface targets by means of reducing an aircraft's radar detection range and its infrared, visual and acoustic signatures to degrade the chance and range of detection [37]. Thus, ideal stealth technology assets enable its users to operate freely and conduct missions securely, even in the most risky enemy zone.

Though it is not possible to become completely stealthy, either delaying the detection or lessening an opponent's ability to track target course after detection provides a major advantage to low observable users [6]. With stealth technology, defenders might not be able to respond at all. If a surface-to-air-missile battery defending a target observes a bomb falling and surmises that there must be stealth aircraft in the vicinity, it is unable to respond if it cannot get a lock on the aircraft in order to feed guidance information to its missiles [38]. Thus low observability also decreases the effectiveness of tracking systems which guide SAMs and interceptors for final fire engagement.

Another advantage of stealth technology is optimizing the force and ammunition. Because low observables have greater survivability in deployed airfields and they are safer to penetrate into deep enemy zones, they can also get closer to high value, but strongly defended targets. For example, one or two stealth aircraft can accomplish a mission while repeated sorties with many conventional aircrafts may be required [37]. Moreover stealth aircraft increases the operational success rate of precision bombs by allowing their deployment closer to the target.

Stealth aircraft can also improve the mission capability of friendly air forces by providing domination and enhancing air superiority over the target airfield by eradicating air defense assets during the first stage of an air operation. This also enables the use of conventional aircrafts that can accomplish their missions in a less risky enemy zone.

“Potential synergy between low observables and electronic counter measures (ECM) [37]” is another advantage of stealth. While radar capabilities are increased with technological advances, stealth and ECM can cooperate to defeat them and improve survivability in air operations. If jamming is required in an operation, the platform with the smaller RCS will require less power on the enemy radar transmitter to jam. Moreover, a low observable aircraft may not need to use electronic counter measures intensively, compared to its counterparts. When the mission dictates, its capabilities of low signature increase the operational benefits of electronic warfare suites. For example, it enhances decoy performance which is deployed to disrupt the enemy's air defenses and dilute their effort to shoot down the mother airframe. Because stealth design already provides signature reduction, smaller and cheaper (both of which are very important qualities in aircraft design) decoys may be adequate for low observables to provide desired results. Low observables also increase their own jammers’ effectiveness or other friendly electronic warfare aircraft’s jamming capabilities by means of reducing the distance of burn through range, which is required for enemy radars to break away from the jammer effect. Thus, friendly jammer aircraft can support low observables from further distances which increase their own survivability [37], [39].

To summarize, stealth technologies provide flexibility in tactics and mission planning. They reduce the risks of operations against heavily defended targets in enemy territory with their enhancements to survivability. Additionally, stealth aircraft maintain the sudden attack advantage in the battlefield, and they maintain the ability to escape from defensive fire before, during and after a mission. Thus an air force needs stealth technology to neutralize enemy air defenses and to destroy high value, strategic targets while improving friendly forces' air superiority. An air force with these capabilities will control the airfields and operate safely while reaching and penetrating into an enemy's deepest territories [37].

III. STEALTH TECHNOLOGY DETAILS

> *It is hard and expensive to manufacture and maintain a stealth vehicle, but it may be easy to hit critical targets and gain Military Dominancy by using stealth vehicles. So, a balanced investment should be considered for stealth vehicles* [38].

A. DECEIVING THE EYE

> Visual stealth becomes more important as RCS is driven down, because the visual signature becomes dominant - that is, the signature that can be detected at greatest range [40].

The earliest method to confuse an enemy was deceiving the eye through the use of camouflage. During close-in air combat, a fighter pilot or air defense artillery gunner, tracking another fighter, bomber or spy plane, within nominal visual range, gains an advantage by seeing the adversary first. So, in air warfare, camouflage is considered an effective technique in conjunction with flight performance, speed, range and maneuverability to gain the air advantage over an adversary. While not always applied effectively or scientifically, military assets have employed visual signature measures to deceive their opponents.

Other than classical camouflage paint, the first attempts to defeat the human-eye were by covering aircraft surfaces with transparent materials to make them less visible. Just prior to WWI, this technique was applied to the Linke-Hoffman R I heavy bomber, shown in Figure 22, German Fokker E.1 fighter and Gotha bomber and was employed by covering the aircraft first with emaillit and later cellophane (or cellon) skins. However, these first attempts were not successful. The cellon covering was not a good material to cover aircraft surfaces due to being dangerously slack during long periods of wet weather. It reflected sunlight and became more opaque under cloudy conditions [3]. Further, it was not transparent at some angles and was discolored, producing the opposite effect [3], [6].

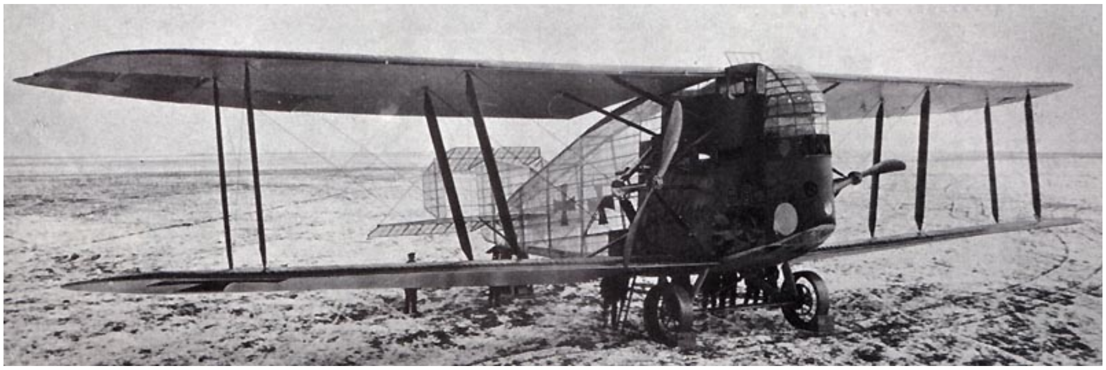

Figure 22. The Linke-Hoffman R I 8/15 Super Heavy Bomber with the Cellon, Transparent Covering, on the Rear Fuselage
(From [3])

For military aircraft, especially for stealth assets, visual low observable capabilities are essential in deceiving opponents. Camouflage blends the aircraft with its environment. However, because the aircraft environment is susceptible to aspect changes and the relative position of the observer can vary, camouflage should be chosen very carefully. In cases where the observer is below the aircraft, blending the aircraft with the sky background should be considered. However, this is dependent upon altitude, general weather conditions and time of day. In cases where the observer is above the aircraft, blending the aircraft with the terrain becomes the best approach, as depicted in Figure 23.

The operational task and the type of aircraft under consideration are also very important. Special terrain tones or mixed colors are chosen according to an aircraft's operational area. That kind of color schemes are dependent on local flora and terrain features, like sand, and are applied to the upper sides of aircraft designed for low altitude operations. The lighter blue or grey tones applied to the lower sides of an aircraft are intended to match the sky. These countershading effects reduce the visibility from threats located below. Night missions or very high altitude operations require matte and dark colors. Low observable aircraft, such as the F-117 and B-2, usually have black or dark gray hues because they typically operate at night. Moreover, reflections from cockpit glass or other smooth surfaces can be minimized with special coatings.

Figure 23. The Kingdom of Jordan’s F-16 with the First Advanced Visual Mitigation Method Application in the World (From [41])

Visual low observability in daylight is of concern to modern air forces. Earlier attempts, during World War II and later Vietnam, to decrease daytime visibility of aircraft proved successful during experimental programs. One of the basic principles that affect the ability to see an object is its luminance difference from its background or the amount of light scattered from it. For example, if an aircraft flies at high altitude, the reflected light from its underside increases, while the luminance of the sky decreases. So a black or dark toned U-2 spy plane which flies at more than 70,000 ft appears white to an observer below the aircraft. In daylight, because the background of the sky is clear, dark tones can be detected more easily compared to light ones. When this contrast difference is eliminated, it is possible to hinder visual detection until at very close ranges [42].

One of the best known studies on reducing the range of visual detection focused on counter illumination, as displayed in Figure 24. This approach was applied in Project Yehudi, in which specially designed illumination was used to mask shadows and eliminate contrast. During the WWII era, German submarines were a major threat to merchant marine shipping off the East Coast of the United States [42]. Anti-submarine patrol aircrafts were manufactured and planned to counter this threat. However, surfaced submarines could easily detect attacking anti-submarine patrol aircraft visually at long ranges and escaped by diving. Project Yehudi aimed to reduce the visual detection range by decreasing the contrast between the aircraft and the sky. Engineers fitted some patrol and attack aircraft with rows of lights, spaced at a distance of 0.5 to 0.6 meters along their edges and around the forward fuselage. The intent was to reduce the visual detection range of the aircraft and increase the chance of detecting submarines on the surface. Tests proved that the Yehudi system lowered the visual acquisition range from twelve to two miles. However, during this time, radar systems to track submarines became available. Diving and escaping, after visual detection of these aircraft no longer gave the operational advantage to the submarine. Using these radar systems, which were installed on aircraft, enabled their users to find and track submarines for bombing missions. Thus, there was no need to equip aircraft with Yehudi lights for submarine operations and further, it was costly to deploy aircraft with them [42].

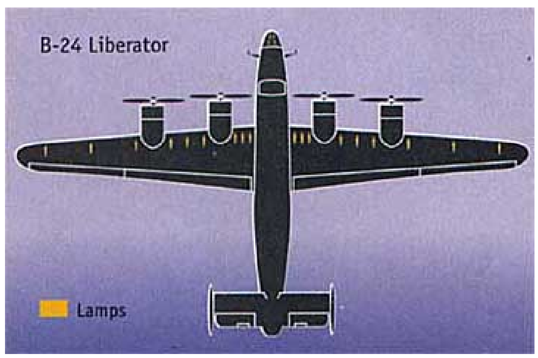

Figure 24. B-24 Liberator with ProjectYehudi Lights (From [43])

In a similar project during the Vietnam War, Compass Ghost, shown in Figure 25, an F-4 Phantom was modified to reduce its visual detection by enemy aircraft, such as the smaller MIG-21. The F-4 had nine high-intensity lamps on the wings and body with a blue-and-white color scheme which helped reduce detection range by nearly 30 percent [44].

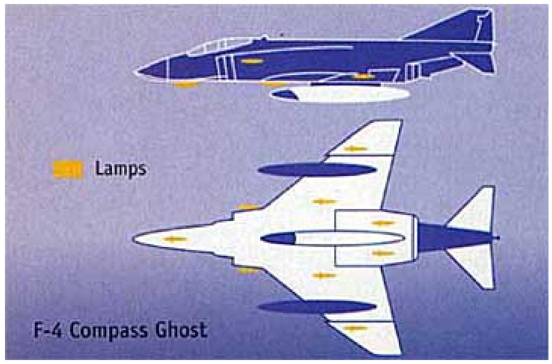

Figure 25. F-4 Phantom with Compass Ghost Project Lights (From [43])

A similar, but more complex system was also planned for deployment on the F-117 project. However, both prototype aircraft crashed before system test. The project included a central light source and fiber-optic links to external apertures which would automatically illuminate at a light intensity using the sensors on the opposite side of the aircraft [42].

More recent research in this area has shown that exclusively counter-illuminating specific aircraft surfaces, such as inlet and lower-wing body junctions, can be very useful. These surfaces generate the highest contrast which increases an aircraft's total visibility in daylight. The Bird of Prey project, which was characterized as a stealth technology demonstrator, used some new visual stealth approaches developed from this research and other previous experiences. Its color scheme, counter shading pattern and other covert technologies helped to decrease its visual detection, the main goal of the project. All these technologies are still relevant and may be used operationally in the near future, particularly with the advent of better computer control systems and visual simulators. The challenge is to do so consistently without augmenting other signatures [40].

Figure 26. Bird of Prey
(From [45])

Another concern with regard to visual stealth is suppression of condensation trails, or contrails. These are formed at altitude by the condensation or even freezing of water vapor created as a by-product when jet fuel is burned. Chemical agents have been used in different designs by injecting them into the exhaust to change the physical magnitude of the water droplets created in the air. Another way to minimize the risk of being detected by contrails is mission planning, which dictates choosing convenient altitudes to minimize the probability of their formation [7].

Meticulously chosen colors, paintings, illumination and novel technologies can augment the low observability of the asset. These applications leave an enemy with a low probability of detection by the human eye or a visual-based system. Some military technology researchers attach extra importance to visual countermeasures. While most signature reduction efforts are made to degrade radar and thermal sensors, in the future, the defender may seek to stalemate an opponent by means of modern visual detectors with relatively longer range and sensitivity capabilities. It is clear that newer systems, such as long-range electro optical television systems mounted on interceptors and SAM fire control units [7], will require stealthy aircraft to yield upgraded visual countermeasures.

Whereas many solutions for visual stealth aim to delude the un-aided human eye and do so with some level of success, there are still other ways to detect camouflaged objects. One technique is the use of visual moving image filtering [46], which discriminates the image from background by relative motion. With this technique, the detection of a moving image is not only possible in real-time but also with high resolution and lower level noise. Although this is just one of the many ways to process moving image information, it may have some usefulness in robot vision and can also be chosen to help the human eye to detect visually stealthy aircraft via monitoring results on a display [46].

B. RADAR INVISIBILITY: DESIGNING A "STEALTH” AIRCRAFT

1. Radar Principles

> Radar is an electromagnetic system for the detection and location of reflecting objects such as aircraft, ships, spacecraft, vehicles, people, and the natural environment [47].

The word RADAR came from using the capitalized letters of the phrase Radio Detection and Ranging. The wide spread military use of it during WWII changed the progress of the war. It later became an indispensable navigation and traffic control system for civilian purposes.

Radar uses the principle of sending a radar wave, which is a form of electromagnetic radiation, in a desired direction with a transmitter, and then collecting the reflected signals from a target with a receiver. Once reflected signals are received, the range to a target can be calculated by evaluating the interval of the radar signal’s travel; the half time of total interval gives the distance of the target while the radar signal propagates from the transmitter and returns to the receiver after reflection from the target [47].

This study is not intended to discuss complex radar principles, however, the fundamental mathematical model of the radar equation can be useful in understanding the important relationship between the main variables; radar cross section of the target, frequency and effective radiated power of the radar, distance between the transmitter, target and receiver. The radar equation is expressed as:

$$P_r = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4} \tag{3.1}$$

where P_r (watts) is the attained power by the radar receiver, P_t (watts) is the transmitted power from the radar emitter, G_t and G_r (unitless) are the gains of the transmitter and the receiver that generates the multiplier for the effective power, σ (square meters) is radar cross section (RCS) and λ (meters) is the wavelength. Wavelength can be calculated by using the formula:

$$\lambda = \frac{c}{f} \tag{3.2}$$

where c equals to, $3x10^8$ (meters per seconds), because the signal radiates at the speed of light, and f is the radiated signal's frequency (Hertz). As the detection range is very important for a low observable aircraft, the statement for the range acquired from Equation (3.1) should be analyzed.

$$R = \left(\frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 P_r} \right)^{1/4} \tag{3.3}$$

As seen in Equation (3.3), detection distance varies by the quarter root of RCS. Because the only factor which can be changed by a low observable aircraft designer is RCS, it becomes crucial. However, the fact that reduction in the RCS decreases only by the fourth root of the distance, requires designers to be very careful, because only dramatically large changes in RCS give favorable results. If a given radar has a detection range of 100 miles against a target with a RCS of 10 m^2, its approximate detection range to different RCS values calculated with basic radar equation are shown in Table 2. This results again show that, only enormous reductions in the RCS can make significant changes in the detection range, such as 1000 times reduction (RCS from 1000 m^2 to 1 m^2 which equals to -30 dB) in RCS brings % 82.22 detection range reduction (56.23 miles equals to % 17.78 of 316.23 miles, thus total detection range reduction is % 82.22). Another example from Table 2 is; reducing the RCS from 81 to 5 m^2 only changes the detection range by about half (168.70 miles is twice as much to 84.09 miles), despite the fact that this kind of reduction requires many design changes.

RCS (m^2)	**Approximate Detection Range (miles)**	**Detection Range Reduction Rate (Compared to 1000 m^2 RCS)**
1000	316.23	----
100	177.83	% 43.77
81	168.70	% 46.65
10	**100.00**	**% 68.38**
5	84.09	% 73.41
1	56.23	% 82.22

Table 2. RCS Versus Approximate Detection Range

2. Radar Cross Section (RCS) and RCS Reduction Methods

> *"… one stealth designer has defined his job as designing a very bad antenna and making it fly* [48]".

A target is detected by the radar only when the radar's receiver gets adequate energy back from the target, furthermore, this energy must be above the electronic noise or signal to noise threshold to be detected. There are many variables in the transmission-scattering-reflection sequence which determine the maximum detection range. These are transmitter effective outgoing energy, beam width, RCS of the target, total energy back from the target, antenna aperture (or size) and the receiver's processing capability [49]. Among these variables, RCS is the main concern of this study.

A radar beam is shaped in 3 dimensions like a cone, so as the range increases, the area seen by this cone increases. However, with this increased range, the reflected target energy and detected receiver energy diminishes. So, even in the best of circumstances, only a small portion of the original energy can be used by the radar to process.

Increasing the radar transmitter power, “a long time Soviet Russian favorite [48]” or deploying bigger antennas with more gain helps to obtain a longer detection range. However, these approaches have limitations, such as increased cost and an increase in noise back to the system. Most of the cost for an increase in energy is wasted on empty space. Furthermore, larger antennas and larger energy generating units are cumbersome, especially for mobile systems. Nevertheless, with a good understanding of basic electromagnetic principles and radar phenomena, sophisticated radar designs that have better detection performance and greater precision are being developed each passing day [48].

Up to this point, only the radar designer’s concerns are mentioned. For the stealth designer, the only variable to decrease the detection range is RCS. This is why RCS is the key term for low observables where reduction in reflected RF signal signature is intended. Any attempt to make an asset RF low observable focuses on RCS. If a target’s RCS can be decreased to a level low enough for its echo return to be below the detection threshold of the radar, then the target is not detected. In this context, RCS reduction is a countermeasure which has developed against radars and, conversely, new radar techniques with more sophisticated designs are produced to detect targets with low RCS [50].

Radar cross section is the size of a target as seen by the radar [51]. In more scientific words, RCS is a measure of the power that is returned or scattered in a given direction, normalized with respect to power density of the incident field [52]. The normalization is made to remove the effect of the range, and so the signature is not dependent on the distance between the target and the receiver. The RCS helps to measure objects against a common reference point, which is very useful in the low observable technology world in determining the performance of design goals. In this context, RCS can also be described as the size of a reflective sphere that would return the same amount of energy back. The projected area of the sphere, or the area of a disk of the same diameter, is the RCS number itself [49]. However, one important thing that should be understood is that this area is not the geometrical cross section of the body. A proportional definition of RCS can be made as [50]:

$$\frac{\text{Power reflected to receiver per unit solid angle}}{\text{Incident power density} / 4\pi} \tag{3.4}$$

A more convenient formula for RCS of a target can be defined as [53]:

$$\sigma = \lim_{R\to\infty} \frac{4\pi R^2 \times \text{power density in scattered field}}{\text{power density of incident plane wave}}. \tag{3.5}$$

RCS is a function of many factors. These factors include target geometry, its material properties, the radar frequency and waveform, polarization of the incident wave and the target aspect relative to the radar [50], [53].

Considering the first two factors, which are under control of the stealth designer, there are four main principles to reduce the RCS of an airplane. The principles are designing the shape, using special materials (RAM) on the surfaces, active cancellation and passive cancellation. In addition, a fifth consideration is plasma technology, which is also sometimes included as an active cancellation type. However, there is no proven application of this technology, other than some speculative Russian designs.

All of these methods have trade-offs. For example, shaping methods to decrease the RCS of an aircraft may spoil its aerodynamic performance, and result in handling and maneuverability problems. Material selections and coating also increase the weight, cost and the maintenance requirements. Moreover, applications of these materials are usually effective only in narrowband and in limited spatial regions. So the enemy's likely threats and the main mission of the aircraft must be considered very carefully in order to achieve desired results. However, a combination of these RCS reduction methods is applied to maintain the RCS below a specified threshold level over a range of frequencies and angles [50].

Other than its SI (International System of Units) derived unit of area, square meters, there is also another way of measuring RCS, which is especially used in the electronics engineering world. Most electronic engineers work with the decibel (dB), which helps to make calculations dealing with very large or small numbers much easier. The dB definition of RCS, can be expressed in dBsm (decibel square meters) in which the reference value is 1 m^2. This means that a RCS value of 20 dBsm equals 100 m^2, 10 dBsm equals 10 m^2, 0 dBsm equals 1 m^2, -10 dBsm equals 0.1 m^2, -20 dBsm equals to 0.01 m^2, etc. The equation for determining RCS value is:

$$\sigma_{(dBsm)} = 10\log_{10}\left(\frac{\sigma}{\sigma_R}\right); \qquad \text{where } \sigma_R = 1\text{m}^2. \tag{3.6}$$

In Figure 27, typical RCS values of several targets in dBsm are given.

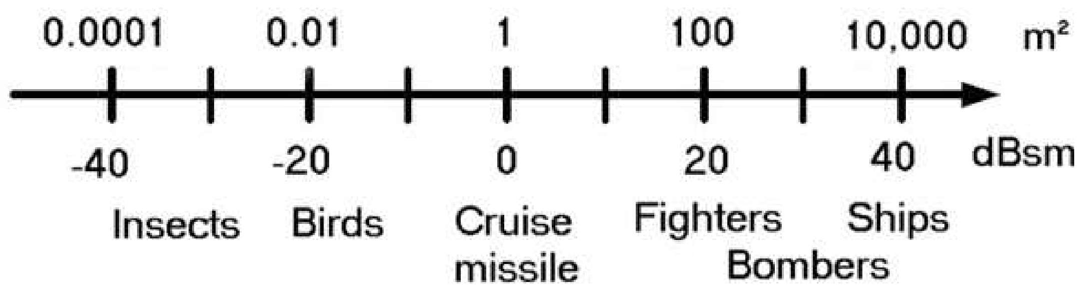

Figure 27. RCS Values of Several Targets (From [50])

Exact RCS levels of military assets are classified, however, it is hypothesized that today's true stealth aircraft have an RCS value around -30 dBsm (or 0.001 m^2) and new technological improvements promise to achieve values of -40 to -50 dBsm or 0.0001 to 0.00001 m^2. If these reductions are obtained, a radar, which could detect a nominal non-stealthy target with 5 m^2 (~7 dBsm) RCS at 80 miles, could detect the target in the -50 dBsm case at a range of three miles, which, from an operational point of view, is too late [42].

Figure 28 shows several aircraft and their approximate RCS values. Being classified, these are not exact RCS of the aircraft. However, this figure can give an idea that physical area is not the main concern and specially designed aircraft have remarkable RCS reduction. The methods of RCS reduction will be discussed further in the following sections.

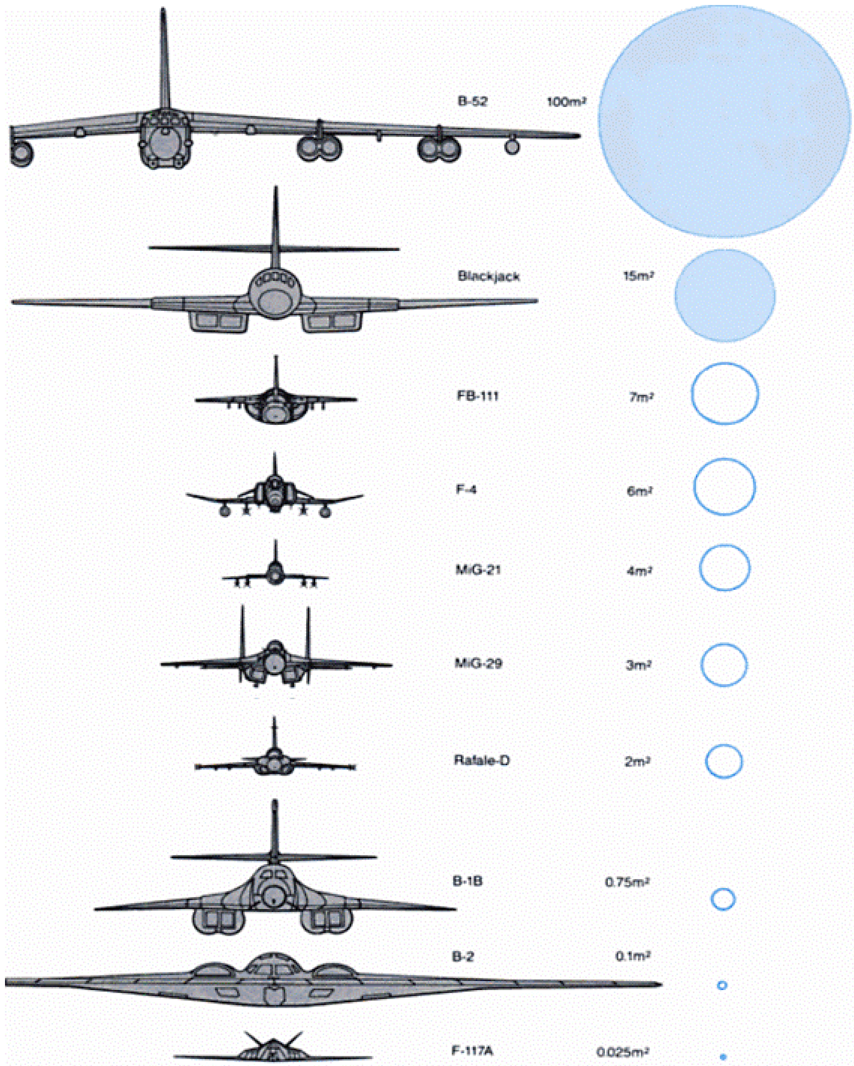

Figure 28. The Approximate RCS of Aircraft (From [7])

a. Shaping the Airframe

Before studying the shaping factor, the first RCS reduction principle, analyzing the major RCS contributors of an aircraft, can be useful in gaining a better understanding of the subject. The complex shape of an ordinary aircraft reveals many surfaces that can reflect incoming signals back to the radar, including air inlets, compressor blades, vertical stabilizers, external payloads, all cockpit instruments, all cavities (discontinuities) and corners. Figure 29 shows these contributors. All these contributors must be worked on very precisely to get desired reductions in RCS values.

Figure 29. The Minor and Major Contributors to RCS of a Fighter Aircraft (From [49])

Other than these contributors, the angle of the incoming radar signals is also very important. This is because, as the normal of a surface to a signal changes, total reflected energy and the RCS also change. For example, an aircraft with a 25 m^2 head on RCS, may have a 400 m^2 broadside RCS. Figure 30 illustrates a RCS pattern of a target reflecting a radar echo that is of relatively low frequency. The amplitude values for the pattern are relative basis, so don't represent a real aircraft. The target is located in a plane where 0 degrees represents the nose on position. To understand RCS value variation of an aircraft, in level flight, against radars at the same altitude but at different angles, the target is rotated in the yaw axis. Such patterns are used to analyze the ability of an aircraft to penetrate air defenses [54].

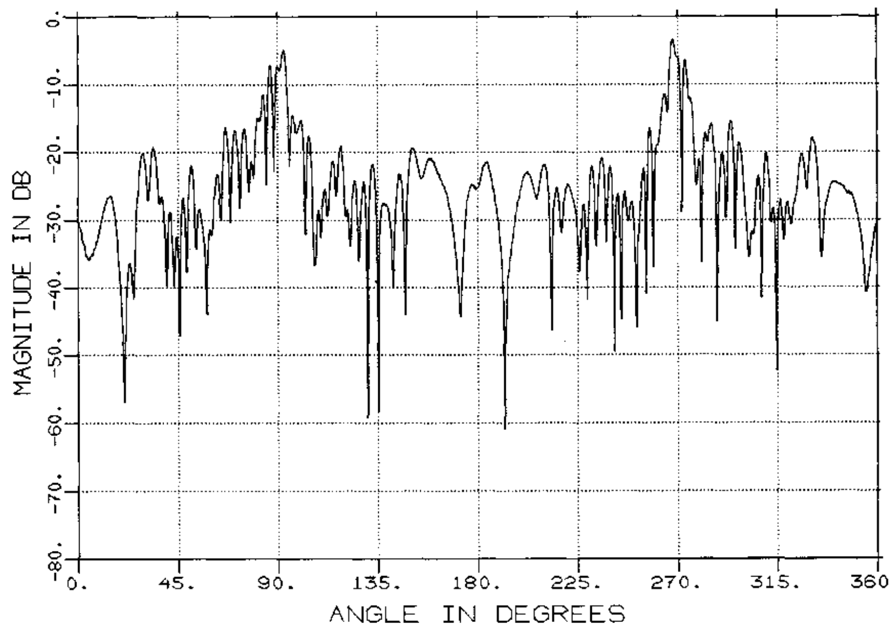

Figure 30. RCS Pattern of an Aircraft at Changing Yaw Axis (From [54])

Some features of an airframe design present dramatically large RCS values. A flat panel, which is a good reflector, is one of these, since it is normal to the radar beam. If this surface is rotated, this will result in reflecting the incoming beams to other angles and will create a smalller RCS for a monostatic receiver. Bill Sweetman, a former editor for Jane’s, and a well-known Stealth advocate, quotes a stealth designer:

> A flat panel is the brightest target, and also the dimmest. If the panel is at right angles to an incoming beam, it is a perfect reflecting target. Rotate it along one axis and most of the energy is deflected away from the radar. Rotate it along two axes and the RCS becomes infinitesimal [55].

Conventional vertical stabilizers are one of these flat reflector panels. Canting them inwards or outwards, with high-angles, can prevent incoming radiation from returning back to the radar and also when a rudder-elevator combination is used, the retro reflector of a dihedral, should be avoided. Here, a retro reflector dihedral is two surfaces that are positioned at 90° from one another and these surfaces reflect the radar wave front back along a vector that is parallel to but opposite in direction to the angle of incidence. Thus, this double bounce maneuver will result in increasing the RCS.

Rather than leaving them as external parts or hung on pylons, hiding the engine(s) and ordnance inside the fuselage/wings of the aircraft or making them blended components within the whole body or wings will reduce the RCS. This is depicted in Figure 31. Moreover, internal storage gives better aerodynamic performance, as the drag reduces. However, available space inside the body for ordnance is usually limited, which decreases the operational performance of the asset.

Figure 31. F-22 Raptor's Weapon Bays (From [56])

Compressor blades are another large signal reflector. Along with increasing the RCS of a target, some identification systems, such as radars using non-cooperative target recognition (NCTR) techniques, or one of the measurement and signature intelligence systems (MASINT) technologies, can be used to collect and process the strong radar returns from the engine compressor movements or periodic rotation of the blades of a turbine to discriminate between enemy and friendly assets [57]. Thus, an aircraft engine (with all possible components) should be kept out of reach of radar signals for low observable designs.

Using wire mesh (as in the F-117 and RPV Q-2C), specially curved air inlet nacelles that prevent the direct reach of RF signals to compressor blades (such as the B-1 B) and carefully chosen engine (inlet) locations will also help to reduce RCS. However, placing engines at their most optimum location to reduce RCS raises another important problem, determining the direction of expected RF signals. For example, if a radar threat is expected from below, putting the engine inlets at the top of the wing or airframe would be an effective measure. This is the more likely situation for high altitude bombers, reconnaissance and maritime patrol aircrafts. B-2 and F-117 bomber aircraft are good examples of this kind of design. However, for an air-superiority fighter, estimating the threat direction is a much more complex issue and there is no satisfying solution to this problem. So, the use of serpentine ducts and inlet wire meshes are more effective solutions to conceal the engines from radar signals.

Cockpits and their interior instruments, such as pilot's helmet, seat, control components and displays, reflect RF signals and increase the RCS, as the canopies and windshields are normally transparent to the radar beams. Some special absorbent (or reflecting) layers and coatings are used on the canopies of the stealth aircrafts to decrease the RCS of the cockpit as well as their unique external shapes. Along with the stealth aircrafts, some other fighters and EW assets such as F-16 Fighting Falcon and EA-6B Prowler also use such coatings either to reduce RCS or to shield the powerful signal emitted by the jammers from reaching the cockpit and crew. Controlled cockpit canopy shape, with "transparent conductor thin film (vapor-deposited gold or indium tin oxide) [49]." on it, block the incoming radar signals to reach the inner components and diminishes the amount of reflected radar waves back to the radar. [7], [49].

Other RCS reduction methods concerned with shaping, include avoiding gaps and holes in the design and using covert gun ports, as shown in Figure 32, to hinder discontinuities on the airframe surface. Performing high precision maintenance also helps to obtain and sustain these low RCS levels. In one case, a single screw not tightened as required was discovered to be the reason for an unexpected RCS increase in the F-117 prototype [49].

Figure 32. An Opening Door Covers the Muzzle to Preserve the F-22 Raptor's Stealth Qualities
(From [58])

The biggest effort in reducing the RCS is given to the forward aspects of the aircraft as illustrated in Figure 33. However, in this case, greater returns for the other aspects or at least some angles are inevitable. This tradeoff promises some advantage to countermeasures of stealth such as well designed bi-static radar networks. Secondly, though shaping is the first principle in reducing RCS and must be carefully considered in the design of low observables, long wavelengths are less affected by the shape of the airframe and its details. These two subjects and their effects on counter technologies will be discussed in Chapter IV.

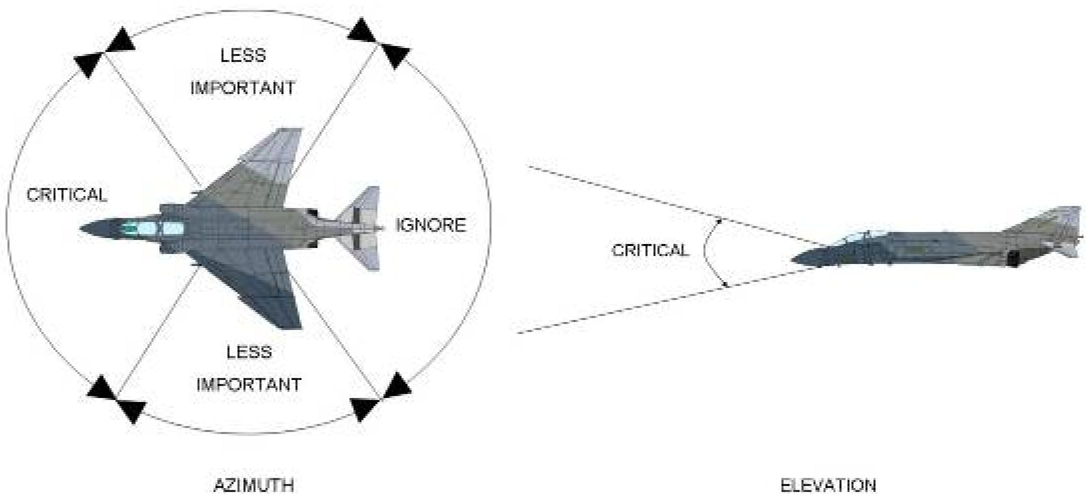

Figure 33. RF RCS Importance According to the Expected Threat Angles
(After [39])

The RCS of the airframe can be reduced by geometrically controlling the incoming signals' reflection (directionally) and scattering. The first way to accomplish this is to use flat surfaces and rectilinear surfaces all around the aircraft fuselage, which are oblique to the radar signals. The F-117 Nighthawk, shown in Figure 34, is a very good example of this kind of RCS reduction technique with shaping. F-117 Nighthawk uses careful faceting technique to reduce RCS by scattering the incoming signals in nearly every direction [49].

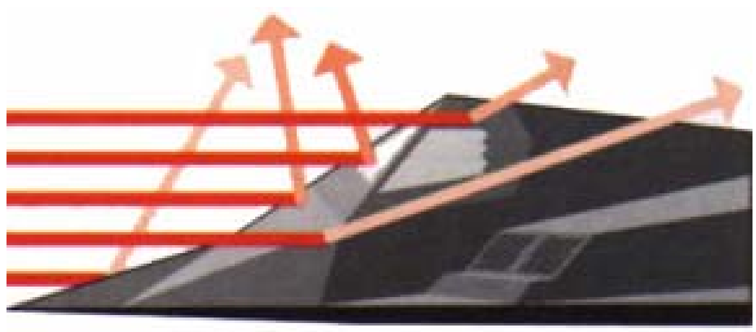

Figure 34. F-117 Nighthawk's RCS by Scattering the Incoming Signals Nearly Every Direction (From [49])

The second reduction method is similar and involves reflecting the incoming signals in a limited number of directions rather than scattering them in all directions. So a monostatic receiver never gets the transmitted signal back, unless the radar signal reflects with two 90 degree angles from a surface, which is improbable when extreme look-down angles are not present. If a bistatic system is considered, its receiver can only get the radiated beam when the spatial geometry is perfect [49]. In this technique, every straight line on the entire airframe should be designed carefully; shape of the aircraft, from main aircraft components such as wings, vertical and horizontal stabilizers, engine inlets, rudders, to all other moving parts such as rudders, elevators, ailerons, weapon bays, landing gear doors, canopy fasteners, etc., should be aligned in the direction of the few selected spikes (to reflect the incoming signal towards only these specific directions), as shown in Figure 35. Using serrated (sawtooth shape shown in Figure 36) parts on surfaces may also help achieve the desired results [49].

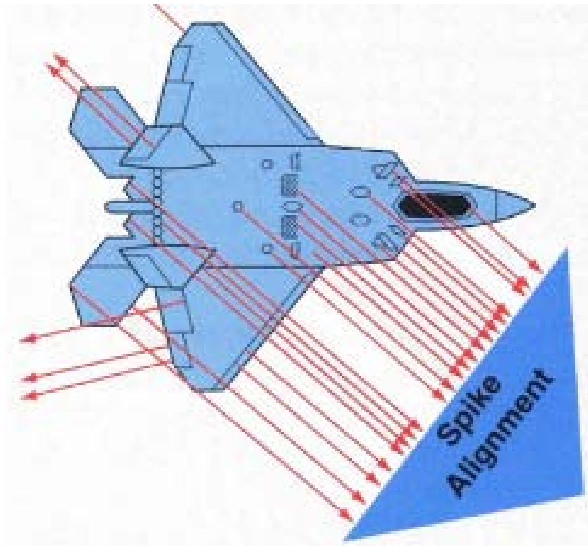

Figure 35. F-22 Raptor's RCS Reduction Technique by Shaping (From [49])

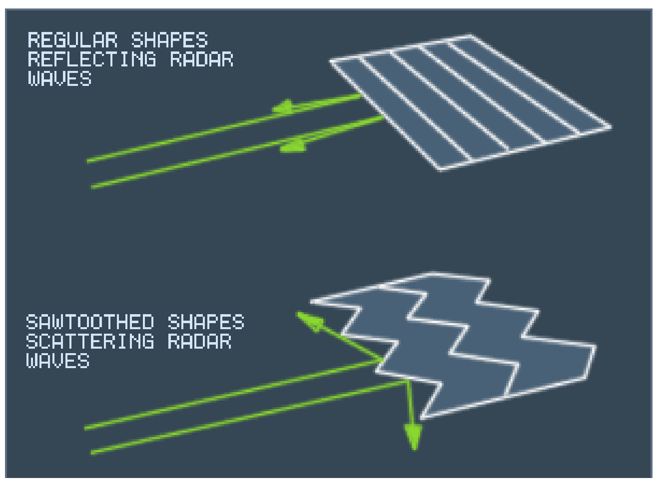

Figure 36. Serrated Shape for RCS Reduction Measures (From [59])

The third method is modeling the aircraft with a compact, smoothly blended external geometry [49] which has changing curves. These curves do not have regular reflection characteristics and they usually diminish the radar signal's energy by capturing them inside the curvature. The B-2 Spirit, especially its engine nacelles, was made with this kind of RCS technology. However, this method requires very precise calculations, thus only the latest (after 1980s) low observable aircraft have had the chance to use it in their computer based designs.

As mentioned, the main purpose of shaping is reducing or, ideally, eliminating the major RCS contributors. However, shaping measures for low RCS has some tradeoffs, such as poor aerodynamic performance, increased costs more maintenance requirements or less ordnance capacity. Despite these drawbacks, which will be discussed in the following sections, the gains in RCS reduction compensate for the diminished qualities for the purpose of improving aircraft survivability during operations.

b. Non-Metallic Airframe, Radar Absorbent Material (RAM) and Radar Absorbent Structure (RAS)

Stealth aircrafts should have extremely low RCS levels, however achieving such a goal is not possible by shaping alone. Some material designs, such as radar absorbent material (RAM) and radar absorbent structure (RAS) applications are also necessary.

Modern aircraft are generally made of composites, which consist of two or more different materials that have dissimilar physical, chemical or electromagnetic properties. Generally, composites are not metal and their RF signal reflection properties are very poor, thus non-metallic airframes are considered to not show up on radar. However, the non-reflected RF signals penetrate the non-metallic airframe and this time the reflection occurs from inside which results from the radar images of engines, fuel pumps, electrical wiring and all other components. Coating or painting the surfaces of airframes with special metallic finishing is the preferred way to prevent the penetration of RF signals through composites. On the other hand, composites are still important. Forms of composites, which consist of some poor conductors of electricity, such as carbon products, and insulators, such as epoxy resin, are used in the airframes to cancel the forms of creeping and travelling waves, by resisting electrical and magnetic currents which reradiate [7].

Though RAM's performance to decrease the RCS has been enhanced by a factor of ten, since the mid-1980s, an expert still indicates "…shape, shape, shape and materials… [42]" as the most important factors to design a stealth aircraft. It is clear that RAM is not an alternative for the airframe design, and it cannot transform a conventional aircraft into a stealthy one, however for better RCS values, some parts of the asset, especially edge reflections and cavities (such as inlets), should be healed using RAM, where no other solution is likely [42].

One of the special RAM coatings is made of reinforced carbon carbon (RCC) [7]. For the most part, RAMs, such as RCC, reduce RCS by absorbing (an amount of) the incoming signal and converting RF energy into heat or by destructive interference. With their appropriate dielectric or magnetic properties, different RAMs are used to get desired RCS results over the maximum possible frequency range. RAM technology is based on the idea of establishing desirable impedance which poses good matching and absorbing qualities, so that the RAM can accept and then attenuate the incident wave [60]. Dielectric qualities of RAM can also be explained as naturally occurring, electromagnetic waves of radar bouncing from conductive objects. However, the molecular structure of the lossy materials causes RF energy to expend its energy by producing heat. Then the heat is transferred to the aircraft and dissipated while the residual RF energy loses its effectiveness, basically with help of friction and inertia or molecular oscillations. Finally, this results in less reflection back to the radar receiver [49].

Together with absorption, another way of RCS reduction, by using RAM, is destructive interference. However, there is an important distinction between the phenomenon of absorption (Figure 37) and destructive interference applications. As mentioned above, the absorption process, which covers ohmic loss (based on the motion of free charges in an imperfect conductor), dielectric loss (based on permittivity), and magnetic loss (based on permeability), is possible by transferring the incident RF wave's energy to the airframe material as it passes through. On the other hand, the destructive interference (also known as "resonant RAM" or "impedance loading") principal is based on coatings, or the "Salisbury Screen" method, which are used to reduce RCS by cancellation of multiple reflections [60]. This method is considered both a RAM and a passive cancellation method. This study will discuss destructive interference in the passive cancellation technique section.

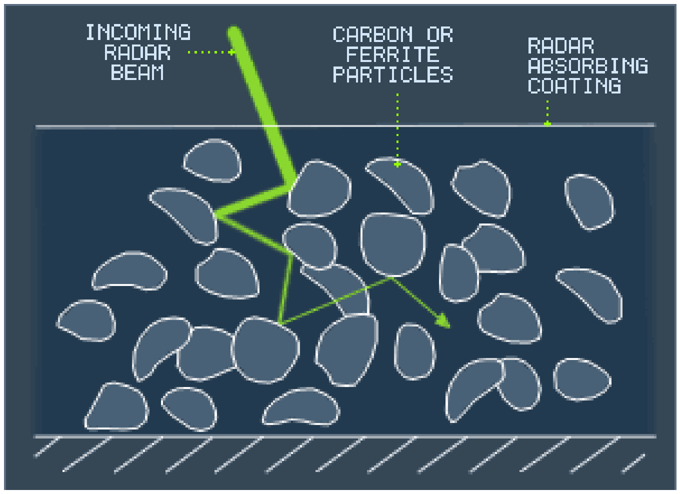

Figure 37. Radar Absorbing Material Illustration (From [59])

RAM includes many types of materials. Six RAM examples, low-dielectric foam (epoxy); lightweight lossy foam (urethane); thermoplastic foam (polytherimide); sprayable lightweight foam (urethane); thin MAGRAM silicone resin sheet; and resistive card (R-card) made of metalized Kapton, can be seen in Figure 38 in the order of clockwise from upper left [61]. Another example, a ferrite-based paint, which is called "iron ball", was used on the U-2 and SR-71 to reduce the RCS.

Figure 38. Four Thick Radar Absorbing Material Foams and Two Samples of Thin Radar Absorbent Sheets
(After [61])

RAM has some limitations. Although the use of RAM is strengthening for low observability, it never gives perfect results and can never be assumed to decrease an aircraft's RCS values to a large extent. It can absorb a portion of the incident energy, with the rest being reflected. Moreover, certain kinds of RAM can give expected results only for certain frequencies and angles of the incident radar wave. Using different kinds of RAM to broaden the RF spectral coverage, along with thicker and heavier amounts, increases the effectiveness. However, the optimum RAM weight and depth should be evaluated while considering the impact of the application of bulky coatings, which may demolish other flight and mission characteristics of the asset. Inconvenient weather conditions, such as rain, may also decrease the performance of most RAM. Furthermore, aircraft shelters should be constructed with special qualities to provide required RAM protection and maintenance. This is the reason that early B-2 planes were not deployed at US bases abroad where these kind of special shelters were not available [49].

Because thick and solid RAM coatings or paintings, which are heavy and bulky, are required but not feasible to get desired RCS reduction over wider bandwidths, an alternative method of using such materials at the inner skin of the airframe is preferred. Radar absorbing structures involve building special materials in special ways, such as honeycomb, as shown in Figure 39, to attenuate radar waves into load-bearing structure [50].

Figure 39. A Sample of Radar Absorbing Honeycomb Material (From [61])

The honeycomb structures have very important advantages. First of all, their hexagonal passages, which are bonded together, are physically very strong, flexible and light. From a RCS perspective, their depth, which does not cause considerable weight, is used to form many surfaces to reflect, absorb and attenuate the radar signal. One kind of honeycomb is made up of an outer skin of kevlar/epoxy composite, which is transparent to radar, and an inner skin of reflective graphite/ epoxy [49]. The nomex core, between them, has absorbent properties and its increasing density, front to rear of the honeycomb, improves the effectiveness. The small amount of front-face reflection of the incident radar wave is followed by the radar wave to reach the thinly spread absorber on the outer edges of the core where another small part of the energy is absorbed and the remainder is bounced. So, the travelling wave meets more densely loaded core material as it goes on. Each time, some amount of energy is either absorbed or reflected, and finally the outermost layer of the absorber once again attenuates it [49] and the radar wave, which is checked into the structure, never checks out to free space again [49].

Another RAS form is used on the leading and trailing edges of low observables, such as the wings and fuselage skin strakes of the SR-71 Blackbird, which is depicted in Figure 40. In this method, gradually increasing absorption is applied to trap the energy, similar to the honeycomb structure. However, in this case, the physical shape of the structure is a saw-tooth pattern. The external surface is coated with a high frequency ferrite absorber. The interior begins with a low-absorption layer and is followed by a more absorbent layer, so; while the deepness increase the absorbent properties are also augmented. The "V" shaped geometry, shown in Figure 41, causes the radar signal to bounce towards the opposite side, while the material properties of the structure absorb and provide the incoming signal to diminish the energy, so each bounce results in the loss of some amount of the energy [49].

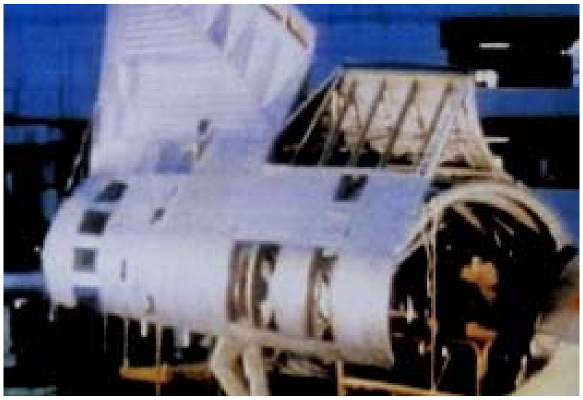

Figure 40. Triangular Patches of RAM and RAS on the SR-71 Blackbird's Wing Leading Edges
(From [7])

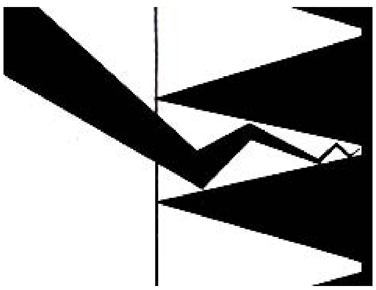

Figure 41. The Acute Wedge Shape for Trapping Incoming Signal with the Help of Absorbing Materials
(From [6])

The state of the art F-22 Raptor, shown in Figure 42, is the U.S. modern stealth fighter. It has many low observable material properties including RAM, RAS, and IR topcoat. RAS is used to minimize scattering from hard edges, while RAM is used to reduce scattering from surface breaks [62]. Moreover, the IR topcoat reduces the IR signature, along with ensuring the radar and infrared signatures are balanced. Early low observable programs made extensive use of RAM and RAS, which resulted in weight and manufacturing problems. However, modern stealth aircraft designers, with the help of analysis and design tools, combined with extensive testing, have minimized the use of RAM on assets, such as F-22, while still maintaining a low signature. So, modern aircraft use less RAM and RAS materials compared to early generations of low observable aircraft which save significant weight and cost [62].

Figure 42. F-22 in the Robotics Coating Facility for Low Observable Material Applications
(From [62])

c. *Passive Cancellation System*

Special material used for signal cancellation purposes to reduce RCS fall into two categories: RAM RCS reduction methods (resonant RAM) and passive cancellation. The resonant RAM method was also introduced as destructive interference or impedance loading in RAM applications. Here all these terms and so passive cancellation system refers to "RCS reduction by introducing a secondary scatter to cancel with the reflection of the primary target [60]."

In this method, special coatings, which are also called “resonant absorbers”, are chosen to cancel the incoming signals by being reflected two times (some times more than two is also possible for wider frequency covering), one from the front and the other from the back of the layer. Theoretically, having a back face wave that totally travels one half wavelength more than the one that is reflected from the first layer is essential. Having the correct thickness causes the second reflection to have a 180 degree phase difference with the round-trip (first layer) reflection, thus first and second waves will cancel each other. However, this method strictly relies on layer thickness or ¼th of the wavelength matching.

This method, is also known as “Salisbury screen”, and illustrated in Figure 43. A resistive screen, which is placed in front of the reflective back plate, bounces nearly 50 % of the incident radar beam (blue wave in the Figure 43) back to incoming direction (purple wave in Figure 43), while the other 50% of the radar wave passes through and reflect from that grey plate (red wave in Figure 43). When the distance between these two plates are ¼th of radar signal’s wavelength, red and purple waves cancels each other. Because such a thickness is only effective for specific frequencies, this cancellation is called as a “narrowband technique.” On the other hand, from a RAM application techniques perspective, dielectric and magnetic loss mechanisms are categorized as broadband absorbers, while they can generally be deployed to cover wider frequency bands than passive cancellation coatings [50].

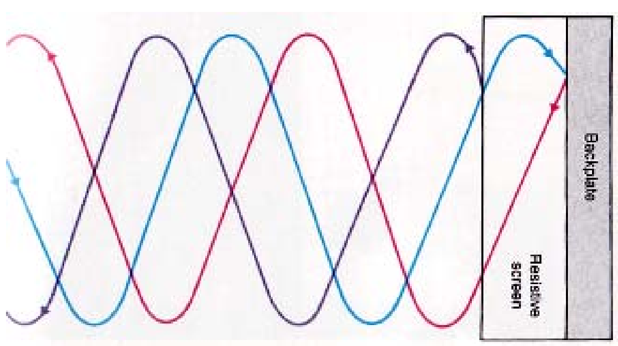

Figure 43. The Salisbury Screen (From [7])

Passive cancellation was studied enthusiastically in the 1960s; however, its limited use made it unpopular and resulted in the connotation that it was not a useful RCS reduction method. Obviously, it is not practical to design such a treatment to neutralize all of the echo sources while passive cancellation RCS reduction techniques cannot suppress the radar and weapon systems' relatively wide frequency extent. Moreover there is also a risk of strengthening the reflected signal with the change of frequency, or viewing aspect.

d. Active Cancellation System

Active cancellation is a way of creating a new waveform which will cancel the original radar signal reflected from the airframe. This method is very similar to active jamming techniques. However, active cancellation methods require transmission of very low power levels compared to conventional EW jamming techniques. Here, the main purpose is reducing the RCS while cancelling the reflected radar signal by a process of modifying and retransmitting the incident radar waves, rather than having the radar jammed. The method is also called "active loading". The active cancellation platform must radiate counter signals, which have the same amplitude but reversed phase fom the radar (Figure 44). Moreover the radiation must be towards the same reflected direction to cancel the bounced signal.

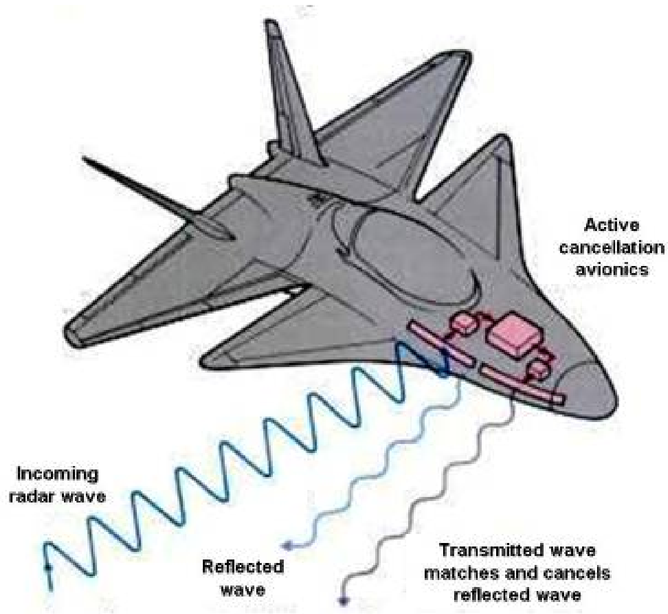

Figure 44. Active Cancellation System
(From [7])

Using such a process requires some data, including angle of arrival, intensity, waveform and the frequency of the received signal. Obviously, the emission must coincide in time with the incident pulse. Thus, this kind of a replication is very complex; moreover, it requires smart systems to calculate the airframe's own echo characteristics in order to generate the exact pulses for cancellation [49], [52], [60].

There are two active cancellation levels; fully active and semi active. Fully active systems are those that receive, amplify the threat signal and retransmit the required cancellation signal which is out of phase. Here, the transmitted wave parameters, such as signal intensity, phase, frequency and polarization, must be carefully adjusted to compensate for the changes. The second one is semi active cancellation, by which limited changes in threat signal parameters are met to compensate. The fully active cancellation process is very complex with a requirement for transmitter and receiver parts (such as antenna) to cover wide threat angles, frequencies, power amplitudes, and polarizations, making the design impractical. Semi-active systems are less complicated; however, still require receiver and transmitter units with smart controller units or computers [60].

Active cancellation systems should meet some basic rules which must be fulfilled in a completely correct way to be effective. First, the systems must have a capability of analyzing the incident wave in real-time, while the first captured signal may be shifted, or its parameters such as pulse repetition frequency (PRF), signal frequency, etc., may be changed. Second, the new transmitted signal must have just enough power (the similar principle with Low Probability of Interceptor (LPI) radars) to cancel the real radar signal, because a smart radar processor may check the received signal and determine the jamming-like counter attack from spikes considered too powerful. Thirdly, the aspect of the threat radar signal must be specified with precision to send the false signal in only that direction. However, continuing changes of the airframe's velocity vector will compromise this effort and complicate the operation of active cancellation [49].

In this context, active cancellation systems are complementary to other passive stealth techniques. The use of passive techniques, such as shaping or RAM, reduces the burden of active cancellation and diminishes the need for an application of active cancellation signal which has its own risks towards a hostile receiver. However, passive stealth techniques have some vulnerability. For example, reflected signals in particular directions may be received and processed by third party detection systems, while active cancellation may neutralize these drawbacks. Moreover, application of passive RCS reduction techniques on present conventional designs includes many difficulties and complexities, coupled with less effectiveness and increased cost. Active cancellation may provide these conventional aircraft some low observability for operational advantage, while these methods must work perfectly, driving high reliability.

Although there are some speculations regarding deployed military aircraft systems, there is no proof nor any publicly declared operational system. However, studies are ongoing as active cancellation is a promising RCS reduction technique. Advances are dependent on developments in computing power and electronics technologies. Especially large aircraft may utilize such a solution in the future [42].

e. Plasma Stealth

Plasma is a partially ionized and electrically conductive gas by means of the ability of the positive and negative charges to move somewhat independently [63]. Its free electrons make plasma respond strongly to electromagnetic fields. Thus using plasma, which is sometimes considered an active cancellation technique, has been studied and proposed as a possible method of RCS reduction. The inspiration for this method emerged in the late 1950s after spacecraft with a natural plasma layer over their airframes experienced communication interruption incidents while traveling through the ionosphere. Basically, radar waves (actually all electromagnetic waves of certain frequencies) traveling through this conductive plasma cause electrons to exchange their places, ending up with the electromagnetic waves losing their energy and transforming it to other forms, such as heat. Interaction between plasma and electromagnetic radiation is strongly dependent on the physical properties and parameters of the plasma [64]. The most dominating of these properties are the temperature and the density of the plasma. Another important issue is frequency of the incident radar beam. Radar waves, below a specific frequency, are reflected by plasma layer. Plasma layer's physical properties have significant effect on this process. Long distance communications with HF signals by means of ionosphere scattering and reflection is a good example of this same phenomena. Thus, RCS reduction plasma devices should also control and dynamically adjust the plasma properties, such as density, temperature and composition, for effective radar absorption results.

Plasma stealth technology has some drawbacks from a low observables perspective. Some of these include, emitting own electromagnetic radiation with a visible glow, existence of a plasma trail of ionized air behind the aircraft [64] before dissipation by the atmosphere, and difficulty in producing a radar-absorbent plasma around an entire aircraft traveling at high speed [64]. However, some Russian scientists have declared achieving a hundredfold RCS reduction with plasma technology and this result (if real) is sufficient enough to focus on this method for further research and success in the stealth world [64].

Another application of plasma is utilizing this technology to deploy antenna surfaces to generate low observability characteristics. While metal antenna poles are reflective parts, a hollow glass tube filled with low pressure plasma can provide an entirely radar transparent surface when not in use [65]

Although there are some problems in the operational processes associated with plasma, such as the high energy requirement in long interval applications and the necessity of holes in the plasma fields for aircraft onboard radar activation, Russian plasma stealth research teams have announced the development of a plasma generator which weighs 100 kg and is thus feasible for a tactical air platform. This critical technology may be available on the Su-27 versions (such as Su-34 and Su-35), MIG-35 fighters and also the MIG 1.44 prototype, see Figure 45, according to recent claims by Russian officials [49], [64].

Figure 45. Russian MIG 1.44 has been Told to have Some Plasma Stealth Capabilities (From [64])

C. ACOUSTIC "STEALTH" (REDUCING AURAL SIGNATURE)

Because the probability of detection of radar occurs at greater distances than other signal detection methods, it demands the highest priority in the development of aircraft low observable technology. IR and after that, visual signatures fallow the radar, while sound is the least important of the four aspects of stealth [66]. Practically speaking, acoustic detectors are unable to meet the demands of today's sensor technologies in the aviation world, due to the very low propagation speed of sound waves [67]. However, a comprehensive stealth design includes measures to diminish the ability of acoustic sensors to locate an aircraft [68]. Furthermore, in the future, technological improvements in sensitive aural signature detection systems may minimize low observables' advantages over the focused areas, such as radar, IR and visual signatures, if they are not also concealed by acoustic stealth measures. In the same way, stealth aircraft, which are undetected by other means of tracking or visual systems (including eyesight), can further enhance their advantage by also deploying with features to defeat acoustic detection systems.

Despite the poor qualities to detect targets in free space, using acoustic detection devices in some other mediums can be preferable. It is not the focus of this study, but outlining the importance of acoustic stealth in other application areas may be valuable, in this manner. For example, in submarine warfare, having different requirements, reducing aural signature plays a significant role in the physical medium of sea water.

Aircraft acoustic signature reduction focuses on the engines, which produce a significant amount of noise. The slipstream of the aircraft also produces noise, but it is inconsequential when compared to the roaring of the engines. There are several ways to prevent the sound of engines from being detected. Flying at high altitudes reduces the detection risk; however, mission requirements may sometimes compel low-level flight. Cruising around at the speed of sound may be another solution, but this cannot conceal the asset when it flies away from the detection source. Additionally, most aircraft cannot fly more than 10 to 20 minutes at such high speeds and designing an aircraft which can fly for longer periods introduces a number of complexities. For example, the F-22 Raptor can almost fly an entire mission above the speed of sound using its "supercruise" capability, which does not require afterburner use. However, this capability has many drawbacks, including high engine cost and complex fuselage design.

The most promising approach in minimizing aircraft aural signature is making assets quieter by design. In fact, more efficient engines tend to produce less noise. Aircraft engines which inhale a large volume of air but push a small amount, such as high-bypass-ratio turbofans, are quieter than those that inhale a small volume of air but push a large amount, such as low-bypass-ratio engines. Despite this efficiency and acoustic signal reduction advantages, most combat aircraft use low-bypass-ratio engines, which are more suited for applications that require immediate thrust, high velocity and acceleration, and agile maneuverability.

When quietness becomes a bigger concern, high-bypass-ratio turbofans are preferred, even though high performance and speed is reduced. The A-10 Warthog is a good example of this kind of design. Because it is deployed for close air support missions, to friendly ground forces, and its main targets are ground enemy forces, like tanks, armored vehicles and large groups of troops, it needs to fly over these targets several times. A reduced aural signature is crucial in increasing the A-10's operational success rate due to its requirement to conduct multiple reattacks. Thus noiseless engines, together with other low observability features, such as IR and visual signature reduction methods, help these aircraft improve their survivability and mission capability [66].

Successful example of acoustic stealth is demonstrated by the Lockheed YO-3A quiet reconnaissance aircraft, shown in Figure 46. This aircraft, which was used by the U.S. Army in the Vietnam War, was deployed for tracking enemy forces that were moving at night, in large groups with equipment, inside dense forests. Conventional reconnaissance or observation aircraft were easily detected by enemy forces from their engine sounds; therefore, several studies focusing on reducing engine noise were commissioned. One of these resulted in the Q-Star prototype, shown in Figure 47, which was developed from X-26 sailplanes, using a liquid cooled engine buried in the rear fuselage for more effective silencing. After several experiments, fourteen Lockheed YO-3A aircraft were produced and used to respond to the requirement for avoiding acoustic detection and fulfilling the mission. These aircraft had a modified light plane engine utilizing a long exhaust pipe. This exhaust pipe was attached to another long muffler fitted on the fuselage side. Moreover, the engine had a large, slow-rotating propeller, which was six bladed, wooden and rubber belt driven. This propeller was later replaced with a three bladed, constant speed counterpart for improving silencing [3], [69].

Figure 46. YO-3A with Effective Noise Cancelling Mufflers on the Right Side of the Fuselage (From [70])

Figure 47. Q-Star with Novel Engine Propeller Design to Reduce the Noise (From [71])

The U.S. F-117 Nighthawk and B-2 Spirit, all aspect stealth aircraft, also incorporate design features that reduce engine noise, such as sound-absorbing linings inside their engine intakes and exhaust cowlings [72]. Further, their engine inlets and exhausts are located on top of their wings, they have the ability to fly at relatively high altitudes, and they cruise at subsonic speeds with non-afterburning engines, all of which improve their acoustic signature measurements. Supersonic speeds generate sonic booms which are usually unacceptable for stealth purposes due to the increased risk of detection.

D. IR SIGNATURE AND IR STEALTH

All substances with a temperature above absolute zero (0° K, or -273.15° C, or -459.67° F), emit electromagnetic waves. The heat content of a material produces molecular vibrations which cause electron oscillations. These oscillations provide electromagnetic coupling that produces an emission of energy. This emission is called infrared radiation (IR). IR has a wavelength spectrum of 0.7 to 14 micrometers, and the amount of radiation emitted is primarily dependent on the physical temperature of the associated object (proportionally). The emissivity characteristics of an object are related to the material's molecular structure and the surface conditions of the object. IR energy that comes from another body is either absorbed or reradiated by the object according to its emissivity properties [73].

As with visible light, IR energy also travels in a straight line at speed of light. Similarly, IR energy is either reflected or absorbed and converted to heat when it hits the surface of an object. These absorption and reflection qualities change with material specifications. For example, polished surfaces reflect more IR energy but also have a much lower emissivity than matte surfaces [68].

IR energy considerations are important to stealth designers, because IR detectors, also known as infrared homing devices, such as passive missile guidance systems, can use IR emissions from a target to track it. Detector systems, especially missile guiding seekers, which detect the radiated infrared signals of their target, are often referred to as "heat-seekers". If unaided by IR countermeasures, aircraft are vulnerable to detection by such systems by means of the strongly radiated energy from their hot bodies. Some precautions to mitigate such detection include, reducing or suppressing an aircraft's IR signature and adding some noise, deploying decoys or flares, and jamming the sensor by emitting high power signals towards the detector.

For an asset designed to remain undetected, one of the most important measures is reducing or suppressing the aircraft's IR emissions. Thus, sources, surfaces or components which produce and/or conserve heat are of great concern to low observables. Moreover, the IR detection capability of the new IR Search and Track (IRST) systems, such as shown in Figure 48, and Electro-Optic (EO) systems deployed on the SU-27, Eurofighter Typhoon, and F-35 Lightning II, reveal the importance of IR signature reduction. These EO detectors absorb electromagnetic radiation and output an electrical signal that is useful for tracking and targeting their target. Another major advantage of these systems is that they are passive systems in which a target never knows that there is a threat trying to detect it. Further consideration for IR detection is revealed by the efforts required to increase combat effectiveness of stealth aircraft. When radar detection range is minimized by RCS reduction methods, other signatures such as IR, visual and acoustic become more pronounced, especially for close range engagements.

Figure 48. IRST Sensor of the F-35 Lightning II (From [74])

IR signal reduction is focused on engine exhausts. The back side of an engine is the major source of IR radiation in an aircraft, and when the afterburner is applied, the heat increases significantly, by nearly fifty times, since IR energy emitted from the engines is proportional to the fourth power of absolute temperature [7]. Thus, the second generation stealth F-117 Nighthawk and the third generation strategic stealth bomber B-2 Spirit have non-afterburning engines. On the other hand the fourth generation stealth F-22 Raptor has the ability to cruise at supersonic speeds, but without afterburner. Being dependant to high mach numbers for operation survivability, the first generation stealth SR-71 Blackbird is also an exception, with its high power afterburner engines.

One method to decrease the IR signature of the engines is to use exhaust masking. This is accomplished by placing the engines on top of the body and the wings. This is the reason the F-117 A and B-2 exhausts cannot be seen from below, which is shown in Figures 49 and 50, respectively. Over the rear conical sector of the aircraft, the hottest parts of the tailpipe can be easily detected by IR seekers. While outside of this sector, sensors can only detect the hot parts of the nozzle surface. Another technique to decrease the IR signature is using the aircraft's aft fuselage and vertical surfaces to shield the jet pipes from view over as large a part of this rear sector as possible [7].

Figure 49. The Body of the F-117 is Designed to Mask IR Emission from Engines (From [75])

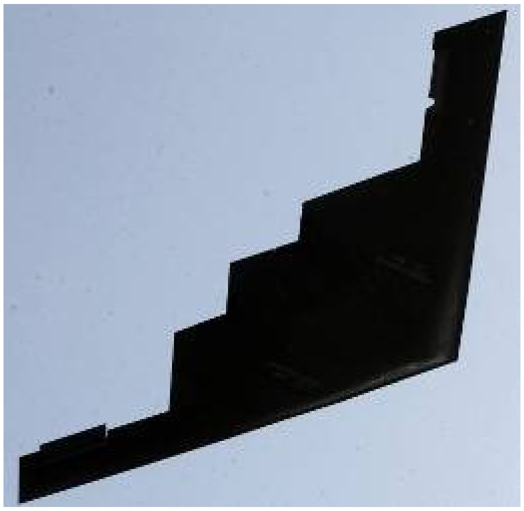

Figure 50. The Engine Nozzles of B-2 are Concealed to be Seen from Below (From [76])

Another method to decrease IR signature is the shaping of exhaust geometry. Exhausts that are shaped flat and wide, as shown in Figure 51, are effective in this regard. This increases the perimeter of the plum compared to conventional round nozzles, and results in an increased mixing rate of exhaust gases, cooling them with air. This reduces probability of detection, but thrust efficiency is decreased with flat and wide designs. High bypass engines also benefit from the mixing of air with exhaust for exhaust nozzle temperature reduction purposes. Masking the hot turbine stages with curved jet pipes and concealing the forward emissions of the engine with curved air intakes are other measures to reduce IR signature.

Figure 51. F-22 Raptor's Saw Toothed, Wide and Flat Shaped Nozzles to Reduce Both Radar and IR Signatures (From [77])

After engine heat, kinetic heating of the aircraft body is the second major source of IR radiation. Some closed-loop cooling systems and special materials, such as IR signal absorbent material, can be used to dissipate the heat from the body as well as the engine and exhaust parts. However, this method has some disadvantages; such as increased weight and special maintenance requirements, similar to RCS reduction oriented RAMs. Dumping the heat into the fuel is another technique to reduce kinetic heating and was first used in the SR-71 Blackbird. However, at high mach numbers, the high temperature from kinetic heating is inevitable. In general, limiting aircraft to relatively low speeds is required to minimize this source of IR radiation.

E. MODERN EXAMPLES OF AIRCRAFT THAT USE "LOW OBSERVABLE OR STEALTH TECHNOLOGIES

1. F-117 Nighthawk (retired “Stealth Fighter”)

The F-117, shown in Figure 52, is considered a second generation stealth aircraft, and an advancement over first generation variants, like the SR-71 Blackbird and other early low observables. It was the first aircraft designed with a focus on all aspects of stealth, although RCS was the leading concern. In earlier low observable designs, the low observability was either an added feature or a partial consideration to improve survivability. Instead, the F-117 was designed to be stealthy first, and other specifications were aligned to this purpose.

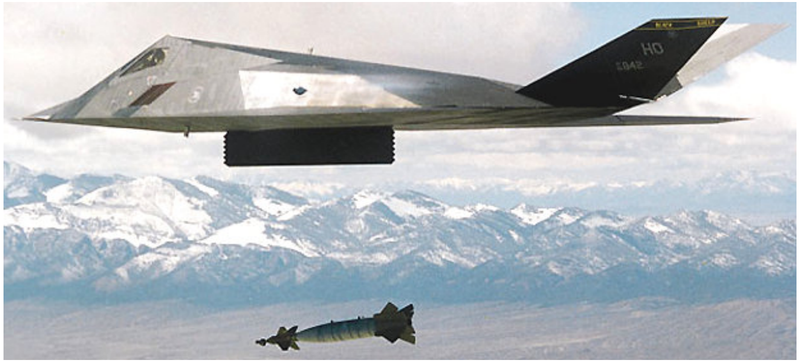

Figure 52. F-117 Night Fighter Releasing a Laser Guided Bomb (From [78])

This design was based on the Experimental Survivable Testbed (XST), a technology demonstration, also known as the Have Blue project, shown in Figure 53. Although more realistic than the “hopeless diamond” concept, shown in Figure 54, which was aided by sharp surfaces without extended parts, the XST was designed from an electrical engineering perspective rather than an aerodynamic one.

Figure 53. Lockheed's Proof of Concept, XST or Have Blue, in the Senior Trend Program
(From [79])

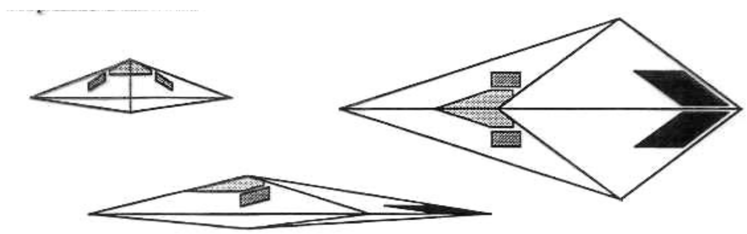

Figure 54. Have Blue was Developed from Bizarre "Hopeless Diamond" Concept
(From [79])

Similar concerns dominated the F-117's pyramidal lines which were produced in fleet numbers and used operationally. Its RCS reduction techniques were mainly based on faceting. This was a unique and successful design feature, achieving extremely low RCS against conventional radars of the era. Without sufficient computer program aids to make complex RCS predictions, faceting was the only feasible way to design the aircraft. This made the F-117 a pioneer of the stealth world. Even though aircraft retirement has been initiated, its capabilities remain unmatched.

The F-117 was deployed as a single pilot, twin-engine powered, stealth, night strike, light bomber with the ability of cruising at high sub-sonic speeds (max. 0.92 mach), carrying 5000 lbs bombs (usually two, each weighing around 2000 lbs) and having a range of 900 miles, with extension by air-refueling.

The F-117A Nighthawk's main mission was the attack of important and strategic ground targets, such as enemy command and control centers, air defense units and weapon launch units (i.e., mass destruction weapons), by penetrating dense defenses using its stealth technology and smart bombs. In some phases of its production, the F-117 was envisioned to have an enlarged mission envelope by including air to air capabilities. However, in the end, the aircraft remained a precision ground attack aircraft with total stealth characteristics. It was used against high value enemy targets, and usually deployed at night. It was postulated that after an initial attack with these aircraft, the enemy's defense capabilities would be destroyed, and conventional bombers would be tasked to fly their missions in hostile territory with reduced risk and a greater certainty of mission success.

There are numerous low observable technologies for which the F-117 was the first operational aircraft. Faceting was one of these, where the fuselage of the aircraft was produced with straight lines, which was different from the conventional curved approaches. The wings have three flat surfaces, one on the top and two on the underside. The aircraft has outward-canted thermoplastic graphite rudders. Because of its unusual aerodynamic shape, a fly-by wire control system is used for handling. Flight data is taken from four special faceted low observable air pitot probes in the nose of the aircraft. The entire body is coated with RAM. The cockpit panels, as well as other access panels such as weapon bays, have serrated shapes to reflect the incoming signal in directions other than toward the radar receiver. The faceted cockpit glass, shown in Figure 55, has special coatings which prevent radar waves from penetrating into the cockpit, thus eliminating further reflections. The engine intakes have fine mesh grids, shown in Figure 56, which are 2.5 cm by 1.5 cm, to conceal the engine blades that would otherwise contribute to the RCS. The forward-looking IR (FLIR) and downward-looking IR (DLIR) panel apertures are covered with wire mesh, as shown in Figure 57.

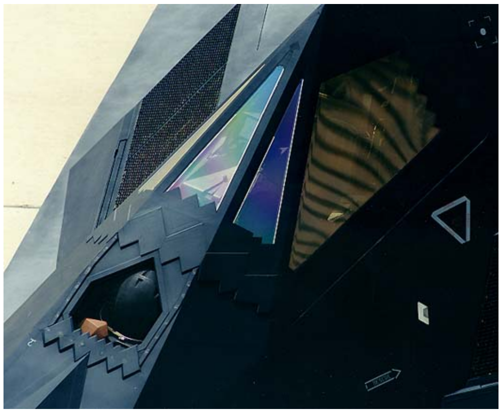

Figure 55. Reflection of F-117's Cockpit Coating (From [80])

To avoid signal detection by hostile receivers, no radar is deployed on the aircraft. The inertial navigation system is aided by flight computers and a global positioning system (GPS) satellite navigation receiver (this was a later upgrade). For locating target and guiding weapons, IR (FLIR for initial detection and DLIR for close range) and electro-optic laser designator systems are used to take advantage of their passive nature. All of the ordnance is carried internally in centerline weapons bays. If a determination is made that there is a risk of being detected, the aircraft's automated system blocks the bomb doors from opening.

Figure 56. Thin Mesh Grids, at the Engine Intakes of F-117 (From [81])

Most of the design features are used against radar detection, but some are for IR signal reduction. Together with some IR signal reducing coatings on the surface, a portion of the inhaled air bypasses the engine and is utilized to decrease the temperature of engine efflux by forming a mixture consisting of this air mass and hot engine efflux. This mixture is ejected through narrow-slot exhausts in the rear fuselage [7] and diminishes the aircraft's jet plume IR signature [7].

Figure 57. F-117's Fine Wire Mesh of FLIR Aperture, and Faceted-serrated Shape of its Canopy
(From [81])

2. B-2A Spirit (Stealth Bomber)

The B-2, as shown in Figure 58, is a long-range, multi-role, heavy strategic stealth bomber with the capability of carrying both conventional and nuclear payloads. It is piloted by two crew members, with a place for a third flight-member. Because of its nuclear mission, it is radiation hardened. It can carry up to 40,000 pounds of armament: 16 nuclear bombs, 16 to 80 conventional bombs, or 8 to 12 precision guided attack bombs. All of these must be located in its internal bomb bays, shown in Figure 59. If mission requirements dictate, a mixed bomb configuration is also possible. By using a flying wing concept, the B-2 has minimal surfaces contributing to drag, and its four non afterburning turbofan engines within the body-wing blended shape give it a considerable lift factor. This enables the aircraft to carry large payloads with fuel efficiency to intercontinental ranges (nearly 6000 nautical miles at up to a 50,000 ft mission ceiling), that can be extended with refueling. It has a high subsonic (maximum speed of nearly 0.85 mach) cruise speed which both provides mission capability and contributes to its low observability.

Figure 58. B-2 Spirit Flying Wing Aircraft (From [82])

Figure 59. B-2's Open Bomb Bays (From [82])

"It would be a superb bomber even if it weren't stealthy [7]," however, the B-2's third generation low observable characteristics, which were designed using computer technologies of the 1980s, increased its operational value. Similar to the F-117, its RCS reduction methods were focused on either reflecting the incident radar signal away from the radar receiver, or absorbing it as much as possible. However, it was not shaped with faceting, which would add aerodynamic difficulties. During the design phase, both aerodynamic and stealthy objectives were united and accomplished by means of the flying wing concept. RCS predictions were made with computer-aided design. Being a flying wing, it was not very maneuverable, but the normal cruising handling problems were resolved by a fly-by-wire control and stability augmentation system.

Unlike the F-117, the B-2 is painted with a bluish-gray anti-reflective paint [83]. Black paint is more visible than this specially chosen color in daylight flight operations and would increase the visual signature of the B-2 bomber. However, B-2's painting enhances its ability to satisfy daylight and night attack missions. When the B-2 is cruising in an area where there is a greater chance of radar detection, its control surfaces are used less to reduce the RF signal reflections from them. In this case the aircraft's yaw control is provided by differential engine thrust [83].

The B-2 has smooth, curved lines and seamless rounded surfaces with 14 straight edges, aligned at one of two fixed angles [7]. These edges reflect the incident radar beam towards those two angles, thus monostatic radars cannot receive them. This configuration of B-2 is also very advantageous versus bistatic radars which are considered for anti stealth purposes. Because there are only two reflection angles from this aircraft, it is very complex for bistatic radars to be settled at correct geometrical positions.

Serrated edges are used extensively in B-2's design and cockpit windows have fine wire mesh for reducing RF signal reflections. Engine nacelles and nozzles (ahead of the trailing edge) are all placed above the wings as a design measure for both RF and IR signal reduction. The four engines are concealed from the reach of direct radar signals by the curved shape of the nacelles. The air intakes have a very complex shape, with a slit-like secondary inlet below the main opening [3] and two extra air supply doors, as shown in Figure 60, on the upper surface of each nacelle to increase the performance of the engines at taxi, take-off, while flying at low speeds and under cases of turbulence. The heat of the exhausts is also eliminated by mixing airflow obtained through the boundary layer splitter slot to reduce the IR signature [83].

Figure 60. Auxiliary Air Intake Doors are Required for B-2's Take Off (From [82])

B-2 designers used extensive RAM and RAS, especially at the leading edges as further treatment for surface wave propagation. However, these nearly perfect stealth measures also require extensive maintenance. The B-2's pre-flight preparation before an ordinary mission requires approximately 119 hours of total maintenance, which is both time consuming and costly [84]. Furthermore, maintenance of the aircraft requires special climate-controlled hangars.

The B-2 has a low probability of intercept (LPI) radar with target search-location-identification-acquisition modes, and weapon delivery, terrain following, terrain avoidance and navigation system capabilities. Because LPI radar signals are hard to detect, they are less likely to spoil the stealthy characteristics of the aircraft. The B-2 uses radar, GPS and a computer-aided inertial navigation system, along with an astro-inertial unit, which obtains position fixes using a telescope to lock on to star positions [83]. Furthermore, there is a rearward-facing laser radar system which is used to detect exhaust contrails and warn the pilot to move to a safer altitude where contrails are not formed. The aircraft also has some electronic countermeasure deployments.

3. F-22A Raptor

Following the success of the stealth F-117A and the B-2A bombers, the U.S. Air Force began work on a new stealthy air superiority fighter project, the Advanced Tactical Fighter (ATF), at the end of 1980s. The YF-22, shown in Figure 61, was selected for this role to replace the aging fleet of F-15s. Thus, it was designed as a one seat, next generation, multi-role, air superiority stealth fighter and after some development changes

YF-22 was turned into F-22A Raptor. The mission of the Raptor includes escorting other attack aircraft to their targets, hunting enemy fighters, and destroying air defenses such as SAM sites. U.S. forces expect the F-22, shown in Figure 62, to provide air superiority by dominating the increasing capabilities of integrated air defense systems and hostile air forces with its precision ground attack capability and air-to-air sophistication for the next 40 years [85]. The main concept of the F-22 is “first-look, first-shot, first-kill capability [85]” by using its stealth capabilities, advanced sensors and precise air-to-air and air-to-ground weapons. It is very maneuverable with its large control surfaces and two thrust vectoring engines with a mission ceiling of more than 50,000 ft.

Figure 61. YF-22
(From [86])

Figure 62. F-22 A Raptor
(From [87])

The Raptor has many innovations, as well as, heritage from earlier stealth aircraft. Because it is an air superiority fighter, it requires a sophisticated radar system with the capability of long range detection, while concealing itself from detection. This is possible with its all weather LPI radar suite, the active electronically scanned array (AESA) APG-77, which consists of an interlinked set of small transmitters and receivers, shown in Figure 63, and the ALR-94 passive receiver system. Figure 64 shows the nose radome of the F-22 where APG-77 radar set is fitted in, moreover Figure 64 reveals some of the shaping differences of F-22A Raptor from its predecessor YF-22 (See also Figure 61). F-22's radar is capable of limiting its emissions and sending radar signals in a narrower beam, 2° in azimuth and 2° in elevation, by means of data received from the passive receiver system. With nearly 30 antennas on the wings and fuselage, this passive system detects threat radar transmitters at an approximate range of 250 nautical miles to align the LPI radar's signal transmitting procedure without being detected. The LPI radar has a long range target acquisition capability (nearly 120 nautical miles) with multiple target tracking. Moreover, the LPI radar can focus its emission on an opponent's radar receiver to overload its sensors, and it can detect threats with identification, along the lines of stand-off SIGINT platforms, such as the RC-135 Rivet Joint [85]. It can also pass all its radar data to other F-22A Raptors (and possibly other suitable data-link capable aircraft) via a secure intra-flight datalink. When all ordnance is expended or mission dictates, the F-22A can loiter in the mission zone to provide electronic surveillance. This gives the F-22A somewhat electronic jamming and signal intelligence role.

Figure 63. F-22's APG-77 A Active Electronically Scanned Array Radar (From [88])

Figure 64. F-22's Radar is Fitted Inside the Nose Radome (From [89])

The F-22 uses less RAM and RAS than earlier generation stealth aircraft. Some of the RAM is a sprayed-on type and it covers the edges of doors and control surfaces. RAS is used on the body, wing and tail edges, and its conductive metallic coating prevents radar energy from penetrating the composite skin [90]. The F-22, like other stealth aircraft, has a carefully designed shape that contributes to RCS reduction. The forward fuselage is diamond-shaped in cross section and the fuselage has large surfaces. The aircraft has inlet ducts which are both curved inwards and upwards to provide shielding to front faces of the twin engines from direct illumination by hostile radars [7]. It has trapezoidal wing and twin tails and canted rudders. There are many serrated surfaces and the cockpit has special coatings to decrease the amount of reflections back to a hostile radar receiver. It carries its payload in three weapon bays. Two of them are on the sides of the fuselage and one is in the central bay. The weapon bays have saw tooth edges and are open for less than a second when launching ordnance. An M61A2 Vulcan 20 mm rotary cannon is deployed for close contact conflicts and it is also hidden in a trap door. Stealth design requires the cannon door to open only when canon is in use [7], [90].

The F-22 has two afterburning engines. It can use its super cruise ability to fly at speeds greater than 1.5 mach without using the afterburners and can sustain this speed much longer than conventional fighters. The super cruise gives an advantage in fuel efficiency, while penetrating and leaving enemy territory quickly. In this context, not using afterburners also reduces the IR signature of the aircraft. Further IR signature reduction is provided by painting the entire airframe of the F-22 with a Boeing-developed camouflage topcoat [90] and using fuel for active cooling of leading edges.

The payload of the F-22 can be increased with its four underwing pods, shown in Figure 65 and Figure 66, if the mission is suitable for this non-stealthy configuration. The pylons under the wing can be jettisoned after expending ordnance to regain low observability. Furthermore, development of stealthy ordnance is under research [90]. The exact RCS level of the aircraft is confidential; however it is hypothesized to be -40 dBsm (0.0001 m^2) at certain critical angles [90].

Figure 65. F-22 with Two External Fuel Tanks Payload (From [91])

Figure 66. F-22 with Two External Missiles Payload (From, [92])

4. Some Modern UAV and Cruise Missile Examples

Along with manned aircraft, unmanned aerial vehicles (UAVs) or unmanned aerial systems (UAS) and cruise missiles also take advantage of stealth technology. UAVs maintain significant advantage over manned aircraft. They do not put human life at risk, since there is no pilot on board, thus affording them the ability to enter even the most risky battlefield environments. Additionally, they can stay airborne for extended periods because there are no crew restrictions. Further, they weigh less, cost less, are smaller, have more payload, and more maneuvering capability than comparable manned aircraft. To increase their survivability, just as in the case of manned aircraft, stealth technologies are now being applied to UAV design.

Modern stealth UAVs use similar techniques as manned aircraft to reduce their signatures. Most stealth UAVs are flying wing designs without tails, with sharply canted surfaces, engines located on top of the fuselage and internal payloads. Serrated surfaces and RAM/RAS are also used for further RCS reduction. Some of the prototypes, such as the “Joint Unmanned Combat Air Systems (J-UCAS)” include further treatment to decrease the risk of visual detection. Active coatings are being tested in its design to provide the ability to alter the colors and luminance in order to blend with the background. Challenges remain, but this may be practical in the future with new technologies, like high-brightness, low-power light-emitting diodes (LEDs) and better computer control systems with visual simulators [93].

The RQ-3 DarkStar, Boeing X-45C (Figure 67), Northrop Grumman X-47A (Figure 68), BAE Systems Taranis, and the Dassault nEUROn (Figure 69) are some UAV examples which have used stealth technology.

Figure 67. Boeing X-45 C
(From [94])

Figure 68. Northrop Grumman X-47 A
(From [95])

Figure 69. Dassault nEUROn
(From [96])

Some modern cruise missiles also use stealth technology to achieve their lethal missions without being detected by early warning radars, intercepted by precise SAMs or diverted by countermeasures. One of them is the AGM-129 Advanced Cruise Missile (ACM), shown in Figure 70. This missile has two separate conic-like parts forming the nose which are joined to each other by faceting. Flat fuselage, forward swept wings and the engine intake, which is hidden under the body of the missile, also contribute to reduce RCS. . Furthermore, the jet engine exhaust is shielded by the tail and cooled by a diffuser to reduce the infrared signature of the missile [97]. RAM is also used to reduce radar reflections. In order to reduce RF signal emission from the missile, no radar is used. Navigation is possible with a combination of inertial navigation and Light Detection and Ranging (LIDAR) terrain contour matching (TERCOM), supported with highly accurate speed updates provided by a laser Doppler velocimeter [97].

Figure 70. AGM-129 ACM
(From [98])

F. DISADVANTAGES OF STEALTH APPLICATIONS

During the Cold War, U.S. forces focused on defeating the Warsaw Pact military in their homeland. This required an air force that could maintain air superiority over all battlefields in Soviet Russia. However, the leadership of the Warsaw Pact, preferred to defeat their opponents with long range strategic missiles protected by heavy air defenses formed with surface-to-air missiles (SAMs). This exposed penetrating U.S. reconnaissance and bombing aircraft to heavy defenses. U.S. force structure compelled Russia to focus on detection and tracking technologies to counter U.S. Air Force asset penetration into its airspace. These strategic approaches resulted in the expansion of U.S. interest in low observables and Soviet Russia's efforts to form a strong air defense by means of more powerful acquisition systems and SAM launchers.

These challenges reveal that stealth technology is an inevitable requirement for today's modern forces to dominate the battlefield. Its many advantages give the user tactical combat superiority and an overwhelming dominance over an opponent. However, designing, manufacturing, operating and maintaining stealth assets has some cons. The use of the terms cons, disadvantages or drawbacks here does not intend to thwart advances in this sophisticated military technology, but it implies that there are some challenges to deploying these technologies. These challenges must be balanced by designers and users.

The first of these drawbacks is the poor aerodynamic properties common to stealth airframes. Rather than aerodynamic perfection, stealth aircraft are designed according to requirements for RCS reduction, and in general this results in handling difficulties. Most modern aircraft are made unstable at one axis for greater maneuverability; however, stealth aircraft are usually unstable in all axes. Unlike other modern fighters, stealth assets require highly redundant, fly-by-wire systems for flight safety, which increase the cost and add extra weight to the airframe. During training and experimental flights, there were many failures of these flight control systems, some of which resulted in crashes; one known B-2 crash, one of seven F-117 crashes, and both F-22 crashes were related to flight control unit malfunctions. Moreover, most stealth aircraft do not have engines with afterburners, thus they do not have high speed performance, and are not suitable for dogfighting. The F-22 Raptor is an exception and may be a future solution to this problem. It is both an agile and stealthy air superiority fighter, and that is why its shape is more conventional than other stealth assets.

The second disadvantage of stealth aircraft is the requirement to either restrict electromagnetic emissions completely or emit them in a very careful manner, such as via

LPI radars. Fully autonomous systems and applications using different systems, other than radar, reduce this risk; however, these systems have many constraints that limit the operational capability of the aircraft. LPI is a potential remedy and is a property of radar that, because of its low power, wide bandwidth, frequency variability, or other design attributes, makes it difficult for it to be detected by means of a passive intercept receiver [99]. So, radars and radio and data connection methods, based on the same principle, are realistic solutions for remaining stealthy. LPI technology is more necessary to low observables than any other asset. LPI can be used to support systems, such as altimeters, tactical airborne targeting, surveillance and navigation [99], while it also matches with other stealthy qualifications. However, such sophisticated LPI systems, which require continuous development to counter new receiver designs, result in very high costs and deployment of complex electronically instrumentation and software.

Another drawback is the high maintenance costs associated with stealth. To remain low observable, an aircraft's surfaces must sustain their faultlessness. Surfaces must be examined very carefully, considering the fact that even an improperly tightened screw might degrade the stealthiness of an aircraft. All RAM coated parts and special paintings must be treated before each mission. Moreover, this kind of maintenance requires special shelters, such as the B-2’s climate controlled hangars, shown in Figure 71. After each sortie, B-2 Spirit has to be maintained for nearly 119 hours with experienced staff and high-tech automated devices. It is preferable to deploy these aircraft on missions from their home bases only where they can be prepared for flight. The issue is that long range sorties conducted from the homeland against overseas targets still places a serious economic burden on stealth aircraft operators [100].

Figure 71. Special Climate Control Maintenance Shelters of B-2 Spirit (From [101])

The fourth disadvantage is that stealth aircraft are limited by the amount of ordnance they can carry. This is because in full stealth mode, aircraft are required to carry all of their ordnance internally, at least until the time when stealth weapons become operational. Thus, pre-operational intelligence is critical and the judicious use of ordnance is important, as reattack of targets is limited by inventory. Furthermore, when the weapon bays are opened, the RCS increases which raises an enemy's probability of detection.

Another drawback of stealth aircraft is their visual signatures. Although decreased by paintings, night missions (dependency on nights and weather conditions is another drawback), and other camouflage tactics, stealth aircraft are still visible to the naked eye. Currently, experiments are being conducted to develop approaches for total cancellation of visual illumination; however, there are no known applications of such a system on operational stealth aircraft at this time [100].

The sixth disadvantage is the negative reaction of the public to aircraft failures. Based on mission experience during various wars, stealth aircraft have proven to be extremely successful. However, there are several known failures that have had a negative influence on public opinion. Incidents include the shoot down of an F-117 (and there are speculations that more than one F-117 took severe damage from enemy fire) on 27 March 1999 during the Kosovo War. Other losses include shoot downs of U-2 Dragon Ladys and several low observable UAVs during the Cold War. Normally, such small numbers of shoot down incidents over battlefields and other losses of military aircraft during training are neglected. But, the loss of such expensive military assets, which are thought to be impervious to enemy defenses, receives significant public interest In addition to the shoot down of the F-117 over Serbian airspace, eight F-117s, two F-22A Raptors and one B-2A Spirit have been lost during training flights.

The final and the most important con of stealth technology is the cost. Cost is affected by three factors. The first factor is the level of effort required to achieve a perfect low observable capability. Though perfection has not been provided, gained capabilities have taken a very long time to achieve and have come at a high cost. These efforts have been effective, but designers have worked hard to find methods of defeating radars and other sensor systems.

The second cost factor is the total cost of improving operational effectiveness of stealth assets using other technologies, such as complex fly by wire systems, high-tech computer and control units, special super cruise engines, LPI radars, navigation, precision targeting systems, and stealth armaments, which are under development. These factors require spending exorbitant amounts of money. Moreover, production of all three currently operational stealth aircraft reveals that total program expense, together with sunk costs of these projects per aircraft, is extremely high. Projected production amount, actual production amount, average procurement unit cost per aircraft and program unit acquisition cost per aircraft with sunk-costs are presented in Table 3 [102], [103], [104]. The table exposes that relatively small production numbers increase the project total cost per aircraft. The reason for this is the increase in single airframe cost, when projected production amounts are decreased to relatively small numbers due to cost growth associated with unexpected commitments or changes in requirements. Moreover, it is difficult to recover development costs through sales to other nations, a common practice for non-stealth weapons systems. Stealth assets are protected from foreign military sales due to security concerns. In this context, the U.S. Congress has banned their sales by declaring their critical technology, even though these sales would likely to recover some of these costs.

	F-117A Nighthawk	B-2A Spirit	F-22A Raptor
First projected production amount	89	132	750
Actual production	59	21	Continuing. 127 of total 184 have been produced
Average Procurement Unit Cost per aircraft	$42.6 million	$737 million	$185.4 million
Program Unit Acquisition Cost per aircraft	$111.2 million	$2.13 billion	$353 million

Table 3. The Table Shows that Relatively Small Production Numbers Increase the Project Total Cost Per Aircraft

The third cost factor concerns operational expenses. For example, while the B-2 Spirit can be deployed any where in the world within 12 hours, "…it is operationally crippled by its exorbitant replacement cost and results in a challenging risk/benefit analysis when considering its deployment [100]." Table 4 compares the B-2A Spirit with other U.S. strategic bombers; semi stealth B-1B Lancer and the highly conventional B-52H Stratofortress, which were also designed and produced for heavy bombing missions.

	B-2A "Spirit"	B-1B "Lancer"	B-52H "Stratofortress"
Date Deployed	1993	1985	1955
Prime contractor	Northrop Grumman	Rockwell	Boeing
Cost per aircraft	~$2.2 billion	$200 million	$74 million
Number in inventory	21	95	85 (+9 reserve)
Weapons payload	40,000 pounds	72,000+ pounds	70,000 pounds
JDAM payload	16	24	12
Speed	~600 mph (high subsonic)	900 mph (mach 1.2)	650 mph (mach 0.86)
Crew	2	4	5

Table 4. Comparison of the Three U.S. Strategic Bombers (From [105])

Despite all these drawbacks and challenges in producing stealth assets, stealth technology has fulfilled the air force requirements for battlefield survivability since its first applications. Thus many assets have been developed and deployed. These airframes used stealth technology in favor of their tactical combat superiority and overwhelming dominance over an opponent. In this context, specially designed air defenses with new radar systems and tactics have been required to withstand against low observables. Next chapter will discuss counter stealth technologies which focus to improve solutions for air defenses by means of exploiting the technological limitations of stealth technology.

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IV. COUNTER RF STEALTH TECHNOLOGY

> *Until detection, everything else is irrelevant; none of the subsequent events of warfare are possible without detection* [39].

As mentioned in Chapter III, like all other technologies used in military applications, stealth technology has some disadvantages and limitations. While one side tries to improve the survivability of an airborne asset by means of reducing certain detectable signal signatures, the opponent, conversely, exploits those same signatures and employs sophisticated techniques to improve detection capability and reduce the effectiveness of the low observables. Generally, efforts which are used to neutralize or decrease the military advantages of stealth are referred to as “counter stealth” or “anti stealth”.

Stealth technology mostly focuses on defeating conventional monostatic radar systems which cover the microwave band. Thus, the success of counter stealth endeavors is focused mostly on novel and unique air defense infrastructure configurations. These designs include either radars operating in other bands (HF or far above those of traditional microwave radars), specially designed receiver units and sensors able to detect low observables or new applied techniques and smart tactics.

Radar-based air defense systems are intended to detect targets first and then to attack. To form an effective air defense system, the main principles of engagement are important to consider. These include detecting via early warning (EW) radar and acquisition radar, tracking by means of fire control radars, generating a fire control solution, slewing and arming the weapons for firing position, fusing the warhead and conducting damage assessment [39]. For effective counter stealth purposes, these engagement events should be considered step-by-step to get the ultimate result. In the next section, the detection and tracking issues associated with engagement will be discussed.

A. OBTAINING STRONGER RADAR RETURNS AND USING MORE SOPHISTICATED ALGORITHMS AT THE RECEIVER

One technique to improve the detection capability of radar is transmitting more energy and using a more sensitive receiver. Although this improves the effectiveness, increasing the size and weight is required, which results in decreased mobility and increased cost. Moreover, additional sensitivity of the receiver means extra clutter and a greater number of false targets. Extra clutter and false targets overload the device and slow down the computational performance of the radar. These effects can be sorted out only with highly sophisticated processors that also increase cost [7]. Despite these drawbacks, increasing the transmitted power and receiver sensitivity enable the radar to obtain stronger reflections from the target. Thus, more reflected power enhances radar's capability to form the signature of the target on the radar. All counter stealth radar types, which are discussed further in this chapter, will need to optimize and employ both of these important qualities to improve their detection capabilities.

Other qualities of interest include radar scanning method and processing ability. Normally, traditional radars cancel out signals which are under a threshold value and display only meaningful targets. As a result of their small RCS values, the energy returned from low observables is typically below threshold and therefore, the target is undetected. However, electronically scanned radars, with fast scanning speeds, allow the evaluation of suspected signals over a greater time period, observing targets of interest with the main transmitted beam and several received beams. A similar operating mode, without a selected threshold, uses the "track-before-detect" method. This technique utilizes "computing-intensive algorithms" to discriminate the real target from the clutter and other undesired data. This discrimination occurs while tracking all received signals, over a certain time period, then determining and cancelling false targets from their "unreasonable and unrealistic behaviors [7]". These types of applications are an important improvement to all types of radar counter stealth capabilities.

Stealth aircraft reflect inbound microwave radar signals to a degree less than that of a small tennis ball when illuminated from a frontal aspect, where RCS measures are most pronounced. Therefore, generating a meaningful detection from ordinary clutter is a difficult task, especially at longer distances. Even if the problems of transmitting more power and using more sensitive receivers are solved, current system capabilities would still be limited in their ability to detect low observables at distances required to tip the operational advantage in favor of the defender. However, future developments in radar computing power, augmented by advanced algorithms, such as “track before detect”, may provide the processing capability required to improve detection range and to defeat stealth assets.

B. VERY HIGH FREQENCY (VHF) AND ULTRA HIGH FREQUENCY (UHF) RADARS

In general, radars using VHF and UHF, as well as high frequency (HF) and lower bands, are called low frequency radars. These low frequency radars, such as those that operate at C (0.5-1 GHz.), B (250-500 GHz.), and A (up to 250 MHz.) bands, are designed and manufactured more easily compared to radars that use higher frequencies. This is the main reason earlier radars were operated at such low frequencies. Furthermore, low frequency radars have long-range performance utilizing surface waves and are less affected by atmospheric interference and absorption. However, they have some operational disadvantages, including the requirement for physically big antennas and poor resolution. Modern radars have several advantages of these radars and have replaced them. These advantages include smaller sizes, better low altitude coverage and improved target discrimination. Moreover, advances in signal processing and increased computing power have expedited the modernization of air defenses with new radars using higher frequencies. Thus most modern surveillance radars operate at D (1-2 GHz.), E (2-3GHz.), and F (3-4 GHz.) bands and are well-suited for detecting aircraft. Target tracking systems, which are tasked to direct missiles to their intended targets, are operated at even higher frequencies, such as X (8-12 GHz.) or Ku band (12-18 GHz.). (The frequency band categorizations noted in this paragraph are in accordance with “EU, US, NATO ECM” military standard radio waves.)

When low observable assets are designed, their RCS reduction features like RAM, edge alignment, faceting and other shaping methods, are focused primarily on defeating new military early-warning/surveillance and target acquisition radars. In general, when the wavelength of radar frequency is much shorter than the cardinal dimensions of the low observable airframe or its separate parts, as in Ku (wavelength is 1.66 to 2.5 cm) and X (wavelength is 2.5 to 3.75 cm) band target tracking systems, then reducing total RCS of the asset is better served by shaping methods. The wavelengths of these decimetric, or milimetric band radars are in optical scattering region and they are much smaller than the size of aircraft and its components. Thus shaping features can be used to change the directions of reflections which provide low observability. However, these methods are less effective in the Raleigh and Resonance regimes of scattering, which are depicted in Figure 72. The length of radar wave according to the physical dimensions of the target determines the physics of radar scattering [106]. In the Raleigh scattering regime, the physical size of the target is close or smaller than the wavelength in magnitude, and the reflection increases when the physical size is larger.

The resonance phenomenon is produced when an airframe's dimensions (or their exterior body surfaces) are the same size as a half wavelength, creating in-phase reflections from the ends of the targets. The same principle is demonstrated in the use of chaff, which is comprised of metal foil cut to a size nearly half that of the targeted radar's wavelength. These particles resonate and reflect the incident beam and behave as if they were larger detected objects. Therefore, these particles in great numbers appear as real targets and jam the radar monitoring them [39], [106].

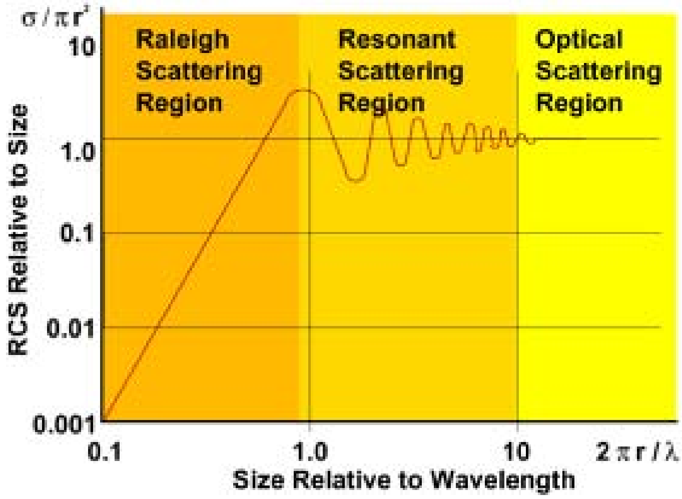

Figure 72. The Physics of Radar Scattering (From [106])

The resonance effect is a characteristic of conducting and lossy bodies. This effect results in a higher RCS when a target is illuminated by a radar operating at resonant frequencies as opposed to non-resonant frequencies. Targets may have many resonant frequencies due to the presence of multiple exterior components, like the fuselage, engines and wings. This phenomenon actually occurs at every frequency; however, when the half wavelength is approximately equal to the size of the surface of airframe, the strongest resonance takes place. Practical aircraft shapes and common RAM applications are ineffective in canceling these resonance effects. Thick RAM coatings are needed to defeat resonant effects, but these are not feasible for aircraft. However, electrically breaking up the structures of aircraft and adding loss to these surfaces with coatings may be helpful to some extent [39].

Figure 73 illustrates the planform perspective of the F-35 JSF in the 2 metre band VHF (150 MHz.) radar. There are many parts of the aircraft at which Raleigh scattering is possible since shaping features are smaller than this wavelength. Red circles around aircraft's nose, inlets, nozzle and other junctions between fuselage, wing and stabs show the areas of this kind of scattering. Moreover, resonance scattering is also highly likely since straight edges with yellow lines are 1.5 to two wavelengths in size. Use of this kind radar wavelength will simply decrease F-35 JSF's low observability characteristics [107].

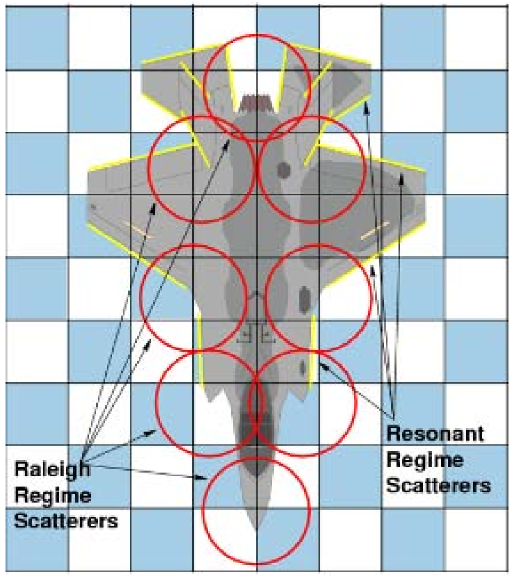

Figure 73. F-35 JSF in the 2 Metre Band VHF (150 MHz) Radar (From [107])

Radars which use UHF, and especially VHF bands with wavelengths on the order of a meter, satisfy the physics of resonance or Raleigh scattering, thus stealth aircraft are detected by them at greater distances compared to more common higher frequency radars. However, there are problems gaining meaningful detections. Angular accuracy of these radars has been deficient until recently. The required antenna size for effective results requires "ungainly systems which are usually slow to deploy and stow, even if designed from the outset for mobility [106]". They also have poor low altitude detection performance. Another problem is that these low frequency bands are usually used by other communication and broadcast networks, thus these bands carry a great deal of noise. Originally it was difficult for missile seekers to home in on their large beams, but they are now designed to emit high power beams coupled with a large antenna size. These are required to produce narrower beams and sufficient resolution. These factors reduce mobility, and radiating high power through a large antenna makes them vulnerable to anti-radiation missiles [106].

Despite such limitations, some old-fashioned Russian low-band radars, such as the 55Zh6 Nebo, 1L13 Nebo SV (Figure 74), Nebo SVU (Figure 75) and 5N84 Oborona, are still operated and provide valuable early warning coverage. Moreover, these radars are thought to be very useful in guiding other precise tracking sensors and platforms. The high power aperture X-band 30N6E Flap Lid/92N2E Tomb Stone series and the 9S32M Grill Pan systems provide this kind of sector information to launch missiles from the S-300PMU, S-400/S-400M and S-300VM systems. They generate small acquisition boxes to improve tracking quality and locate stealth assets by means of using an extreme amount of RF power directed towards a smaller volume of airspace. The more sophisticated Nebo SVU, Gamma DE (Figure 76) and Protivnik GE (Figure 77) systems are also able to directly lock on a missile with their great accuracy. After launch, the data link capability of these systems guides the missile to the target to a close range [106].

The idea that Russian low-band radars are artifacts of the Cold War with little combat value [106] is not an accurate statement. In reality, they have been modernized using technologies such as active phased arrays, digital moving target indicator, space time adaptive processing and digital pulse Doppler techniques. Moreover these systems, which are also marketed as counter-stealth products, have digital signal and data processing capabilities with contemporary display components and solid state transmitters. By using such modern and low frequency radars, either for surveillance, aiding other precise systems or directly tracking targets for missile launch systems, the surprise attack advantage of stealth aircraft may be suppressed [106].

Figure 74. Russian Low Frequency (VHF) Radar 1L13 Nebo SV (From [107])

Figure 75. Russian Low Frequency (VHF) Radar Nebo SVU (From [107])

Figure 76. Gamma DE L-band Low Frequency (Upper UHF) Radar (From [107])

Figure 77. Protivnik GE L-band Low Frequency (Upper UHF) Radar (From [107])

C. HIGH FREQUENCY (HF) OVER-THE-HORIZON RADARS (OTHRs)

Over-the-horizon radars (OTHRs), which operate in the high frequency (3-30 MHz) band, enable “wide area surveillance” by means of reflecting radio waves off of the ionosphere. These systems are also known as sky wave radars (Figure 78). In these systems, targets completely obscured by the horizon are detected by bouncing signals from the ionosphere. The range of these systems is not limited by either the curvature of the earth or the direct line of sight. There are several defense-related applications for these systems; such as ocean surface monitoring and locating aircraft, and they are, to some extent, considered promising techniques for detecting low observables [108].

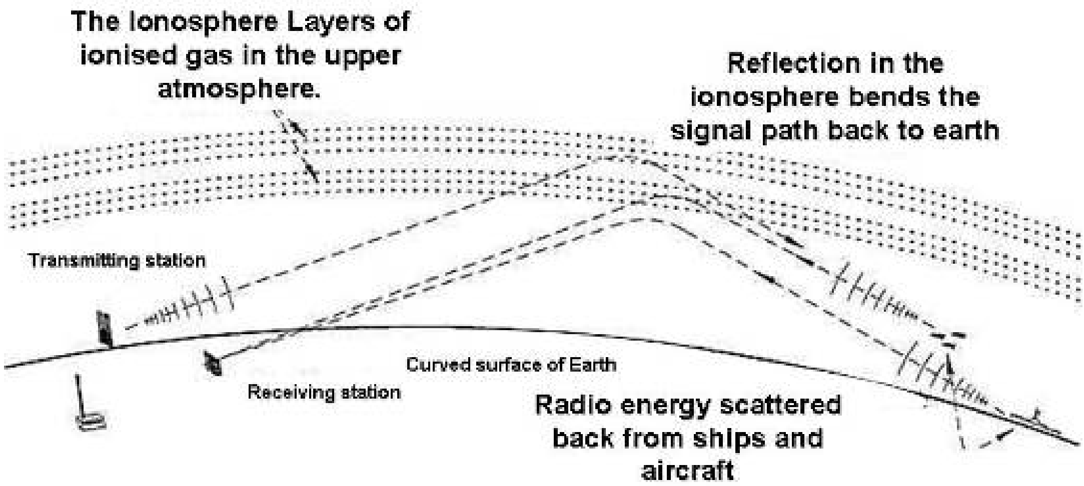

Figure 78. Over-the- horizon Radar using Sky-wave Propagation (After [109])

Over-the-horizon radar wave propagation can also be accomplished by surface waves as shown in Figure 79. This approach results in a reduced detection range when compared to HF radars based on the sky wave phenomenon. Surface wave transmission, in which the coupling effect between the conductive surface of the Earth (mostly sea) and an HF radio wave, cause energy to bend around and follow the curvature of the earth for several hundred kilometers. The radio energy travels along the curvature of the Earth in its path and some portion of this energy follows a similar path when it is reflected back from the target [109]. In this way, surface wave radars yield low-level radar detection capability, well beyond the horizon, which is not possible for normal radar sets. However, sky wave radars have much larger detection ranges up to 1000-4000 km, while the detection capability of the surface wave phenomenon is around 10 to 400 km.[108], [109].

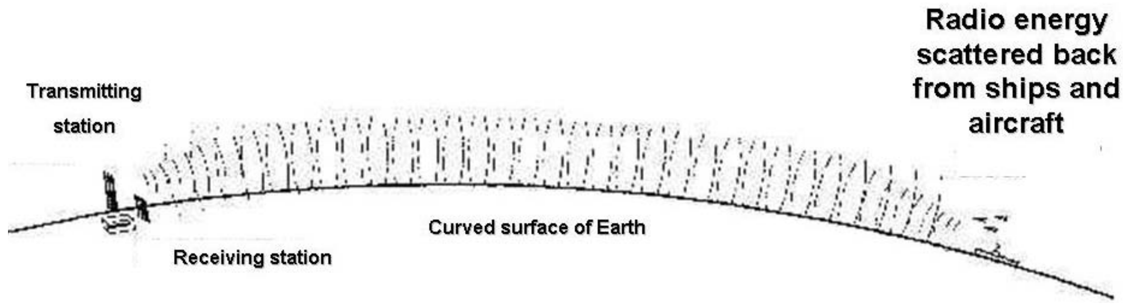

Figure 79. Over-the- horizon Radar using Ground-wave Propagation (After [109])

HF radars receive only small amount of radar energy back from the target and "extracting genuine target plots from the noise and clutter picked up by the receiving system [109]" is a hard and complex procedure. Advanced transmitting systems, together with sophisticated signal processing units which use digital Doppler analysis and great computing power, are required for these applications. Modern HF radars are usually deployed with phased-array antennas to control the direction of the radar beam energy, while receivers are separated (in most cases) from the transmitter, to rule out the effects of direct coupling. During signal processing, range is calculated by using time delay and monopulse phase comparison techniques are used to determine azimuth angle. So, meaningful target detection information is only possible with "very precise knowledge of the frequency and phase of the transmitted signal, and ensuring that inter modulation products and other forms of distortion [109]" are reduced. Moreover, target detection is likely only after background noise and clutter is eliminated by using target motion information generated from Doppler changes in the frequency. This procedure integrates the returned signals over relatively long periods of time, allowing the detection of even slow moving objects, such as ships and vehicles [109].

OTHRs have some operational problems. First of all, there is insufficient bandwidth allocation to allow recognition of the reflected returns of a target through the associated interference. For example, when range increases, the signature of a small target, close to sea level, interferes with sea clutter. Good quality propagation technology is required to decrease such effects. Moreover, other system noises, such as radio and television broadcasting networks, and phenomena, such as ionospheric clutter, meteor clutter and solar radiation cause problems for signal processing and detection-related precision calculations. Additionally, ionospheric effects, which vary with time of day, complicate frequency selection and management. System location is another problem. These systems require large areas to be set up. Although there are some military mobile systems, they are still cumbersome due to their huge antennas [108].

When counter-stealth applications are considered, the biggest problem is obtaining positional information of the target. In general, these systems have real early warning qualities with the ability of showing the presence of a target in a specific region. However, the detection is not accurate enough to provide tracking capabilities sufficient for initiating retaliation [109] and, they only indicate that it is likely that a strike is on the way [110]. HF radars must be developed for greater accuracy and to give meaningful guiding detection to engagement systems. Another important problem for sky wave OTHRs is overcoming minimum detection range; the reflection from the ionosphere occurs at smaller incident angles than the critical angle. Critical angle is the steepest angle at which a radio signal can be refracted by the ionosphere, and bigger angles cause the radar wave to follow its way without reflection. Thus this angle also determines the shortest range for the detection. Critical angle changes with hourly, daily or seasonal conditions of the ionosphere and according to selected frequency. Affected from critical angle and its change, OTHRs are generally not capable of detecting targets within a radius of about 500 nm (~900 km). Thus, stealth aircraft can change course or carry out evasive maneuvers to defeat the OTHRs [7].

Despite these drawbacks, OTHRs have several advantages over to low observables. First of all, they have very long range detection capabilities. Because HF radars have wavelengths between 10 to 100 meters, all airborne assets generate some kind of resonance, and shaping measures together with RAM are not effective. Moreover engineers working on Australia's Jindalee OTHR report that “… it detects turbulent wake from targets [110]”. Currently, modern HF radar systems are still produced and some of them are also used to detect low flying, low signature targets, such as tactical ballistic missiles and low level flying stealth penetrators [110]. Dan Boyle from Jane’s Information Group states that:

> Most of the OTH radars transmit signals in the range from about 5MHz up to 28MHz. The B-2 Stealth bomber has a fuselage which forms a half-wave resonator at just over 7MHz, while a wing will resonate at about 2.8MHz. Tests have shown that cruise missiles can be detected by OTH sky wave radar, although performance is said to fall off as the length of the missile drops below half a wavelength, some 5.3m at 28MHz [109].

Several countries such as Australia (bi-static Jindalee Operational Radar Network (JORN), see Figure 80), Canada, China (Type-110), France (Valensole, monostatic Nostradamus), Italy (CONDO-R, mobile TPS-828, see Figure 81), Japan, Ukraine, United Kingdom, the Russian Federation (Steel Works) and The United States (MADRE, WARF, AN/FPS-95, Cobra Mist, AN/FPS-112, AN/FPS-118, AN/TPS-71) have OTHRs and are working on them for purposes of early warning surveillance over a wide area, detection of cruise missiles, surface ships and to some extent, low observables. Although detection range may vary with target, the best-known OTHR characteristics are shown in Tables 5 through 8 [108].

Figure 80. The JORN Transmission Antenna Array (From [108])

Figure 81. Italian TPS-828 Mobile Coastal Radar System (From [108])

Country	Australia	Canada		China		
Name or Type of the System	Jindalee-B	SWR-503	SWR-610	OTH-B	PD-OTH-B	SW-OTH
Operating Frequency	-	HF (3.5-5.5 MHz)	HF (6-10 MHz)	HF (6-22 MHz)		-
Waveform selection	-	-	-	FMCW	Pulse Doppler waveform	-
Monostatic/Bistatic	Bistatic	-	-	-	Bistatic	-
Transmitter Power (PT)	560 kW peak 158 kW (52 dBW)	-	-	200-1200 kW average	-	-
Transmitter Antenna Power Gain (GT)	21 dB	-	-	18 dB	-	-
Receiver Antenna Power Gain (GR)	32 dB	-	-	26 dB	-	-
Coherent Integration Time (tc)	17 dBs	-	-	6 dBs	-	-
Angular Resolution (Δθ, degrees)	0.5	-	-	5	-	-
Range Resolution (ΔR, km)	20	-	-	15	-	-
Detection Range	1000-3000 km	407 km	333 km	700-3500 km	700-3500 km	≤ 400 km
Note	-	-	-	-	-	-

Table 5. Australian, Canadian and Chinese OTHRs (From [108])

Country	France		Italy	USSA	
Name or Type of the System	Valensole	Nostradamus	CONDO-R	IRIDA OTH-SW	OTH-B Woodpeckers
Operating Frequency	HF	HF skywave (3-30MHz)	I-band (8-10 GHz)	HFsurface wave (7-15MHz)	HF (4-30MHz)
Waveform selection	Pulse waveform	Phased-coded pulse waveform	-	-	-
Monostatic/Bistatic	Monostatic	Monostatic	-	Bistatic	-
Transmitter Power (PT)	100 kW peak (24 dBW)	50 kW	-	65 kW peak 16 kW average	20-40 MW (From [31]) 1.2 MW (61 dBW)
Transmitter Antenna Power Gain (GT)	20 dB	-	-	-	-
Receiver Antenna Power Gain (GR)	26 dB	-	-	-	-
Coherent Integration Time (tc)	25 dBs	-	-	-	-
Angular Resolution (Δθ, degrees)	1	-	-	-	-
Range Resolution (ΔR, km)	22.5	-	-	-	-
Detection Range	-	800-3000 km	-	280-300 km	-
Note	-	-	-	-	-

Table 6. French, Italian and Russian OTHRs (From [108])

Country	Ukraine				UK	
Name or Type of the System	Transportable OTH-SW		Shipboard OTH-SW	Transportable SkW_OTH	Alenia Marconi OTHR	Overseer
	200 km	300 km				
Operating Frequency	HF (18-25MHz)	HF (6-24MHz)	HF (18-25MHz)	HF (5-28MHz)	HF surface wave (3-30MHz)	HF surface wave (4-12MHz)
Waveform selection	-	-	-	-	-	-
Monostatic/Bistatic	Bistatic	Bistatic	-	Bistatic	-	-
Transmitter Power (PT)	-	-	-	-	40 kW peak	40 kW peak
Transmitter Antenna Power Gain (GT)	-	-	-	-	-	-
Receiver Antenna Power Gain (GR)	-	-	-	-	-	-
Coherent Integration Time (tc)	-	-	-	-	-	-
Angular Resolution (Δθ, degrees)	-	-	-	-	-	-
Range Resolution (ΔR, km)	-	-	-	-	-	-
Detection Range	~200 km	~300 km	~170 km	600-2600 km	~ 370 km	~ 370 km
Note	-	-	-	-	-	-

Table 7. Ukrainian and British OTHRs (From [108])

Country	USA					
Name or Type of the System	MADRE	WARF	AN/FPS-95 (Cobra Mist)	AN/FPS-112	AN/FPS-118 (CONUS-OTH-B, Maine)	AN/TPS-71 (ROTHR)
Operating Frequency		HF (6-28MHz)	-	-	HF (5-28MHz)	HF (5-28MHz)
Waveform selection	Simple pulse waveform	FMCW	Simple pulse waveform	Phased-coded pulse waveform	FMCW (FMCW)	-
Monostatic/Bistatic	-	-	-	-	Bistatic	Bistatic
Transmitter Power (PT)	25 kW (27 dBW)	43 dBW	250 kW	-	1200 kW	200 kW (53 dBW)
Transmitter Antenna Power Gain (GT)	28 dB	20 dB	-	-	-	21 dB
Receiver Antenna Power Gain (GR)	22 dB	30 dB	-	-	-	34 dB
Coherent Integration Time (tc)	20 dBs	11 dBs	-	-	-	-
Angular Resolution (Δθ, degrees)	1	0.5	-	-	-	0.5
Range Resolution (ΔR, km)	7.5	0.8	-	-	-	-
Detection Range	-	-	-	-	926-3334 km (800-2880 km)	926-2963 km
Note	-	-	Not in current use	Not in current use	-	-

Table 8. U.S. OTHRs
(From [108])

D. BISTATIC AND MULTISTATIC RADAR TECHNOLOGY

Bistatic radar is a radar configuration where the receiver is geographically located separately from the transmitter (Figure 82). This configuration provides many opportunities in both commercial and military applications [111] over its monostatic counterpart. In fact, the idea to design bistatic radars is not new. Before WWII, scientists started working on such systems to obtain frequency separation by means of isolated radar receiver and transmitter sets, especially related to continuous wave (CW) experiments [111]. During WWII, the Germans used the British Chain Home radars as illuminators for their Klein Heidelberg bistatic systems which were also the first passive radar applications [112].

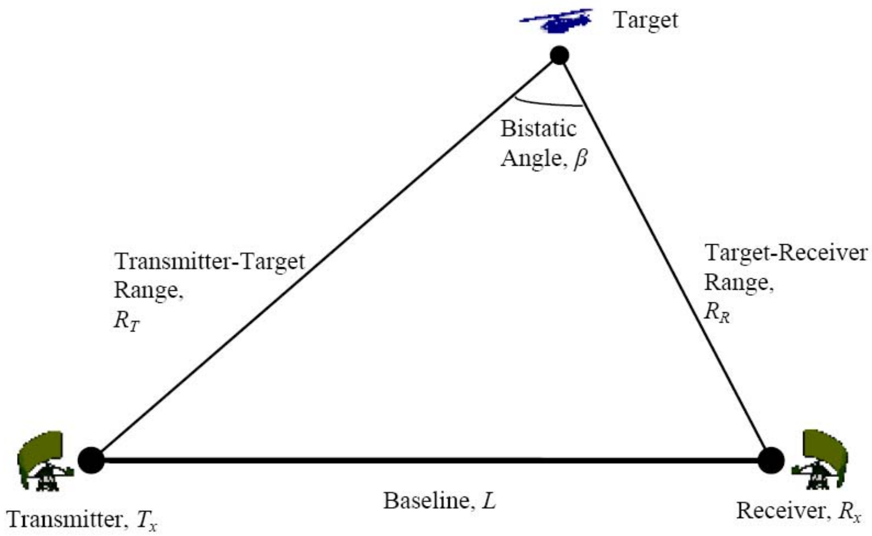

Figure 82. Bistatic Radar Configuration (From [111])

The multistatic radar configuration, depicted in Figure 83, is a very complex system with its many distributed receivers associated with a single or multiple transmitters [111]. Such a network-like construction provides the user with wide area tracking and increases the chances of detection. When several transmitter and receiver units are linked up, the number of beams increases the probability of detection considerably. This is possible by searching for bistatic reflections from targets in a given airfield volume in a centrally controlled manner or by synchronization with receivers. After each receiver unit collects the reflections from targets, a digital processor analyses them and produce meaningful tracking information from several directions simultaneously by those distributed receivers. Clearly, more effective surveillance can be achieved since the large number of tightly packed beams enables the system to look at the same place for a longer time [113]. With processes such as digital beam-forming, it is more likely that unwanted signals will be suppressed efficiently.

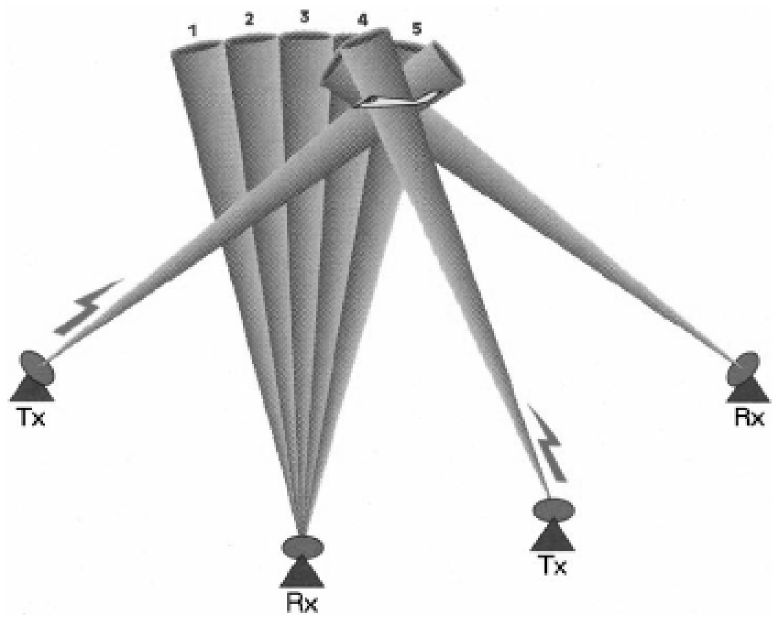

Figure 83. Multistatic Radar Configuration (From [114])

There are many advantages of bistatic and multistatic radar configurations. First of all, because the receiver is passive, it is undetectable, and safe from attack by anti-radiation missiles or deliberate directional interference and jamming [111]. There is no need to use a transmitter-receiver switch or duplexer devices which are lossy, expensive, and heavy. In many cases less radiated power is adequate for detection compared to a monostatic counterpart. "If the target angle can be measured at both sites, as well as the bistatic range, data can be checked for self-consistency to remove false alarms [111]".

Although bistatic and monostatic theories are promising for effective radar systems, there are also some technical challenges associated with them. Most of these can be mitigated by implementing greater computing power in these systems. First of all, sensitive time cooperation is required to maintain synchronization between transmitters and receivers, "… in respect of transmitter azimuth angle, instant of pulse transmission, and (for coherent processing) transmit signal phase [112]." Widespread use of Global Positioning System (GPS) signals in military systems may be a remedy to this problem. However, the GPS also has its own challenges in the battlefield. The second problem is the clutter and elusive signals which are returned from a variety of directions other than true reflection angle. Sophisticated algorithms, together with advanced computing power, which “follow the consistent returns and wash-out spikes that seem inconsistent with the target’s expected motion [114]”, may also detect new solutions to these problems.

Notwithstanding the technical complexities of an ordinary bisatic or multistatic radar system, there are even more challenges in getting enough desired signal back from low observable targets. First of all, the special designs of third and fourth generation stealth assets concentrate reflections at very few angles, with narrow lobes. Moreover, reflection angles continuously change with airframe speed and maneuvering. Thus, even if a bistatic radar is placed at the correct angles, it can only obtain the reflected signal for a short while. The multistatic configuration may be a promising solution, but in this case, too many sets of receiver and/or transmitter are required, which is not practical nor feasible. Searching a large volume, which is required for an effective surveillance system, is also a difficult task, and detection is only possible with the intersection of transmitter and receiver coverage.

Despite many limitations, these configurations remain among the most likely solutions to the detection of stealth airframes. As stated before, the main principle of RF RCS reduction, which was generally focused on counter monostatic radars, is based on shaping measures, like faceting, where a radar beam is reflected to a direction other than the incident direction. However, when a bistatic design is considered, there is an increase in the probability of low signature asset detection.

E. PASSIVE RADAR AND PASSIVE EMITTER LOCATION TECHNOLOGY

Passive radar, which is also known as passive coherent location (PCL) or passive covert radar, is a specific case of bistatic or multistatic radar; however, it differs from them by not having any dedicated transmitter unit. Instead, passive radar is designed to use other transmitter systems’ existing signals, which are reflected from targets, for processing. Many transmitters, such as analog television, FM radio, digital video-audio broadcasting and cell phone networks, may be the source of such a signal. The passive radar system uses a reference channel to sample the waves of those transmitters that are required for processing the incident beam from the target. After reception of both reference and target reflected signals, digital beamforming is used to determine the direction of arrival of signals and spatial rejection of strong in-band interference. This process is followed by filtering clutter and other unwanted signal returns. Cross-correlation of the reference channel with the target signal, enables definition of the object's bistatic range and its Doppler velocity, while association and fusion of line tracks from each transmitter reveal the target's final detection data, including location, heading and speed.

Other passive detection methods are also possible. One technique takes advantage of sophisticated computer power, and it attempts to detect changes in the electromagnetic (EM) radiation in a certain area. Because any target traveling in this area disturbs the EM noise in the selected bands and generates an EM gap, it is technically possible for the passive receiver to detect such traces. However, this procedure requires a very high processing power level. Another method uses a passive emitter location system which exploits the EM signals produced by a target's navigation, communication or aiming units, such as radio or radar emitters. Usually, these kind of passive receivers, which are basically modified signal intelligence platforms, are netted systems, including a central control unit together with several clients (usually three) to perform triangulation. The Ukrainian Kolchuga (Figure 84), Czech Kopac, Ramona and Tamara systems are some of many examples of these passive emitter location systems [114].

Figure 84. Kolchuga Passive Emitter Location Sensor (From [115])

There are many advantages of using such passive systems. First, they are covert systems and immune from hostile anti radiation homing attacks. Moreover, because they do not require dedicated transmitter units, they are usually cheaper than other radar systems. They are usually small and compact systems, thus mobile configurations are possible with high flexibility. One other advantage is that they do not require any frequency allocation. When stealth targets are considered, passive systems also have the advantage of being able to exploit many transmitter units, in most cases. Based on a multi-static configuration, together with the use of low frequencies as reference signals, both of which are less affected by the low observable's shaping features, passive radars are promising methods for counter stealth purposes.

As with the other systems, passive radars also have some operational disadvantages. There is no control over the transmitter units or the emitted signals' properties, such as waveform, power level or direction, despite the fact that the main receiver system is always dependent on them. Most transmitters use relatively low powered signals which result in short detection ranges. The need for reference signal acquisition increases the dependence of these systems on other transmitter units, which, in some cases, may limit the passive radar's operational performance. However, as with most counter stealth systems, the biggest problem associated with passive systems is the requirement for high processing power to coordinate and correlate received signals. Thus, these systems still have limitations in providing the desired detection results against low observables. This is primarily due to the lack of computing power and sophisticated algorithms.

Despite these drawbacks, studies on these systems are ongoing. Some of the promising passive radar techniques which might prove advantageous against stealth targets include BAE System's "Celldar" (Figure 85) that uses GSM base stations as the illuminator of opportunity, Thales Air Systems' "Homeland Alerter 100", an FM radio-based passive radar and Lockheed Martin's "Silent Sentry" that also exploits transmissions from multiple commercial FM radio stations [116].

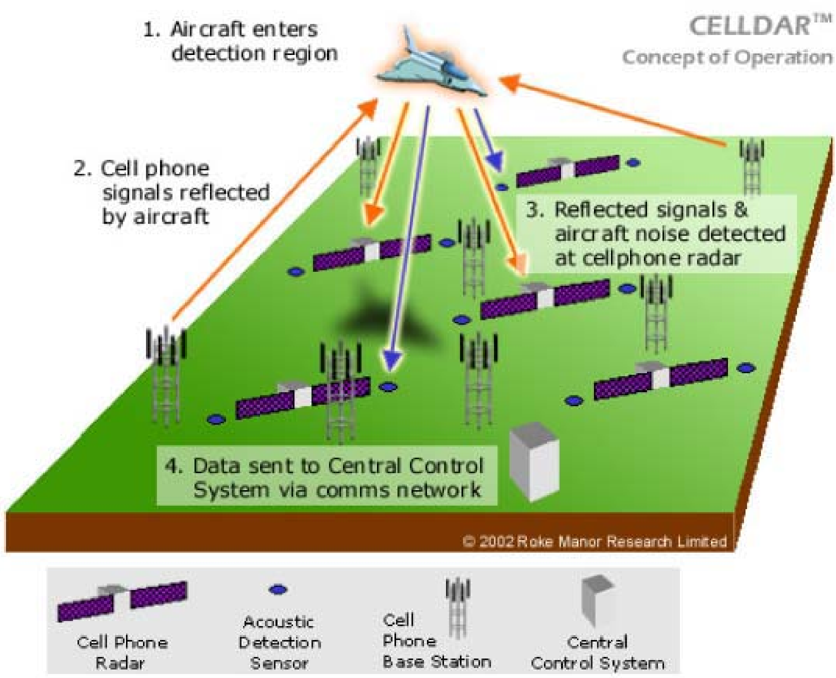

Figure 85. BAe System's Celldar Passive Radar Network Based on Cell Phone Signals
(From [117])

F. OTHER COUNTER RF STEALTH TECHNOLOGIES

There are other technologies which may be used against stealth threats for the purposes of detection and tracking; however, all of these require further development as in the previous counter methods. Space based radars (satellite or very high altitude detection technologies) are one of these; because the most focused signal reduction is in the forward sector of the stealth assets, as “they may be very susceptible to a look-down type of radar [118]”. Despite the limitations associated with space-based systems, like high cost, maintenance support challenges, continuous radar coverage difficulties and limited power in reaching search areas of interest, based on the analysis, “one satellite in geosynchronous orbit or a constellation of 32 satellites in low earth orbit (1000 km) can both detect and track stealth aircraft [118].”

Similarly, airborne early warning and control aircraft (AEW&C), depicted in Figure 86, may also be used for anti stealth purposes. They exhibit several advantages, such as being mobile, having relatively high velocity, dominating the battlefield at high altitude, and positioning, together with being deployed with new radar systems.

Figure 86. Turkish Peace Eagle Project Boeing 737 AEW&Cs (From [119])

Another technique is forward scattering radar (FSR) as shown in Figure 87. In fact, this is a special type of bistatic radar, where the target is close to the transmitter receiver baseline. In FSR configuration receiver and transmitter are located relatively distinct places, thus the reflection angle (β in Figure 87) is a very obtuse angle, nearly

180°, as seen in Figure 87. The forward scattering radar systems are designed to detect the holes or shadows formed by “the presence of a target blocking the signal wavefront from the transmitter [120].” That hole or shadow is an EM field being scattered by the target and its pattern depends on the target’s silhouette. Thus, FSR are not affected by the eluding methods of stealth assets, which use their special shaping characteristic or RAM to reduce monostatic RCS. Although FSR systems are limited by the absence of range resolution and operation within narrow angles, low observable targets can be detected with the steep rise in the target RCS [120]” compared to traditional monostatic radar. Inverse synthetic aperture radar algorithms may improve FSR system target classification, with their high cross-range resolution and relatively simple hardware requirements. Moreover, because aircraft or missile plumes are large and contain ionized gases that affect the ionosphere, these perturbations can also be detected by FSR [120].

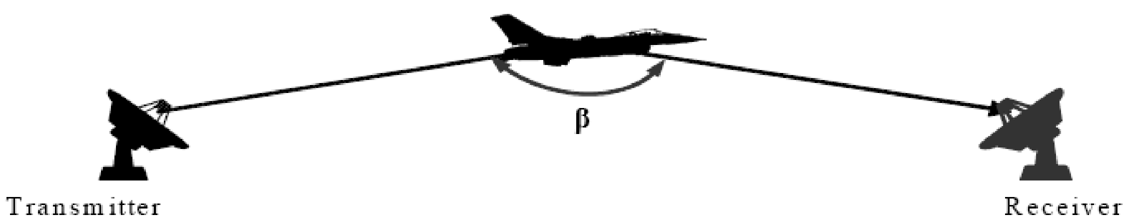

Figure 87. Forward Scattering Radar Configuration (From [120])

Laser Radar (LIDAR) is also a promising technique. LIDAR’s wavelengths, which are much shorter than traditional radar sets, provide it to have “high beam quality, strong directionality and high measuring accuracy [121].” Utilizing these capabilities, LIDAR enhance the detection capability with functions of target identifying, posture displaying and orbit recording. If LIDAR is combined with multi static configurations, the ability of detecting low observables can be improved further. Likewise, LIDAR beams can be effectively used for detecting aircraft wakes and air turbulence. However, problems, such as dependence on weather conditions, large attenuation of laser frequencies and accuracy challenges in directing the laser beam at the aircraft effectively, should be solved prior to deploying these sophisticated designs..

Finally, the new concept of network centric warfare and the technologies developed in parallel with it, present new opportunities for counter stealth. When information is gathered from many sensors, the sum of the final "signal to noise ratio may be improved to the point where stealthy targets can be distinguished [7]." Networking the radars synchronizes the detector elements, which are located at separate places with different capabilities, thus decreasing the performance of stealth. Such network centric design of an air defense system will yield advantages similar to multistatic radar concepts, even if a stand alone radar system does not have any counter stealth property. Because it is very challenging to decrease the RCS of an aircraft at all plane angles, networked radars spread over a wide area will likely obtain some peak returns from a low observable target. Simultaneously sharing the received RF data from the threat airfield and cooperatively processing that information is still a complex task. However, current developments seem to support this concept, with state of art innovations and technical advancements in data communication speed, computing power and receiver sensitivity.

As described in this chapter, there are many new radar concepts applicable to counter stealth assets. However, none of these designs are technically proven to provide a complete and one hundred percent effective solution for defeating low observables. These radars are especially handicapped, when more accurate and greater tracking capabilities are required at the final engagement stage for countering stealth. Thus, the considerations presented in this chapter should be regarded more as methods for decreasing the effectiveness of stealth assets. For comparison purposes, Table 9 summarizes information concerning primary counter stealth radar systems.

	Advantages	Disadvantages	Counter Stealth Consideration
Radars with High Power Emitters, Extremely Sensitive Receivers	* Increased range. * Increased detection capability. * Precise tracking.	* Excessive volume in size and weight. * Decreased mobility. * Increased cost. * Extra clutter and greater amount of false targets. * Requires significantly greater computing power.	* Does not provide meaningful anti stealth capability when applied alone, but can be considered for all types of radar systems to improve their capabilities. * Sending more power to the stealth aircraft means getting more power reflected back to the receiver. * Sensitive receivers also increase the probability of detecting the low signature target. * Track-before-Detect-Capability is promising for stealth detection; however further computing power is required. * Many systems are available.
Electronically Scanned Radars With Fast Scanning Speeds	* Extremely fast scanning rate. * Tracking and engaging many targets simultaneously. * Increased range. * Low probability of interception (High electronic counter measure resistance). * Functionality as a radio or jammer. * Increased detection capability. * Precise tracking. * Simple mechanical designs without complex hydraulics. * Occupies less space. * Reliable. * Less maintenance required.	* Augmented cost. * Requires significantly greater computing power. * Mostly having functionality through a cone of just 120 degrees (as a result of the decrement of the main beam at broadsides). Thus, difficulties of scanning the 360 degree coverage with one system. * At least four radars are required to cover a hemisphere (for full static systems).	* Not an anti stealth technology alone but increases the monostatic radars detection capability. * Preferable especially for airborne platforms such as AEW&C systems. * May be one of the supporting technologies for detecting low observables if used within networks formed by a number of radars and augmented by additional computing power in the future. * Many systems are employed.

	Advantages	Disadvantages	Counter Stealth Consideration
VHF and UHF Radars	* Long range performance. * Less affected by atmospheric interference and absorption. * Designed and manufactured more easily.	* Requires physically big antennas. * Poor resolution. * Poor angular accuracy. * Gain problems. * Slow to deploy and stow. * Poor low altitude detection performance. * Lots of noise in operated bands.	* Satisfies the physics of resonance or Raleigh scattering regions, thus not affected by RAM and shaping precautions. * Stealth aircraft can be detected by them at longer distances compared to common higher frequency radars. * Poor angular accuracy hinders desired tracking capability for targeting systems. * Some systems are employed.
HF OTH Radars	* Longest detection range (1000-4000 km). * No need of direct line of sight for detection. * Not affected by heights of terrain and other obstacles. * Range is not affected by curvature of the earth.	* Expensive. * High system noise and clutter * Dependence on advanced transmitting systems together with sophisticated signal processing units and greater computing power * Insufficient allocated (wide) bandwidth. * Good quality propagation technology required. * Dependence on ionosphere behavior which varies with time of day. * Negative effects of meteor clutter, solar radiation, and behavior of the ionosphere (for sky wave radars). * Requires large areas to be set up. * Does not provide accurate enough positional information of the target, required for further tracking capability. * Unable to detect targets within a radius of ~500 nm (~900 km) (for sky wave radars).	* Satisfies the physics of resonance or Raleigh scattering regions thus not affected by RAM and shaping precautions (better than UHF and VHF radars). * Promising technique for detecting low observables at early warning stage. * Not preferable for precise locating and tracking any target. * Many systems are employed.

	Advantages	Disadvantages	Counter Stealth Consideration
Bistatic And Multistatic Radars	* Increased detection capability due to geometrical effects. * Undetectable (by means of passive receivers). * Safe from attack by anti-radiation missiles or directional interference and jamming. * No need to use transmit-receive switch or duplexer devices which are lossy, expensive, and heavy. * Need of less radiated power for detection compared to monostatic counterpart. * Increased amount of beams from targets at a given airfield volume in a centrally controlled manner or synchronization with receivers (for multi static configuration). * Difficult for low observable target to apply countermeasures.	* Slow and reduced range-angle search capability. * Limited engagement capability and resolution. * Complex system configuration. * Though some components are discarded, total system is expensive. * Need of fast data/network communication between sites/nodes. * Improved computing power and sophisticated algorithms required. * Need of sensitive time cooperation to maintain synchronization between transmitter and receiver. * Too much clutter and many illusive signals in the system returned from a variety of directions other than true reflection. * Decreased low level coverage (especially for bistatic configuration).	* Promising solution to detect stealth airframes due to decreasing effectiveness of RCS reduction measures which are focused on counter mono static radars with shaping measures (such as faceting). * Multistatic radar networks, which are formed with many units, may be required to overwhelm the new generation stealth assets which concentrate reflections at very few angles, with narrow lobes. * Data from other early warning systems may be required to focus at specific angles. * Highly dependent on computing power, thus future advancements in this field may increase the capabilities of these systems. * Some systems are employed for detection of low observables (with relatively poor capabilities).
Passive Radars and Passive Emitter Location Systems	* Covert system, has immunity from anti radiation homing attacks. * Dedicated transmitter units not required. * Procurement cost is low (but sophisticated computing is required for detection of low observables which increases cost). * Small and compact systems, thus mobile configurations are possible with high flexibility. * No frequency allocation required.	* Improved computing power for detecting sensitive targets (increases the cost). * No control capabilities over either transmitter units or emitted signals' properties. * Short range detection as a result of relatively low powered transmitters. * Very precise triangulation is required (for passive emitter location systems).	* Similar capabilities and limitations with multistatic radars to counter stealth targets. * Unlike multistatic configuration, these systems have the advantage of exploiting many undedicated transmitter units, such as broadcast stations and cell phone networks. * Promising technique but needs further development, especially in processing speed and sophisticated algorithms. * Few systems are employed for detection of low observables (with relatively poor capabilities).

	Advantages	Disadvantages	Counter Stealth Consideration
Space Based Radars	* Look-down type of radar. * Highly safe from enemy fire. * Worldwide access may be offered by the satellite platform. * Increased coverage. * Difficult to jam.	* Extremely high-cost and other general problems of space programs. * Nearly impossible maintenance support and component upgrade. * Difficulties in providing continuous radar coverage. * Large power requirement (result of remote range to the target). * Few countries have the ability and technology to deploy space systems.	* Wide area coverage and look-down radar capability increase anti stealth qualities (similar angular capabilities with OTH skywave radars to detect low observables). * Tracking capabilities are poor but can be used for purposes of early warning. * Promising technique for counter stealth in future applications with developments in space based receiver and transmitter systems. * Few systems are employed with relatively poor capabilities.
AEW&C Radars	* Look-down type of radar. * Highly mobile. * Flexible positioning with high velocity, valuable for operation requirements. * Dominates the battlefield from high altitude. * 360° coverage. * Difficult to jam. * Not affected by height of terrain and other obstacles. * Long detection range. * Range is not affected by curvature of the earth. * Increasing friendly aircraft's low probability of intercept characteristics by means of sending air picture data though communication links.	* High-cost. * General air platform problems (such as limited useable area and personnel, etc.) * Difficulties of deploying air platforms continuously for uninterrupted radar coverage. * Detectable by enemy forces beyond its own detection range.	* Wide area coverage and look-down radar increase anti stealth qualities (similar angular capabilities with OTH skywave radars to detect low observables). * Promising system for future applications of counter stealth with tracking capabilities given by new electronically scanned radars. * When these systems are linked with other long-range and low-RCS detection radar sets, much more detection capability may be achieved. * Many systems are employed with promising capabilities.

	Advantages	Disadvantages	Counter Stealth Consideration
Forward Scattering Radar	* Increased detection capability due to geometrical effects. * Relatively simple hardware. * Not affected by shaping characteristics or RAM to reduce monostatic RCS reduction methods. * Difficult for low observable target to apply countermeasures.	* Poor quality for precise locating and tracking any target. * Limited by the absence of range resolution. * Operation within narrow angles. * Requires increased computing power and sophisticated algorithms. * Too much clutter and many illusive signals in the system returned from a variety of directions other than true reflection.	* Preferable for early warning purposes. * Satisfies the physics of resonance or Raleigh scattering regions. * Promising solution for detecting stealth airframes due to decrease in the effectiveness of RCS reduction measures which are focused on counter monostatic radars with shaping measures (such as faceting). * Few systems are employed for detection of low observables (with relatively poor capabilities).
Networked Radars	* Improved signal to noise ratio by sum of the received power from all nodes. * Utilizing radars which have different capabilities and located at separate places. * Angular variety. * Similar advantages to networks of multistatic radar concept.	* Require high data processing capability and computing power in all systems. * Require wide bandwidth for communication between radar nodes. * Deficiencies of network centric warfare concept, such as the problems of faulty data in the system.	* Compatible with network-centric warfare doctrine. * The most promising technique for counter stealth measures, however many advances are required in joint processing, data correlating, communication and radar computing power technology. * Wide networks, with many types of radar required, still a concept due to technological difficulties in applications.

Table 9. Primary Counter Stealth Radar Systems

V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

This thesis has provided a historical background on stealth technology including the evolution of airborne stealth and low observable technology, specifically with an emphasis on RF signatures. Since the Gulf War, the operational advantage to airborne strikers and bombers employing this technology is evident wherever these assets are deployed. From these observations, it is clear that stealth technology is indispensable to any air force aiming to achieve air superiority.

After discussing general stealth technology principles, and RCS reduction methods, radar countermeasures used in the modern era to defeat them were discussed. Experience and studies have shown that conventional air defenses are ineffective against current generation stealth aircraft. Although countering RCS reduction is challenging, there are promising techniques to decrease the performance of stealthy systems. Conventional radars, for the most part, seem to be ineffective. New methods and radar configurations are being deployed for air defenses, exploiting the limitations and drawbacks of stealth assets. Moreover, developments in sensor technology, ongoing advancements in computing power and innovative designs for mobility will improve the capabilities of new air defense systems.

Consequently, it is likely that future stealth aircraft will not be as invulnerable to air defenses as they are today. The competition between low observables and defensive systems will dominate the air battles of the future with the development of new techniques and technologies on both sides.

B. IMPLICATIONS OF COUNTER-RF STEALTH SOLUTIONS FOR THE TURKISH AIR FORCE'S POSSIBLE REQUIREMENTS, RECOMMENDED FUTURE APPROACHES AND CONSEQUENCES

The ideas presented in this chapter do not reflect the official opinions of the Turkish Air Force or any other Turkish authority. They represent the author's thoughts based on extensive research conducted for this thesis study. Further, the following sections should be considered the application of the author's knowledge and thoughts about the implications of counter- RF stealth solutions for the Turkish Air Force, possible future requirements, recommended future approaches and consequences, based on review of the stealth technology literature and counter stealth radar techniques.

1. Turkish Air Force Counter-Stealth Requirements

Turkey's geostrategic position and the volatile international affairs climate in the region dictate that Turkey maintain powerful and modern armed forces. Having an effective air defense system to maintain peace is a strategic part of this principle for achieving air superiority in the region. Several countries have programs to modernize their air forces with new generation aircraft, UAS and cruise missiles which employ low observable technology. It is likely that the coverage of conventional radar systems will be ineffective in coping with forces equipped with these low observable assets. Thus, the unique features of stealth will be a force multiplier. Although low observable capabilities for the Joint Strike Fighter (JSF) are uncertain, the Turkish Air Force's participation in the program should fill any potential gap in capability to balance its strength against other air forces which may be capable of flying low observable fighters.

Maintaining situational awareness over a variety of mission areas, and when needed, utilizing effective weapon systems, are required to sustain air superiority. Thus, a strong air defense network is a necessity. This network should be equipped with surveillance systems to detect hard targets and accurate tracking systems to counter those threats by means of guiding interceptors, together with other surface systems. Absence of a total air picture during conflict will weaken military power and fighting ability.

Therefore, the principle requirement for Turkish Air Force counter stealth is dependent on the effectiveness of its potential adversaries and the degree to which they are equipped with high-valued stealth assets. While conventional radar systems are highly vulnerable to low observables, integration of new radar systems capable of reducing the effectiveness of stealth assets will improve the Turkish Air Force's operational capability and aid in maintaining air superiority over its homeland territory.

Together with counter stealth radars, deployment of new surface-based air defense weapon systems, such as long range surface-to-air missile (SAM) systems and anti-aircraft artillery (AAA), will strengthen the air defense network.

2. Recommended Future Approaches and Consequences

In Chapter IV, several new radar concepts to counter stealth assets were discussed. However, none of these designs are capable of providing a complete and totally effective solution for defeating low observables. In fact, these radars are usually not accurate enough to provide the tracking capabilities necessary for missile systems at final engagement. As such, the following promising technologies should be considered potential methods for reducing the effectiveness of stealth assets and for future deployment.

The ongoing Project Peace Eagle program offers some promising new counter stealth capabilities. The program seeks to purchase four Boeing 737 Airborne Early Warning and Control (AEW&C) aircraft outfitted with multi-role active electronically scanned array (multi-role AESA or MESA) radars. These radars are capable of focusing power on almost any selected point in space while continuing to search and track other targets of interest. Their operation at heights well above ground level increases the possibility of illuminating low observable assets from viewpoints other than frontal aspects. These other areas are typically not as heavily invested in RCS reduction design and the continuously changing aspect with respect to the detection area gives advantages to these systems for counter stealth. Another advantage of high altitude detection systems is their immunity against terrestrial obstacles. The Turkish landscape is mountainous and the islands in the Aegean Sea limit the line-of sight which is required for millimeter radars, such as X-band detectors. Thus, there are many blind areas for conventional surveillance systems. This gap will also be reduced when AEW&C systems are deployed.

When these systems are linked with other long-range and low-RCS capable radar systems, more detection capability can be achieved. Cooperation of AESA airborne warning and control aircraft with new VHF or HF radars which are equipped with greater computing power will improve effectiveness against low observables. Low frequency surveillance radars are promising early detection systems against low observables and can indicate the broad or rough areas of the stealth threat. However, these early warning systems are limited in accuracy and are not suitable for tracking and point location. This limitation can be overcome by obtaining general sector information of a target by means of the HF or VHF radar's surveillance capabilities and then using the AESA's powerful search and dwell modes.

Modernizing older radar systems and improving their capabilities with new computerized components may give better coverage and provide some operational advantages to the Turkish Air Force against low observables. Advances in computer processing speed with the extension of data storing and searching in a given memory area per unit time enable design of new radar systems with increased sensor power. Techniques, such as "track before detect", which may decrease the effectiveness of low observables, exploits these innovations.

The use of mobile systems within an air defense network is another effective way to counter stealth. Mobile radars can greatly complicate and thwart stealth mission planners' tasks. Although stealth aircraft effectively decrease the detection capability of radars, mission planners must still consider radars' exact locations when planning flight routes. This is required because if a stealth aircraft approaches too close to a radar site, it may be detected. On the other hand, mobile systems are capable of changing their locations. They may have equal or less radar coverage compared to immobile systems, but when they change their locations, their radar coverage areas also move which provides imponderable threat for the attacker. This is a considerable advantage for mobile radar users. As mentioned, stealth planners need to decide on a mission route for the aircraft to penetrate the airfield with as possible as minimum risk. However, the risky zones of an air defense, supported with mobile radars, may continuously be changed with the moves of mobiles systems. Finally, planners are forced to make predictions about mobile systems' locations while wrong predictions may violate the observability and so survivability. In this manner, mobile systems' unpredictable orbits contribute to the robustness of air defenses. Therefore, mobile systems will increase the Turkish Air Force's counter stealth capabilities.

Passive radars and locating systems are other likely solutions to anti stealth applications. However, due to technical shortfalls, passive systems require further development both in electronic and computing technologies. Coordinating and correlating inputs from all received signals is possible only with a significant improvement in today's computing power. Moreover, very sophisticated algorithms are required to provide meaningful results. Despite these challenges, passive systems are still promising applications for future counter stealth designs.

There are many television and FM radio broadcasting stations and cell phone network nodes distributed throughout Turkey. Passive coherent radar designs, which are powered with national software, may utilize these transmitters for anti stealth purposes. Similarly, if sets of passive signal intelligence devices are upgraded with an improved capability for joint triangulation operations, they may be used as emitter locating systems for the Turkish Air Force. Therefore, an adversary's stealth assets, which use transmitting systems, such as datalink, radio or radar, could be detected and tracked. This is a very likely outcome in a network centric warfare environment. Here, low observable systems will use these onboard transmitters while being a part of the network in a net-centric manner. Although they may exploit low probability of interception transmitters to decrease an opponent's acquisition, there is always the chance for a sensitive receiver to pick up the required signal for detection.

The networking of elements is another emerging method to improve the effectiveness of air defense systems. Having a radar network in which each node exchanges the data acquired by its receiver provides superior information for detecting and tracking stealth aircraft, as well as other air force assets. Networked radars synchronize the detection elements which are located at separate places with different capabilities. Therefore, illuminating the airfield with many coordinated radar sets will decrease the performance of stealth. Such air defense network centric designs provide advantages similar to those of multistatic radar concepts, even if each individual radar system within the network has no counter stealth capabilities. Because it is very challenging to decrease the RCS of an aircraft at all incident angles, a number of networked radars spread throughout a wide area will likely obtain some peak returns from low observable targets. Effective operation of such an air defense radar network will provide Turkish commanders with better situational awareness, utilizing the performance of a dynamic air picture produced by cooperative radars. However, as mentioned before, sharing the received RF data simultaneously, and cooperatively processing that information are still complex tasks and today's technology is not capable of meeting these requirements. Similar to passive radar systems, networking the radars also requires increased data communication speeds, computing power and more sensitive receivers. Thus, these techniques must be supported by state of art technologies and future innovations to achieve the desired outcomes for the Turkish Air Force.

Finally, to improve the strength of the Turkish air defense umbrella, acquisition requirements lists for new systems and modernization projects should be updated to include counter stealth considerations. Further, implementing policies, such as investing and focusing Turkish research and development toward counter stealth radar technologies, together with cooperative programs with other countries that have stealth experience and capabilities, will help in staying abreast of technological improvements in this area.

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