IDSA Monograph Series
No. 33 March 2014

STEALTH TECHNOLOGY AND ITS EFFECT ON AERIAL WARFARE

VIVEK KAPUR

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INSTITUTE FOR DEFENCE
STUDIES & ANALYSES

Cover Illustration Courtesy: http://www.airforce-technology.com/projects/neuron/images/2-neuron.jpg

ISBN: 978-93-82169-34-5

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First Published: March 2014

Price: Rs. 250/-

Published by: Institute for Defence Studies and Analyses
No.1, Development Enclave, Rao Tula Ram
Marg, Delhi Cantt., New Delhi - 110 010
Tel. (91-11) 2671-7983
Fax.(91-11) 2615 4191
E-mail: contactus@idsa.in
Website: http://www.idsa.in

Layout &
Cover by: Vaijayanti Patankar

Printed at: M/S A. M. Offsetters
A-57, Sector-10, Noida-201 301 (U.P.)
Mob: 09810888667
E-mail: amoffsetters@gmail.com

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PREFACE

Since its induction into war fighting in the early years of the twentieth century, air power has become a major determinant of success or failure of military forces. This reality led the German Field Marshal Erwin Rommel to state that "anyone who has to fight, even with the most modern weapons, against an enemy in complete control of the air, fights like a savage against a modern European Army." Field Marshal Rommel later said with regards to the then situation in Sicily and Italy that "Strength on the ground was not unfavourable to us, it is simply that their superiority in the air and ammunition is overwhelming, the same as it was in Africa." If these statements by one of the greatest general rank officers of Europe are not adequate for the reader, consider the report by Field Marshal Gerd Von Rundstedt, the German commander in France during the Allied invasion, "The Allied Air Force paralysed all movement by day, and made it very difficult even at night."

The effectiveness of air forces and their equipment is driven more by technology than of other military forces used in conduct of conventional warfare. An air force with a major technological advantage over its opposing air force has usually prevailed over its technologically inferior opponent in conventional warfare (The later part of the 1973 Yom Kippur War, Bekaa Valley Operations by Israeli Air Force (IAF) in 1982, and the First Gulf War of 1991 bring out this fact adequately.). Given the importance of air power to the defence of a nation and the fact that air power itself is highly dependent upon technological advances, it is pertinent for all those people who are students of modern warfare and for scholars working on aspects related to national security; to understand current technological advances and the manner in which these affect the conduct of warfare. Only through this understanding would these personnel be able to come to correct conclusions on matters that could affect the security of the nation.

In the past few decades advent of stealth technology has been one of the most important developments in military aviation technology. This technology has played a key role in the currently sole global superpower, America's, ability to shape the world order to its desires. In the past decade stealth technology has started to percolate to other nations quite rapidly. Apart from the US, Russia, China and India have active stealth aircraft programs underway. Stealth technology in piece meal applications can also be found to have been incorporated on other non-truly stealth aircraft in other regions of the world. In this context it is even more important, given the potential for conflict with countries that have active stealth aircraft programmes such as China, for Indian scholars to be aware of the basic technologies that are involved in stealth and the effect of stealth technology on the conduct of aerial warfare.

This monograph aims to provide a concise document that touches upon most of the key aspects of stealth technology, and the issues involved in the operation of stealth aircraft in warfare. It is aimed at providing a concise, yet adequately detailed examination of what stealth technology in the aerospace domain entails and the manner in which this technology affects the conduct of warfare for students and practitioners of military operations, scholars working on military, especially aerospace, matters and the interested lay public at large.

New Delhi

Vivek Kapur
December 2013

ACKNOWLEDGEMENTS

Firstly I owe my thanks to the Indian air Force for permitting me to take the time out from my regular military duties to pursue a two year research project at IDSA. This Monograph owes a lot to the indulgence of Director General IDSA, Dr Arvind Gupta and Deputy Director General IDSA, Brig Rumel Dahiya (retd) who supported the shift to this topic even after just over a year had been spent on another tropic. During the process of researching and writing the monograph, the assistance and advice of members of the IDSA faculty proved invaluable. Amongst the IDSA faculty Brig. Rumel Dahiya (retd), Wg Cdr Ajey Lele, Gp. Capt Naval Jagota, Cdr. SS Parmar, Col Vivek Chadha (retd), Wg Cdr Hemlata Lohani (retd), Mr Amit Kumar, and last but not by any means least Ms. Neha Kohli were especially helpful. Mr Gopal Awasti of the Estate Management vertical within IDSA consistently exceeded all my highest expectations in ensuring that as far as the office equipment and working environment were concerned there would not only be no adverse impact on my work but that these would encourage carefree focus on the task at hand. They took time out of their other activities to guide me in my research and writing throughout the process of my working on the monograph as well as getting it reviewed by suitable experts. Only paucity of space restricts me from typing in names of all other members of the IDSA faculty as their contribution was a little lesser only because the topic and area of research did not fall closer to their areas of expertise. For providing me the kind of support and help that they did I remain indebted to the IDSA faculty. Towards the last mile towards getting this monograph ready for publication Mr Vivek Kaushik devoted considerable effort and energy to get suitable reviews carried out and to get the document processed through the IDSA publishing system.

The reader should carry the impression that this monograph while ostensibly attributed to a single author carries the collective wisdom of

most members of IDSA whether they are involved in research in their own niche areas or in providing the environment for work to progress in a smooth manner. That said it should be clarified that shortcomings in the monograph are attributable to the author alone.

IDSDA, New Delhi

Vivek Kapur
(Gp. Capt.)

LIST OF ACRONYMS

AD : Air Defence.
AESA : Active Electronically Scanned Antenna.
AGL : Above Ground Level.
AI : Airborne Intercept.
AMCA : Advanced Medium Combat Aircraft.
AMSL : Above Mean Sea Level.
ARM : Anti-Radiation Missile.
ATF : Aviation Turbine Fuel.
AURA : Autonomous Unmanned Research Aircraft.
AWACS : Airborne Warning and Control System.
BAI : Battlefield Air Interdiction.
BAS : Battlefield Air Strike.
BVR : Beyond Visual Range.
CAO : Counter Air Operations.
CAS : Close Air Support.
DCA : Defensive Counter Air.
ECM : Electronic Counter Measures.
ECCM : Electronic Counter Counter Measures.
EM : Electromagnetic.
ESM : Electronic Support Measures.
EW : Electronic Warfare.
FGFA : Fifth Generation Fighter Aircraft.
GCI : Ground Controlled Intercept.
GPS : Global Positioning System.
IFF : Identification Friend or Foe.
IFR : In Flight Refuelling.
IR : Infra Red.

IRST : Infra Red Search and Track.

LDSD : Look Down Shoot Down.

LO : Low Observable.

LPI : Low Probability of Intercept.

MANPADS : Man Portable Air Defence Systems.

MTI : Moving Target Indicator.

OCA : Offensive Counter Air.

OTH-B : Over the Horizon Backscatter.

PAK FA : **P**erspektivny **A**viatsionny **K**ompleks **F**rontovoy **A**viatsii Prospective Aircraft Komplex [for] Frontal (Tactical) Aviation.

PRC : Peoples Republic of China.

RAF : Royal Air Force.

RAM : Radar Absorbent Materials.

RCC : Re-enforced Carbon Carbon.

RCS : Radar Cross Section.

RFC : Royal Flying Corps.

RPA : Remotely Piloted Aircraft.

R&D : Research and Development.

SAM : Surface to Air Missile.

SEAD : Suppression of Enemy Air Defence.

SOJ : Stand Off Jammer.

TBA : Tactical Battle Area.

TWT : Travelling Wave Tube.

UAV : Unmanned Aerial Vehicle.

UCAV : Unmanned Combat Aerial Vehicle.

US : United States.

USAAF : United States Army Air Force.

USAF : United States Air Force.

USN : United States Navy.

V/STOL: Vertical / Short Take Off and Landing.

WVR : Within Visual Range.

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INTRODUCTION

1

Stealth as a concept is not new to warfare. Stealth used as a noun means the act of moving, proceeding, or acting in a covert way; the quality or characteristic of being furtive or covert, the act or characteristic of moving with extreme care and quietness, especially as to avoid detection or, to avoid notice. Taken in a military sense stealth could be used to mean the method(s) of avoiding notice of ones own forces by the enemy so that these forces that have evaded notice by the enemy can be deployed in a manner that the enemy, unaware of the forces' existence and / or location is surprised at the strategic or tactical level to his disadvantage in battle. A complete and comprehensive definition of stealth technology could be as follows : "Stealth technology also termed Low Observable (LO) technology covers a range of techniques used with personnel, aircraft, ships, submarines, missiles and satellites to make them less visible (ideally invisible) to radar, infrared, sonar and other detection methods. It corresponds to camouflage for these parts of the electromagnetic spectrum."[1] In more recent times "Stealth Technology has come to be associated more with military aircraft able to evade radar and other sensors designed to detect and engage aircraft. In fact website http://dictionary.reverso.net/english-definition/stealth technology defines stealth technology as "denoting or referring to technology that aims to reduce the radar, thermal, and acoustic recognisability of aircraft and missiles." definitions of stealth technology at other online dictionaries such as www.merriam-webster.com/dictionary/*, and* http://www.dictionary.com etc. are similar displaying a bias towards application of stealth to military aircraft. This monograph is aimed at examining the development of Stealth Technology and

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[1] "Stealth technology", http://en.wikipedia.org/wiki/Stealth_technology, (Accessed December 04, 2013).

aircraft design for stealth and the impact of stealth technology on aerial warfare.

From ancient times combatants have understood the advantages of keeping some military forces hidden from the enemy. Such hidden military forces could then be utilised at crucial moments to achieve surprise and a decisive advantage in battle; either by being applied at weak enemy locations to make a breakthrough or to exploit a weakness in the enemy defences created by other forces. In the two dimensional battlefields that existed in the 'Before Aviation' era, stealth and surprise was achieved through positioning some forces in areas where the enemy would be unable to visually learn of their location due to inadequate line of sight and thereafter using these forces to achieve strategic or tactical surprise followed by a victory. Gaining knowledge about the existence and location of these reserve enemy forces has been crucial in land warfare since times immemorial. This is the imperative, of two dimensional battlefields, that has led armies since ancient times to strive to control the "higher ground". Locating friendly forces at higher locations helped expand the areas that could be kept under surveillance due to the higher or longer line of sight available from elevated positions. The longer line of sight available from higher locations helped detect and track the stealthy or hidden deployment of enemy forces.

At a more tactical level ground forces have used camouflage through modifications of their equipment to reduce their detectability since armies first seriously applied their minds towards delaying detection of their troops in order to gain tactical and / or strategic advantage over the enemy. Surprise was achieved when forces the enemy had not seen earlier unexpectedly entered combat. Means employed have included strapping or tying freshly cut vegetation (grass and leafy twigs) to soldier's bodies, choosing colouring of uniforms and other equipment to match with the prevailing background (green and brown in jungle areas, khaki or sand brown in desert terrain and white in snowbound arctic areas and in mountains); and breaking down of the shapes of personnel and equipment through use of camouflage patterns comprising two or more colours to break the distinctive outline of soldiers and their equipment. War paint, applied directly on the skin especially on faces, has been used since very early times to serve a similar purpose[2]. At a much more basic level in the animal kingdom predators such as the big cats (lions, tigers, panthers etc) conceal their approach from prey by staying downwind of the prey to conceal their odour and use vegetation in the area coupled with their natural colouring and patterns to reduce visual detection until it is too late for the prey to escape. All these measures were intended to delay the detectability of friendly forces by the enemy in order to surprise the enemy. Thus, stealth as a basic concept is not new to war fighting or in the animal kingdom for that matter. In both instances above, of human land forces and predators of the animal kingdom, a stealthy deployment or stealthy movement of friendly forces has been aimed at achieving surprise. In earlier times with warfare limited to surface forces the methods of achieving stealth were quite simple and rudimentary as was the general level of technology available to military forces for fighting[3]. As technology advanced more complex equipment became available to war fighters. The introduction of heavier than air aircraft to the battlefield heralded a major increment in the technology available for war fighting. Early aircraft with their distinctive shape, slow (by today's standards) speeds, and other signatures were relatively easy to spot in the air. As visual means were all that were initially available for spotting of aircraft, visual acquisition was the most prevalent; it was supplemented a while later by equipment meant to detect, amplify and locate in azimuth and elevation the distinctive acoustic signature of aircraft engines. Over time increasingly advanced special equipment was developed to detect and identify the azimuth and elevation of aircraft through use of visual and acoustic sensors[4].

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[2] Notable exceptions to the use of camouflage by ground troops of armies have been when there was a perceived advantage, usually psychological, to be gained through displaying one's own superbly armed, equipped and trained, troops in large numbers and all splendour to intimidate the enemy and to assist in cohesion and control of friendly forces. Here note the bright red uniforms favoured by the British in the 1500s and 1600s.

[3] Initially man fought with hand held sharp edged weapons like the sword, lance, and spear. These gave way in time to the smoothbore muzzle loading musket which itself was replaced by the breech loading bolt action rifle.

[4] "Searchlights and Sound Locators", http://www.antiaircraft.org/search.htm,(Accessed on September 14, 2013).

As the means to detect aircraft progressively became more advanced with advent of increasingly capable radars, these detection means were initially countered through tactical innovations. Initially, purely theoretical studies were conducted, commencing in the 1940s, to determine means of delaying the detection of aircraft. While these studies were being pursued, tactical methods were employed to delay detection of aircraft by enemy forces. These theoretical studies aimed at delaying / denying detection were later taken up for operationalisation, when it was found that tactical means alone were inadequate for the task of achieving adequately delayed detection of flying machines. As aviation continued to be a very high technology enterprise, the application of the concept of delaying detection to aerial platforms received considerable attention and the word "stealth" entered common usage in the 1980s and 1990s as a demonstration of application of very high technology to war fighting. In the process the long history of use of stealth techniques in surface warfare were more often than not forgotten or at least ignored; with cutting edge technology applied to aircraft capturing the mind space and effectively hijacking the word "stealth". In sum it needs to be understood that stealth techniques have been in use in warfare since times immemorial. What is new today is the application of these basic concepts to the high technology arena of aircraft design through the application of advanced scientific techniques. Today, stealth has almost become synonymous with advanced flying machines that are very hard to detect. There is a tendency to regard "stealth aircraft" with a degree of awe and for the uninitiated to assume that these "stealth aircraft" are invincible in battle. Such assumptions derived from an incomplete understanding of the components, techniques and limitations of stealth technology and the manner in which the introduction of stealth technology into the battlefield affects the conduct of warfare.

There is a tendency amongst the lay public, as well as amongst a large section of the scholar community, to take availability of stealth as guaranteeing success. Knowledge about how "stealth" works, counters to stealth and the further implications of these in modern warfare could lead to a reassessment of this initial simplistic impression. Thus, there is a need for a simple and concise treatment of stealth from these aspects, hence this monograph.

SCOPE OF THE MONOGRAPH

This monograph will trace the developments and circumstances that led to the need for and development of stealth technology in the aerial realm, the design for stealth technology in aircraft, and then go on to discuss the way in which stealth technology affects aerial warfare and the offence-defence equation The monograph will look at stealth technology only as applied to aerial platforms and the manner in which this technology affects the conduct of aerial warfare.

This monograph will look at the following areas:-

- The Road to Surprise through Denial of Detection in Aviation.
- Stealth Technology for Application to Military Aircraft.
    - Stealth and Radar.
    - Stealth and Infra Red.
    - Stealth and Visual and Acoustic Signatures.
- Military Air Operations.
- Stealth and Offensive Operations.
- Stealth and Special Missions
- Stealth and Defensive Operations.
- Stealth and Cost.
- The Offence Defence Balance.
- Some Countermeasures against Stealth.
- Conclusion.

2

ADVENT OF AIRCRAFT IN WAR-FIGHTING AND AVOIDANCE OF DETECTION

Aircraft are a relatively new entrant on the battlefield. The first heavier than air flying machine to take part in military operations did so as recently as in the first decade of the twentieth century. Air warfare, more than any other form of modern warfare, has been driven largely by technology. As was the case in surface warfare, in aerial combat also surprise came to occupy a central position for advantage to be gained over the enemy. This surprise could be achieved through different means. While air power was in its infancy during World War-I (WW-I) Research and Development (R&D) lead times forced tactical methods of achieving surprise in battle. This trend of utilising tactics to achieve surprise continued through out the development of air power and it continues even today. However, as the understanding of science and technology of aviation increased over time, parallel efforts to find technological solutions to operational problems also began to deliver results. This progression towards the greater dependence upon technology to achieve surprise in aerial warfare, was achieved in earlier years through utilising difficult to reach operating envelopes, such as "very fast and very high" regime (used by the British DeHavilland Mosquito in World War-II, and by the US A0-12/ SR-71 "Blackbird", the Soviet MiG-25 "Foxbat" and MiG-31 "Foxhound" from the 1960s till today, as the MiG-25 and MiG-31 remain in several air forces). In more recent times this has been achieved through incorporation of stealth technology. This progression is best understood through an examination of the development of air power in the past century, looked at through a "surprise" and "avoidance of detection" lens.

In the development of any technology there are evolutionary changes and revolutionary developments. Evolutionary changes are characterised primarily by the fact that these comprise a series of continuous improvements to existing equipment, weapons and armaments already in use. Evolutionary changes usually result in products and equipment that is recognisable as having been derived from earlier equipment through elimination of earlier drawbacks and also attempts to improve performance over earlier, or legacy, figures. The development of the rifle from the earlier muzzle loading musket and, a few years later, the development of semi-automatic firing mechanisms in rifles, an advance on the earlier manually operated bolt action rifles, are examples of evolutionary changes. These increased the accuracy and rate of fire of infantry soldiers' personal weapons; two advantages that could prove decisive in battle. Revolutionary developments comprise a complete overhaul of the way things are done. These involve application of science and human ingenuity to achieve desired ends in better ways than was thought of earlier. The output of this process usually results in equipment or technology that represents a major leap over the earlier in use equipment and can result in an improvement in efficiency by many orders of magnitude over the earlier methods. The introduction of firearms, and of the battle tank, on the land battlefield; introduction of submarines in naval warfare and the advent of the heavier than air aircraft are examples of revolutionary changes. The widespread introduction of electronic computing systems in weapon systems is another example of revolutionary changes as is the utilisation of space based assets for communication, reconnaissance, surveillance etc. While evolutionary changes do not have a major impact on the way wars are fought, revolutionary changes do. This is because revolutionary developments are the ones that have the potential to give one adversarial side an overwhelming advantage or edge over the other; combined with a necessary R&D lag before effective counters can be developed and fielded by possible opponents. Revolutionary changes also deliver on one of the basic principles of war, 'Surprise'. They also deliver the advantage of technological surprise over the enemy often leading to war winning advantages being gained.

Stealth is one such revolutionary technology with the potential to change the way air power is exercised. It involves technological methods of enabling military aircraft to evade radar and other sensors in the Electromagnetic (EM) spectrum deployed to detect and engage aircraft. Stealth technology is actually a mix of several different technologies that, applied together, aim to reduce the detectability of an aircraft or other platform[5]. The term "Stealth technology" has come into use as

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[5] Air Chief Marshal Sir Michael Knight KCB, AFC, FRAeS. *Strategic Offensive Air Operations.,* Brassey's Defence Publishers Ltd, London, 1989, pp. 82-83.

a catchy term to describe several interlinked techniques and technologies that together aim to reduce the detectability of a craft to observation by myriad sensors (a more accurate term to replace stealth is "low observable (LO)" technology). Though, stealth technology has been applied to land and maritime systems too, its impact has been most profound when used on aircraft'. Due to the perceived high technology nature of modern aviation, the application of stealth techniques to aircraft has attracted the most attention and mind-space. In part this could be attributed to the widespread fear of human impotence in the face of death raining down from the heavens. A fear that exists in all cultures across the world. This monograph will only look at the application of stealth technology in the aviation domain. Stealth technology and surprise are closely related. Through applying LO or stealth technology a weapon system's presence and or location can be concealed from the enemy. The utilisation at an appropriate time and place of this concealed weapon system delivers the side utilising it the advantage of surprise over the enemy as the latter would not be expecting the concerned weapon system to be utilised in that time and space and thus could find his own plans dislocated enough for him to be defeated. As the development of air power over the past century is examined, in the following paragraphs, the achievement of surprise through tactical means and also through technological means such as stealth will be highlighted.

The first experiments to reduce the detectability of aircraft were conducted as early as 1912, in the very infancy of air power[6]. These experiments were spurred by the emergence of the military ability to destroy airborne aircraft. This new capability, in turn, owed its emergence to the realisation of the great effectiveness of the new aerial machines in shaping the outcome of land battles. As visual means of detection of aircraft were the primary and most widely used means of detection then available, these experiments were aimed at reducing the visual signature of aircraft. No decisive results were achieved in these early experiments. Aircraft of the time primarily used camouflage pattern painting on the doped fabric covering the wooden frames of

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[6] Mike Spick, "Modern Fighters", http://www.fas.org/pub/gen/oelrich/SpickPt1.pdf", p. 25

their structure (camouflage painting is a low technology tactical means of reducing detectability through applying land warfare techniques to aircraft, which had merit a century ago and is still in use today due to its continued relevance). Technological attempts for visual signature reduction WW-I involved replacing the fabric covering with transparent materials. The transparent materials used to replace the doped fabric were much heavier than the doped fabric and imposed weight penalties which in turn reduced aircraft performance. These technological attempts at visual signature reduction were unsuccessful and were abandoned when it was found that pure aerodynamic performance was more important than the questionable stealthiness provided by transparent materials used to replace the original camouflage painted doped fabric used on the aircraft[7].

The advent of radar in the 1930-40s added a vital new sensor to the anti-aircraft arsenal. In the corner of a dusty hangar of a Washington suburb sits the prototype of the world's first stealth bomber, a flying wing, designed for Hitler's Luftwaffe during World War-II (WW-II). This aircraft, the Horten Ho-IX, was, however, not intended to be a stealth aircraft. It was built with radar absorbent materials (primarily wood parts glued together due to lack of metals and other such raw materials in war ravaged Nazi Germany during the early to mid 1940s), due to compulsions of availability of adequate conventional aircraft building metallic raw materials. It was conceived just a few years after the advent of the first air defence radars. The fact that in later years its basic shape and concept found application on modern stealth aircraft give it prominence. This aircraft, however, never made it past the flight test stage[8]. While the design of the Ho-IX is recognisable as stealthy today, it was not intended by its designers for stealth; its stealthy design was a by product of use of available materials and innovative design features for achieving long range performance.

Various attempts have been made to achieve 'stealth' at various stages of the development towards modern aviation capabilities. In the absence

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[7] N5

[8] Dan Alex, "Horten Ho IX / Horten Ho 229 Jet-Powered Flying Wing Fighter-Bomber (1945)", http://www.militaryfactory.com/aircraft/detail.asp?aircraft_ id=105, (Accessed August 03, 2013).

of technological means to achieve this, air forces adopted tactical and operational methods to delay detection. In WW-I these tactical means of delaying detection by the enemy and hence achieving surprise involved use of clouds by the then (rudimentary by today's standards) aircraft to avoid detection. Pilots used clouds by flying into them, and confusing observers trying to predict the exit point through linear extrapolation of the direction prior to cloud entry by changing direction while still inside the cloud. Clouds were also usable to evade an attacking aircraft by diving into a cloud, forcing the enemy to lose visual contact due to the reduced within–cloud visibility, thus foiling the enemy's attack. In aerial combat the tactic of diving out of the sun towards potential opponents was perfected. This tactic also delivered the advantage of delayed detection by the enemy, hence surprising him in combat, through purely tactical means with the qualifier that the aircraft used had to possess the technology delivered performance capability to achieve altitudes, speeds and manoeuvre capability required for the tactic to succeed. This type of attack from out of the sun reduced detection distance of the attack by the target aircraft's crew. The unfortunate target aircraft's aircrew had to look into the blinding glare of the sun which made visual detection of the attacking aircraft very difficult. This technique was perfected first by the German forces leading to the fear of the "Hun in the sun" amongst allied aircrew with more experienced airmen cautioning their less experienced compatriots to watch out for the "Hun in the sun"[9]. During WW-II the tactics of the use of clouds and attacks from the sun were retained as it was found that these tried and trusted tactics to delay detection, thus achieving surprise still remained valid and effective. In addition, the improved aircraft performance of the time allowed more technical means to be used also. A few aircraft were designed to fly very high and very fast so as to be virtually undetectable by land based visual, acoustic sensors, and even by the then new and relatively rudimentary radar sensors of the time.

This exploitation of the very high and fast envelope was the first instance of technology supplying the technological means of delaying or denying

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[9] "Beware of the Hun in the sun", http://www.rafmuseum.org.uk/research/archive-exhibitions/worth-a-thousand-words-air-diagrams/beware-of-the-hun-in-the-sun.aspx, accessed on 22 Sep 2013.

detection of an aircraft by enemy sensors. However, a closer examination brings out that this technological solution required to be married with a tactical solution (that of flying fast and high and not trying to operate the new more capable equipment like other less capable machines) for its benefits to be realised. Here technology and tactics were found to be complementary and not substitutes for each other. Air operations in the recent past also indicate this relationship between technology and tactics as will be seen later in this examination of the progression of air power. A prime example of this extreme operational envelope exploitation technique was the British DeHavilland Mosquito. To achieve high performance the Mosquito featured a light but robust plywood airframe housing two powerful Merlin engines that enabled its Mosquito NF-II variant to fly at as high as 11,000 metres (m) altitude[10] at speeds of up to 595 kilometres per hour (km/h) while the Mosquito FB Mk VI could reach 11,000 m altitude and speeds of up to 611 km/h. The Mosquito NF Mk 30 introduced in 1944 could reach the same altitude and speeds of 682 km/h[11]. Such performance put it too high for easy detection especially at night and made interception of the type so difficult as to be practically impossible even if it was detected. Thus, the "high and fast" region of safety was discovered and first exploited in the 1940s.

In the later years of WW-II radars became more widely used for detection of aircraft as well as for direction of interceptor aircraft and anti-aircraft artillery. This was initially countered by the simple technique of use of "chaff". Chaff comprised large amounts of fine aluminium coated glass fibres cut to a precise fraction of the wavelength of the enemy radar to be evaded (lengths of chaff cut to half or one fourth of the radar wavelength being countered were found to be the ideal lengths for chaff to be effective). When entering the expected coverage envelope of hostile radars, aircraft ejected bundles of chaff that spread out and dispersed in the prevailing winds into individual fibres. Each such fibre, due to its precise length and reflective coating was an efficient radar reflector. The result of the use of chaff was to saturate the target

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[10] The word altitude refers to the height of the aircraft Above Mean Sea Level (AMSL).

[11] "Mosquito, de Havilland" http://www.fighter-planes.com/info/mosquito.htm, (Accessed August 02, 2013).

radar with a very large number of radar echoes that effectively masked the radar returns from the actual aircraft. Such simple techniques found widespread use all over the world and chaff continues to be used even today. Chaff was another instance of technology in the form of discovery of the principles involved and development of chaff itself providing a technological means of either masking an aircraft and thus denying or delaying detection. Once again the use of chaff to be effective required precise timing of its deployment thus again combining technology and tactics to deliver the required benefit. Here again technology and tactics are seen to be complementary and not substitutes for one another. However, it soon came to be realised that compared to aircraft the radar returns from chaff remained relatively static. Counters to chaff were developed in the 1950s and 1960s through incorporation of Moving Target Indicator (MTI) techniques in radars by exploiting the Doppler principle in radar data processing. Chaff and its counters led to development of the new field of Electronic Warfare (EW) with its component parts of Electronic Counter Measures (ECM) and Electronic Counter Counter Measures (ECCM) etc. The aim of ECM was to target radars through electronic means while ECCM attempted to counter the techniques used in ECM. The new field of EW showed technology coming to the fore to protect aircraft from detection and tracking by systems operating in the EM spectrum. However, classical EW did not aim to prevent detection of an aircraft but tried to make an aircraft difficult to track by weapons guidance systems. It can be argued that stealth technology, in so far as it tries to neutralise the detection of an aircraft by sensors operating in the EM spectrum is the ultimate form of EW. However, this line of argument will not be pursued further and it is included only to encourage the thinking reader, if he so desires, to explore this line of thought.

An aircraft's ability to complete its mission and return safely to its base is the product of two probabilities: susceptibility, or the probability that it will be hit, and vulnerability, or the probability that a given hit will destroy the aircraft or at least force it to abort its mission[12]

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[12] Bill Sweetman., *Advanced Fighter Technology The Future of Cockpit Combat*, Airlife Publications Ltd, London, 1988, pp. 11

. Survival of the aircraft and its ability to complete its mission would require that the aircraft either evades detection by enemy weapon systems or operates outside their effective envelopes. In the period till the late 1970s/early 1980s emphasis was placed on the latter. This was in part due to technological limitations that did not permit an aircraft to effectively evade detection[13]. It was at the time assumed that as long as a radar system was able to direct radar energy at the aircraft detection was inevitable because aircraft were built of metal that gave high reflectivity. Moreover, the shapes required for high performance, with the technology then available, forced use of structures and shapes of the airframe that added to the aircraft's radar signature. Therefore, it was felt that another limitation of radar systems should be used to advantage. Radar energy is transmitted in near straight lines as it is EM energy. The actual radar horizon achieved by radar is limited by the height AMSL of its antenna and the height AMSL of the target[14]. Thus, for each radar location and target altitude a radar can look out to a certain fixed distance only. The lower the target aircraft flies the lesser this range of detection becomes. For most radars designed and built in the 1950s to the 1980s for an aircraft flying at below 150m, or about 500feet, Above Ground Level (AGL) and a radar with an antenna within about 10 to 20 metres AGL, assuming flat terrain at a fixed height AMSL, the radar horizon was a paltry 20-25 km. Thus, tactics of flying very low, at heights of 150m AGL and below were developed in order to delay detection by hostile radars. Through careful planning of navigation routes it was possible for aircraft flying at low levels to exploit the gaps in radar coverage that were opened up by the restricted low level range of ground based radars to delay detection until they were quite close to their targets. Such tactics helped delay detection by the enemy and through utilising the principle of surprise (through concealment from detection by enemy radars, by utilising the tactical means of low level flying, reduced exposure to enemy interceptor aircraft and ground based weapons like Surface –to-Air Missiles (SAM)

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[13] Ibid, pp. 73.

[14] Radar detection range or Radar Horizon (in nautical miles) = " height of the radar antenna in feet above mean sea level + " height of the target in feet above mean sea level.

which required cueing by radar to detect and track the aircraft. Flying at such low altitudes, however, brought problems of its own such as:-

- Limited field of vision is available to a pilot of a low flying aircraft, due to the restricted visual horizon.
- Aircraft at low levels spend more time in the engagement envelope of SAMs and anti-aircraft guns; consequently the probability of a hit on the aircraft increases. Even unguided weapons, due to their greater proximity become a threat to low flying aircraft. Such unguided weapons could throw up a "wall" of metal ahead of the aircraft through which it could be forced to fly with possibly disastrous consequences.
- Aircraft faced hazards of collision with natural obstructions such as trees and hillocks, and man made vertical structures such as power transmission lines, microwave towers, chimneys etc.
- Flying close to the ground also brought aircraft into conflict with many species of birds that also use the same airspace.
- The aircraft could be manoeuvred only level or upwards with downward manoeuvres restricted due to close proximity to the ground.
- In fact any manoeuvres while flying at low level demanded great skills from pilots due to close proximity of the ground which, at typical tactical speeds of 840 kmph (or 233.33 metres per second), was as little as half a second away. Any relaxation in attention or focus on the on the pilot's part could result in a catastrophic impact with the ground in under one second.
- Hence, losses of aircraft and aircrew due to non-combat causes could be expected to be quite high.

Such problems of low level flying could be overcome to a degree through better training and indoctrination. However, despite these measures the task of extended low level flight was not very comfortable nor was it, later found, tactically sound. During the First Gulf War of 1991, while most coalition air forces adopted medium level or high level operation of their aircraft, the British Royal Air Force (RAF) continued with low level attacks by its Tornado Interdictor/Strike (IDS) and Jaguar aircraft in attacks on Iraqi targets. The RAF suffered a very high rate of attrition, much higher than that suffered by coalition Air Forces that had adopted medium and high level operation, to ground based anti-aircraft fire during these low level attacks[15].

The United States Air Force (USAF) had since the mid seventies decided upon an alternate method that makes extensive use of EW. USAF relied on extensive electronic support to electronically degrade enemy radars rendering them ineffective through development and deployment of specialised escort and Stand Off[16] Jamming (SOJ) aircraft and then operating at medium and high altitudes. Success in this strategy lay in ensuring a technological dominance over potential adversaries so that there was a high level of assurance of being able to electronically degrade enemy radars and other anti-aircraft weapons systems. This electronic degradation, or "soft kills", were coupled with a few "hard kills", where some carefully selected enemy radars and anti-aircraft weapons were physically destroyed through use of bombs and missiles. For more effective "hard kills" specialised weapons such as Anti-Radiation Missiles (ARMs) were developed. These missiles featured a seeker able to detect the target radars EM emissions and home onto these emissions, accurately guiding the projectile till impact at the radar. The 1991 Gulf War served to indicate that the USAF strategy and associated tactics were more effective than those followed by the RAF in view of the relative losses suffered by the two forces to ground based anti aircraft weapons. The learning for all air forces that studied the 1991 Gulf War for lessons was that technology was coming to triumph over mere tactics in the aerial warfare arena. However, a deeper

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[15] "British Royal Air Force Has Tough Job in the Persian Gulf War", http://archives.nbclearn.com/portal/site/k-12/flatview?cuecard=59881, and, "Gulf War air campaign", http://en.wikipedia.org/wiki/Gulf_War_air_campaign (Accessed September 23, 2013).

[16] Escort jamming aircraft stayed in close proximity to the fighter-bombers they were to protect. Escort jammers carried relatively less powerful jamming equipment with lesser range compared to stand off jammers. Stand off jammers carried very powerful jamming equipment and typically stayed several tens of kilometres away from the target radar, often these aircraft did not even require crossing the border, and fro this "stand off" position jammed hostile radars in order to assist the attacking force to get through unhampered.

analysis of these previous aerial battles leads to the conclusion that an intelligent combination of both technology and innovative tactics is required for success in modern warfare. Both technology and tactics can not be substitutes for each other but are actually complementary. The 1991 Gulf War also saw the first combat use of "stealth aircraft", the US F-117 "Nighthawk" (also known as the Stealth Fighter) and the B-2 "Spirit" (Stealth Bombers). The complementary nature of technology and tactics can be seen from the opening missions of this war. The air war started with low level ingress by US AH-64 "Apache" attack helicopters (tactics) that destroyed key Iraqi radars while F-117 aircraft (technology) operating at medium altitudes carried out deep raids into Iraq; the F-117s were followed by conventional strike aircraft, the conventional strike aircraft were escorted by specialised EW assets tasked to electronically degrade surviving Iraqi air-defence systems. The conventional aircraft could exploit the enemy radar and anti-aircraft weaponry free zones created for them by the earlier AH-64 and F-117 attacks[17].

Developments in various technological disciplines of aircraft design have now made it possible for an aircraft to evade detection to a much greater extent than was possible earlier. This has the potential to drastically change the way aerial warfare is conducted as it opens out tactical possibilities that did not exist in the past and so were never considered except in science fiction (such as the fictitious cloaking devices used by space-ships in the science fiction TV and movie franchise "Star Trek").

Today technology has matured to such an extent that aircraft incorporating fairly advanced "stealthiness" have actually been fielded. The nature of these new aircraft could change aerial warfare as it is known . Stealth has emerged as one of the most revolutionary advances in aircraft technology since the advent of the jet engine. There is a requirement to study the technologies that comprise stealth so as to gain an understanding of how stealth works. Having understood this, the impact of stealth on aerial warfare needs to be examined to see

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[17] "Gulf War Air Power Survey Summary Report", http://www.afhso.af.mil/shared/media/document/AFD-100927-061.pdf, (Accessed September 27, 2013), pp 11-20.

how much of a difference this technology makes to the way aerial warfare is conducted. The development of counters to stealth also require to be examined; these counters indicate possible limits in exploitation of stealth technology and hence require to be understood. Such an understanding is likely to lead to a more rational choice of equipment to be inducted for ensuring adequate national defence capability.

For practitioners and students of aerial warfare it is important to understand these new technologies and the way that they affect the conduct of aerial warfare. This would help in an understanding of the trends for the future and form the basis for force and tactics development.

STEALTH TECHNOLOGY

3

Stealth is all about using technology to defeat detection systems that operate using the EM spectrum. Ability to defeat such detection systems would deliver the benefit of surprising then enemy (as the enemy would be unaware of the presence and location of stealth enabled weapon systems). Such surprise, by achieving a high level of stealth, would be delivered primarily through application of technology. To be considered stealthy in practice an aircraft should have minimal signatures in the following areas of the EM spectrum:-

- Radar.
- Infra-Red
- Acoustics
- Visual

These four factors, from the point of view of the methods of reducing detectability in these parts of the EM spectrum, will now be discussed in brief[18].

STEALTH AND RADAR

Radar

In order to understand how stealth technology works against radar it is essential to understand the basic simplified working principles of radars. Radar has become the most important sensor in aerial warfare since its development during WW-II. This is primarily because radar can pick up aircraft and other radar reflective objects in all weather, by day and night and at larger distances than any other sensor currently in use. Radar also gives very precise information on target parameters

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[18] Knight. op.cit., pp. 82-83.

(including azimuth /elevation, range and target vector etc.) thus enabling effective engagement of the target. Other sensors have also been experimented with over the yeas. A few such sensors have used acoustic, optical and Infra Red (IR) as the primary means of detection and tracking. However, it was found that acoustic methods could give only rough indications of the azimuth and elevation of an aircraft without range and any other parameters. Optical sensors proved inadequate due to difficulties in reliably detecting targets especially at large rages, low accuracy in determination of position as well as lack of range and lack of other parameters extraction capability. IR sensors were effective in determination of azimuth and elevation fairly accurately. These IR sensors, however, were severely affected by weather (basically by atmospheric transparency) and, moreover, these required to be coupled with radar or other means such as lasers for range determination. However, IR sensors provided a passive means of detecting and tracking, and when coupled with lasers for ranging, they could provide required target information often without the target being warned that it was being tracked. Hence, these found widespread application despite the limitation of the variable atmospheric transparency affecting their performance. These will be dealt with separately in a later section. Radar is thus the most used and most potent sensor to detect and track aircraft and hence the greatest threat to an aircraft.

Simple Radar System

All radar systems work in much the same way. EM energy is generated in a device called a magnetron or in a Travelling Wave Tube (TWT). This energy is modulated suitably and then channelled to a directional antenna. The modulated radar energy is then transmitted into space by the directional antenna, which focuses the radar energy into a conical beam. When a reflective object blocks part of this beam, that part of the beam is reflected in many different directions. The scattering of the beam is near random and some energy will be reflected back in the direction of the radar antenna that transmitted the radar energy in the first place. Complex time sharing algorithms are used to stagger the transmission of radar energy and leave the radar antenna silent (not-transmitting), i.e. in receive mode, to enable the same antenna to be used for both transmission and reception. Reception and processing of this reflected energy by the antenna and its associated electronics enables the radar to "see" the target and extract data on its parameters.

The received reflected energy is channelled to receivers where its parameters are examined. The time elapsed between transmission of the radar energy till its reception gives the range of the object as the speed of travel of EM waves is constant (at the speed of light which is 3 x 10^8 metres per second (symbol for speed of light is 'c') in free space, the atmosphere, or vacuum).The received radar waves have travelled out to and back from the target (a distance of 2R, where R is the range to the target, Therefore, (R in metres) = [time elapsed in seconds x 3 x 10^8 meters per second]/2[19]. More advanced processing of the received signal provides information such as target speed, target track and heading etc. The basic concept of radar is mono-static and the transmitter and receiver are usually co-located. Most often these two functions are integrated into one and the same antenna, especially where size and weight is a consideration. Hence, usually the same antenna performs both transmission and reception functions, making the radar mono-static. However, there are examples of bi-static radars where the transmitter and receiver antennae of the radar system are different and sometimes are even located in different widely separated locations; Over the Horizon Backscatter (OTH-B) radar is an example of this variation). These will be examined separately later in this monograph. For the purposes of examining stealth technology applied to the radar sensor, it needs to be understood that the basic concept of radar is mono-static.

Radar Cross Section (RCS)

The reflections from a radar reflective target that is illuminated by radar are not proportional just to the size of the target. The material of which the target is made plays a major role in determining the reflection of radar energy from an object. Metals are very good reflectors while wood and several plastics are much worse at reflection of radar energy. Hence, a large object made of say, wood would reflect much less efficiently (or reflect less energy) than a similar object

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[19] In view of the speed of light being of such a vastly greater amount than the possible achievable speed of the target object and of the radar platform, these two speeds can be ignored as insignificant in determining the range. In the time that the radar energy takes to complete the to and fro journey to the target both the radar and the target would have moved insignificant distances.

made of metal. If two targets made of the same material but of different sizes were to be illuminated by the same radar at the same range, it is still possible for the physically smaller target to have a larger signature on the radar due to the influence of shape of the target on radar reflections from it. Hence, the term RCS is used in place of mere physical size as a measure of the radar detectability of a target. RCS equates the returned radar energy from the target to the size of a reflective sphere that would have returned the same amount of energy. The projected area of this reflective sphere or the area of a disc of the same diameter placed normal to the path of the incident radiation is the "RCS number" itself[20]. A small efficient reflector such as a flat metal plate of area 1.0 m^2 , normal to the radar beam, illuminated by a radar operating at 3 giga-hertz would have a RCS of about 12 m^2. For radar operating at 10 giga-hertz the RCS of the same plate would have increased to about 150 m^2. The RCS is thus seen to be a function of the physical size and shape of the target and also the frequency, or wavelength, (as frequency is equal to c / wavelength) of the illuminating radar. The aspect or incident angle of illumination also plays a part in deciding the RCS at that instant. The effect of shape can be clearly understood by examining the issue of corner reflectors. A typical corner reflector is depicted diagrammatically at Fig. 3.1 below. A "corner reflector" comprises two or more flat plates at right angles to each other[21]. If EM energy falls upon one plate of the corner reflector such that it is turned through 90 degrees towards the other plate it will again go through a change of direction by 90 degrees and thus will be sent back towards its source with full strength. A corner reflector can turn an incident radar beam through 180 degrees and thus can return the full strength of the original energy towards the radar showing a signature equal to a sphere of very large diameter and so have a very large RCS[22].

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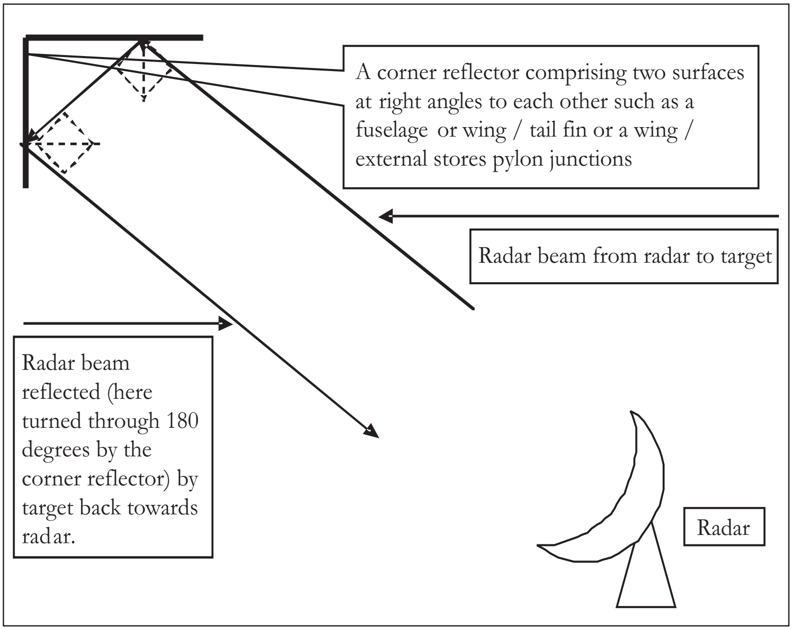
[20] Air Vice Marshal JR Walker, CBE, AFC, RAF. *Air Superiority Operations*, (Brassey's, Defence Publishers Ltd, London, 1989, pp.76-78.

[21] Classic aircraft shapes provide many corner reflectors such as wing and fuselage junctions, the empennage, pylons on which under wing engines or under wing weapons stores are fitted are simple examples found on most un-stealthy aircraft.

[22] Merrill I. Skolnik, *Introduction to Radar Systems,* McGraw-Hill Books Co., Singapore,1981, pp.33-40.

The angle of interception between the incident radar beam and the target aspect displayed in the direction of approach of the radar beam dictate the presentation of corner reflectors and reflective surface to the beam. The frequency of the radar beam dictates which parts of the aircraft will resonate and thus strengthen the reflected energy[23]. The design parameters of all radars are based on the ability to pick up a target of a specified RCS at a given range. Variation in the RCS of the target would therefore affect a radar's target detection range appreciably[24]. Radar has one more limitation touched upon earlier: it works best against metal than any other material. The design features required for stealth against radar are discussed in the following paragraphs.

Fig. 3.1. A Corner Reflector



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[23] Knight. op. cit., pp. 94-99.

[24] Ibid., p.154.

Shape of the Aircraft

As most radar waves impinge on an aircraft at near horizontal angles[25], vertical surfaces on the aircraft have to be eliminated completely or at least kept to the minimum in order to reduce radar reflections. This dictates the elimination, or canting inwards / outwards of the dorsal fin (or vertical stabiliser), elimination of external pylons for weapons carriage with these stores moving to internal weapon bays, and elimination of corner reflectors such as conventional wing fuselage junctions[26]. The last leads to extensive wing body blending such as on the F-16 and Rafale so as to reflect the incident radar energy away from the radar[27]. The ultimate in this direction of aircraft shaping is the elimination of distinction between the fuselage and wings giving rise to a flying wing design such as of the Horten Ho-IX referred to earlier and the B-2 "Spirit" Stealth Bomber[28]. The design is not quite so simple. Any uniformly curved surface would act as part of a sphere and reflect energy randomly, some of it towards the radar site we are trying to avoid. Therefore, the curved surfaces on a stealth aircraft have to be such that they form the surface of a sphere of ever changing radius, the radii tailored to reflect the incident energy away from the radar site (such a design would require powerful supercomputers to design the spread and magnitude of the ever changing radii to ensure that reflected radar energy is directed as desired). Such a design process could be expected to be and actually is very complex and costly. Stealthy aircraft currently in squadron service include the B-2 "Spirit", F-22 "Raptor" and the F-35 "Lightning-II". Each F-22 "Raptor" is claimed to cost,

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[25] Even high flying aircraft fly at altitudes of about 15 to 20 km above the surface while radars have ranges of several hundred km. thus the radar energy incident on aircraft from ground based radars arrives at quite shallow angles. Thus vertical surfaces such as vertical stabilisers efficiently reflect this back towards the radar. This should be avoided for reduced RCS.

[26] Bill Sweetman, *Advanced Fighter Technology The Future of Cockpit Combat*, Airlife Publications Ltd, London,1988, pp. 105-106.

[27] It may be noted, however, that at least in the F-16 when it was initially designed wing-body blending was undertaken not primarily for stealth but for aerodynamic and structural reasons. Once it was realised that this blending also helped in RCS reduction this became a bonus spin-off.

[28] *The World's Great Stealth and Reconnaissance Aircraft*, Oriole Publishing Ltd, Hong Kong 1991, pp. 153-162.

including development and production spending, an enormous $412 million[29]

The USAF's 21 B-2 bombers cost as much as $ 2.1 billion each[30]. Operating costs are also high for these advanced aircraft. In 2010 the F-22 ad B-2 cost the USAF $ 55,000 and $ 135,000 to operate per flying hour respectively[31].

Another approach to the use of shaping to reduce RCS is to make the aircraft body of a number of flat plates inclined to reflect energy away from its origin (the radar location), as on the US' F-117 stealth fighter (which has actually been used for strike or bombing missions and never in the fighter, or air-to-air, role due to the severe limitations on its manoeuvrability and other required performance parameters required for air-to-air engagements caused by its unique stealth design)[32].

Engines

A jet engine with its sharp edged metallic compressor and turbine blades rotating at high speed is one of the most efficient radar reflectors on an aircraft. Masking of the engine from radar energy is one of the most important and difficult aspects of defeating radar. If the main threat is from ground based radars (as for most aircraft), the jet engine inlet and exhaust can be moved above the wing or fuselage in order to deny radar energy from ground based radars direct access to the engines. This is illustrated at Fig 3.2 below. In addition, the engine's inlet and exhaust tunnels can be made serpentine to deny radar beams a direct look at the engine's compressor and turbine blades. This is illustrated at Fig 3.3 below. The insides of the intake and exhaust tunnels

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[29] Ralph Vartabedian and W.J. Hennigan, "F-22 program produces few planes, soaring costs", http://www.latimes.com/business/la-fi-advanced-fighter-woes-20130616-dto,0,7588480.htmlstory, Accessed October 13, 2013).

[30] James Dunnigan, "F-22 Has A Fatal Skin Disease", http://www.strategypage.com/dls/articles/F-22-Has-A-Fatal-Skin-Disease-7-25-2009.asp, (Accessed June, 2013).

[31] Winslow Wheeler, "Air Force Doesn't Know Aircraft Operations, Maintenance Costs; Audit Needed", http://breakingdefense.com/2011/09/21/air-force-doesnt-know-aircraft-operations-maintenance-costs-a/, (Accessed June, 2013).

[32] *The World's Great Stealth and Reconnaissance Aircraft*, Oriole Publishing Ltd, Hong Kong 1991, pp. 164-172.

can be made with radar absorbent structures and coated with radar absorbent materials. To prevent reflections from the air intake and exhaust lips themselves, these could be made irregular in shape[33]. The exhaust could also be made flat with "venetian blind" slats to deny radar beams access to the turbines of the engine.

Fig 3.2 Shielding Of Engines From Radar by Moving Them Above The Wing/ Fuselage

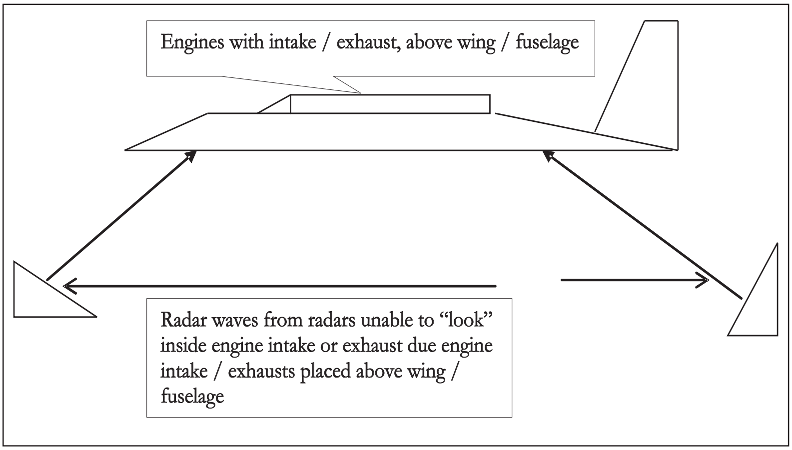
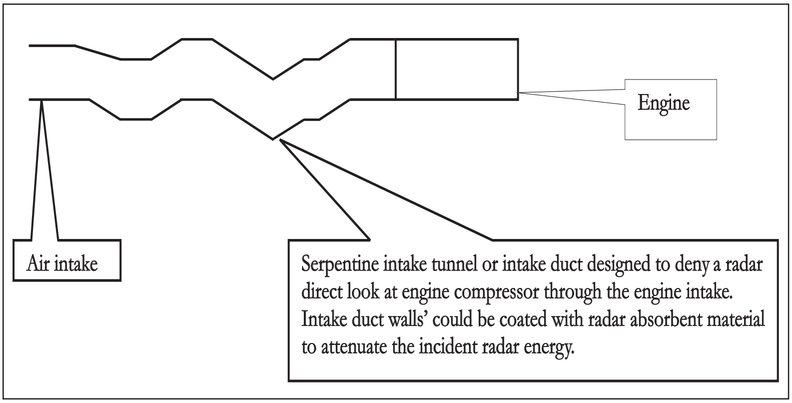


Fig 3.3 Serpentine Intake Tunnel to Deny Radar Direct Look at Engine Compressor



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[33] *The World's Great Stealth and Reconnaissance Aircraft*, Oriole Publishing Ltd, Hong Kong,1991, pp. 153-162.

Substructure

In addition to the external shape of the aircraft the substructure of its construction materials, especially in areas of high radar reflectivity, can be designed to capture and deplete the energy of the radar beams incident upon the aircraft[34]. If the incident radar beam can be depleted to the extent that the returned energy falls below the received radar energy detection threshold of the hostile radar then the aim of delaying or denying radar detection would be achieved. The substructure of the wings' leading edges or the air intake and exhaust lips (which typically are areas of high radar reflectivity) may have wedges cut in their metal sub-structure, under a radar transparent skin. These wedges could be filled with radar absorbing material. The incident radar energy would be captured in the wedges, reflecting within the wedges from one metallic surface to another through the radar absorbent material thus progressively losing its energy. This is illustrated at Fig 3.4 below. Honeycomb structures, by their very nature also lend themselves to this technique[35]. Another method of using the substructure is to design an 'active radar cancellation system'[36] by designing the aircraft's structure to have two layers of 'skin' separated by a distance equal to half the wavelength of the expected radar energy that is required to be defeated. The outer skin material could be tailored to partially reflect the radar energy while the inner layer of the skin could be made of material that fully reflects the radar energy. The result is that the total reflected radar energy in this case would include a considerable part of radar energy that is out of phase by half a wavelength. This is illustrated at Fig 3.5 below. These out of phase portions of the reflected energy would cancel each other out and the effective sum of total reflected energy would be considerably reduced[37]. The former methods are effective against almost all wavelengths, and hence could be termed a broadband

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[34] Bill Sweetman. Advanced Fighter Technology The Future of Cockpit Combat. Airlife Publications Ltd, London,1988, pp.107-108.

[35] Knight. op. cit., p. 102.

[36] This is akin to active noise cancellation headphones available in the market. These transmit signals similar to noise signals but out of phase with noise signals by 180 degrees thus effectively canceling out the noise while leaving wanted audio signals untouched. See http://www.boseindia.com/retail/bose-product-detail.aspx?Prd_Id=56 for more details, Accessed September 09, 2013.

[37] Ibid., p. 102.

technique, while the latter, active radar cancellation technique, is frequency/wavelength specific[38], hence could be termed a "narrow band" technique.

Fig 3.4 Substructure Designed to Attenuate Incident Radar Energy

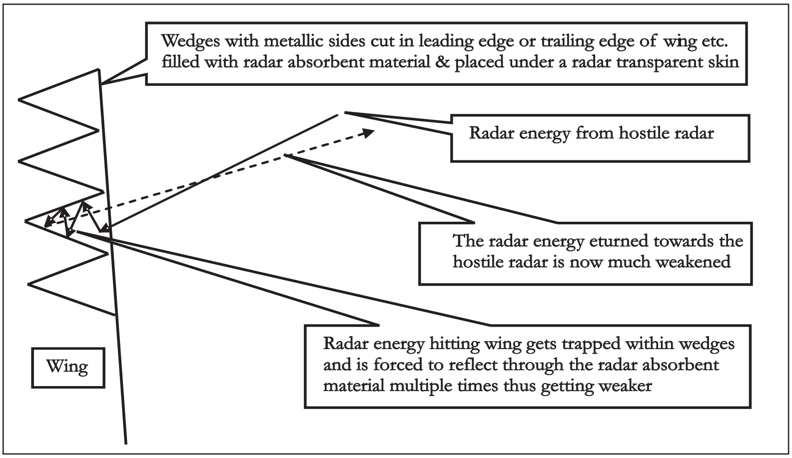
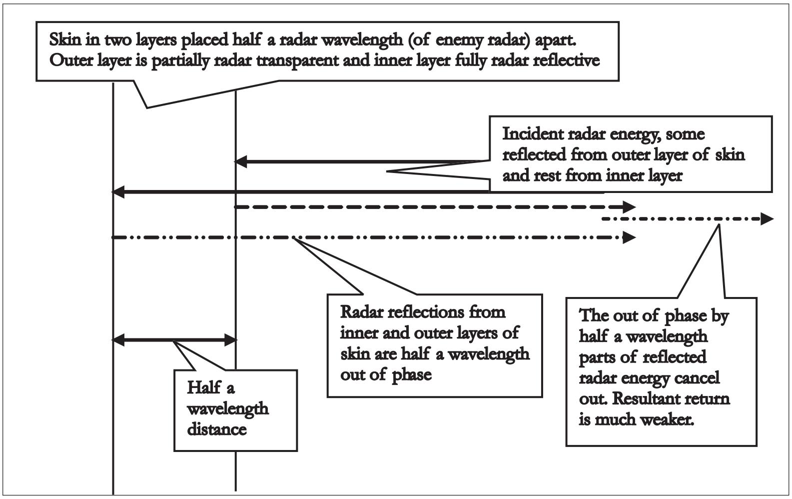


Fig. 3.5 Active Radar Energy Cancellation



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[38] This is because in the second case the need for a half wavelength separation of the two reflective layers has to be targeted at a specific wavelength and hence frequency alone.

Radar Ablative Paints

In their simplest form these comprise paints which contain small iron particles or 'iron balls', hence the common name "iron ball paint". Radar energy falling on such paints induces a magnetic field in the metal particles that are incorporated in the paint. This induced magnetic field switches polarity at the incident radar energy's frequency, converting the radar energy into heat and thus attenuating the strength of the radar energy. These paints carry a weight penalty due to the addition of metal particles. In addition, the effectiveness of these paints depends upon the size of the iron balls in relation to the wavelength of the incident radar energy thus making this paint relatively narrow band. The effectiveness of these paints also varies with the angle of the incident radar beam as this angle determines the thickness of paint that the incident radar beam has to penetrate before reflecting off the metal surface of the aircraft. Application of these paints, especially in areas of high radar reflectivity, can contribute to the reduction of the RCS to some degree.

Radar Absorbent Material (RAM)[39]

There are some materials which are inherently radar absorbent. RAMs feature free electrons in their atomic structure[40]. When RAMs are illuminated by a radar beam, the free electrons in the RAM's atomic structure are forced to oscillate at the frequency of the incident radar wave. The friction and inertia of the oscillating free electrons convert the radar energy into heat and thus help to weaken it. Many carbon fibre composites such as Re-enforced Carbon Carbon (RCC) have very high strength in addition to being radar absorbent and thus can be used as part of the aircraft's structure itself rather than just as coatings[41]. In fact the American made McDonnell Douglas AV8B "Harrier-II" variant of the British Harrier aircraft features a complete wing, the major load bearing structure on any aircraft, manufactured entirely from carbon composites. This innovative wing design and construction

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[39] Bill Sweetman. Advanced Fighter Technology The Future of Cockpit Combat. Airlife Publications Ltd, London,1988, p.107.

[40] Ibid.

[41] Air Vice Marshal JR Walker, CBE, AFC, RAF. *Air Superiority Operations*, Brassey's Defence Publishers Ltd, London,1989, pp.87-88.

enables better aerodynamic shaping and more strength as compared to an all metal wing in addition to radar reflectivity reduction[42]. On this aircraft the choice of material for the wing as based more on strength, weight reduction and optimisation of shape requirements rather than stealth issues as the AV8B was not intended to be a low observability optimised machine but rather one that could operate from very constrained locations using its Vertical / Short Take Off and Landing (V/STOL) capabilities.

In order to defeat radar a combination of all the techniques discussed above are utilised in the design and manufacture of stealthy aircraft.

Finer Aspects

The radar signature of an aircraft is dependent upon several other finer aspects of design and manufacture. These are briefly discussed below:-

- Radar reflectivity is also a function of the change of impedance between two surfaces. A higher change of impedance along the surface of an aircraft would therefore result in a larger radar signature. In order to lower the RCS is should be ensured that there is minimal change of impedance along the aircraft's surface. This requirement demands very close fitting between surface skin panels and very efficient electronic bonding[43] between adjacent parts of the aircraft structure. Very fine manufacturing tolerances are required in order to ensure close fitting between adjacent parts. Such fine manufacturing tolerances raise the cost of production. Due to need for extreme care and precise manufacturing extensive use of expensive computer controlled machining equipment is required. In addition, due to the need for very precise fitting between adjacent components especially skin panels and externally located access hatches, rejection rates of manufactured parts could be expected to be high in comparison to an aircraft manufactured

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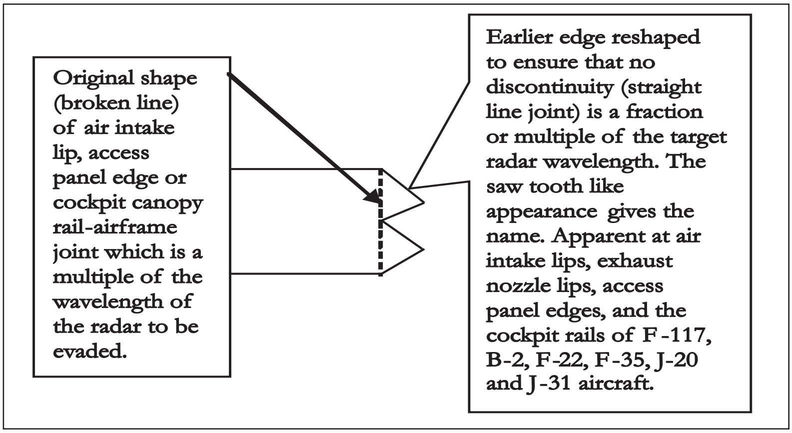
[42] M. L. Huttrop, "Composite Wing Substructure Technology on the AV-8B Advanced Aircraft", http://link.springer.com/chapter/10.1007%2F978-1-4684-1033-4_3, Accessed September 30, 2013.

[43] Bill Sweetman. *Advanced Fighter Technology The Future of Cockpit Combat.* Airlife Publications Ltd, London,1988, p.109.

without stealth characteristics in mind. Rejection of manufactured parts further raises the cost of production.

- In order to further reduce radar reflections from an aircraft designed and built for stealth, even the lengths of discontinuities along all parts of the airframe would have to be kept away from the radar wavelength, and multiples and fractions of the radar wavelength, of the expected high threat radars. This explains the "saw-tooth" shaping of access panels, intake and exhaust tunnel lips, and the cockpit rails in stealthy aircraft (such as the US F-22 "Raptor, and F-35 "Lightning-II", Russian **P**erspektivny **A**viatsionny **K**ompleks **F**rontovoy **A**viatsii (PAK FA) translated roughly as Prospective Aircraft Komplex [for] Tactical Aviation, and the Chinese J-20 and J-31). The "saw tooth" shaping is carried out to ensure that there are no lengths of discontinuity on the aircraft structure that are close to the threat radar wavelength or its multiples. This sawtoothing is illustrated at Fig 3.6 below.

Fig 3.6 Saw Toothing of Linear Discontinuities[44]



Original shape (broken line) of air intake lip, access panel edge or cockpit canopy rail-airframe joint which is a multiple of the wavelength of the radar to be evaded.

Earlier edge reshaped to ensure that no discontinuity (straight line joint) is a fraction or multiple of the target radar wavelength. The saw tooth like appearance gives the name. Apparent at air intake lips, exhaust nozzle lips, access panel edges, and the cockpit rails of F-117, B-2, F-22, F-35, J-20 and J-31 aircraft.

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[44] https://www.google.co.in/search?newwindow=1&hl=en&site=imghp&tbm=isch&source=hp&biw=1280&bih=909&q=F-117&oq=F-117&gs_l=img.3..0l10.2536.3639.0.4029.5.5.0.0., https://www.google.co.in/search?newwindow=1&hl=en&biw=1280&bih=909&site=imghp&tbm=isch&sa=1&q=B-2&oq=B-2&gs_l=img.3..0l10.37438.38293.0.38603.3.3.0.0.0.0.123.358.0j3.3.0....0...1c.1.28.img..0.3.357.fN, https://www.google.co.in/search?newwindow=1&hl=en&biw=1280&bih=909&site=imghp&tbm=isch&sa=1&q=F-22&oq=F-22&gs_l=img.3..0l10.58299.59327.0.59798.4.4.0.0.0.0.128.461.0j4.4.0....0.,

- The cockpit of an aircraft could be compared to a shallow radar reflective pit dug into the smooth carefully contoured surface of the aircraft and is an area of high radar reflectivity. In stealthy aircraft this potential source of radar returns could be and is hidden from incident radar energy by coating the canopy with a thin film of metal a few molecules thick. A metal film just a few molecules thick would not reduce the pilot's visibility appreciably[45]. The metallic molecular thickness coating on the canopy works in a similar way to radar ablative paints in attenuating radar energy and reducing the RCS.

- A stealthy aircraft cannot afford to give away its position by radiating EM energy. The avionics suite would have to be tailored accordingly with near minimal radiation. The radar antenna of any conventional radar on board would have to be shielded. A radar antenna by design is an efficient radar reflector. In fact the radar would preferably be required to be of the Low Probability of Intercept (LPI)[46] types that are more commonly called Active Electronically Scanned Antenna (AESA) radars today[47]. An aircraft that switches on a conventional radar can be compared to a person switching on a flashlight in a dark room. Much as the flashlight betrays the person's presence and exact location in the dark room, the conventional radar's transmissions can be picked up very easily by radar receivers giving away the aircraft's presence and position (through simple triangulation or tracing back the emitted radar energy to its point of origin). IR and other passive detection windows in the EM spectrum and passive navigation-attack systems would also find great favour in such an aircraft[48]. LPI radars are

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[45] "Glass' coating, which protects from radiation, was created in Russia", http://www.aviationunion.org/news_second.php?new=114, and "Patent application title: Outboard Durable Transparent Conductive Coating On Aircraft Canopy", http://www.faqs.org/patents/app/20120328859#ixzz2hg3xGXYP, (Accessed October 02, 2013).

[46] *The World's Great Stealth and Reconnaissance Aircraft.* Oriole Publishing Ltd, Hong Kong 1991, pp. 153-162.

[47] Bill Sweetman. *Advanced Fighter Technology The Future of Cockpit Combat*, Airlife Publications, Ltd, London,1988, p. 130.

[48] Ibid.

able to minimise radar transmissions through their ability to extract required information from appreciably fewer radar returns by leveraging powerful high power computing thus reducing the amount of active radiation required and consequently the danger of betraying their own position. AESA radars do away with the traditional parabolic radar reflective antennae in favour of arrays of transmit receive modules thus eliminating the conventional radar antenna, a potential source of radar signature prominence.

All these methods of achieving radar stealth discussed in the preceding paragraphs could be expected to be used to some extent in a stealthy aircraft. In fact a careful examination of photographs of the stealth aircraft in the world today, the F-22 "Raptor", B-2 "Spirit", F-35 "Lightning-II", J-20 and J-31 show that evidently many of these methods have been utilised on these aircraft. One fact that has to be very clearly understood is that these advanced design and manufacture techniques cannot, as yet, make an aircraft totally invisible to radar. The aircraft's RCS can be appreciably reduced with the radar detection and tracking ranges thus also reducing considerably; however, total invisibility to radar and other sensors in the EM spectrum has not as yet been achieved.

A few educated estimates of RCS figures of modern aircraft, available in the public domain, are listed at Table 3.1 below:-

Table 3.1 RCS Figures for Representative Modern Aircraft[49]

Sl No	Typical target Type / Aircraft	RCS (in m^2)
1	A typical car	100
2	B-52	100
3	B-1(A/B)	10
4	F-15 "Eagle"	25
5	Su-27 "Flanker"	15

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[49] "Radar Cross Section (RCS)", http://www.globalsecurity.org/military/world/stealth-aircraft-rcs.htm, (Accessed June 03, 2013).

6	cabin cruiser	10
7	MiG-29A/B “Fulcrum”	5
8	Su-30MKI “Flanker”	4
9	Mig-21Bis “Fishbed”	3
10	F-16A/B “ Falcon”	5
11	F-16C/D “Falcon”	1.2
12	An average man	1
13	F-18E/F “Super Hornet”	1
14	Rafale	1
15	B-2 “Spirit”	0.75
16	Eurofighter Typhoon	0.5
17	Tomahawk cruise missile	0.5
18	A-12/SR-71 “Blackbird”	0.01
19	A representative Bird	0.01
20	JSF / F-35 “Lightning-II”	0.005
21	F-117 “Nighthawk”	0.003
22	Insect	0.001
23	F-22 “Raptor”	0.0001

Figures for RCS in Table 3.1 show that the RCS of modern stealthy aircraft has been reduced to a great degree but not as yet to zero. Hence, radar detection of these stealthy aircraft is delayed by the low RCS but not eliminated altogether. Therefore, it is clear that these stealthy aircraft will be picked up by radars that are powerful enough but at much lower ranges than those at which non stealthy aircraft would have been detected.

Plasma Stealth

A final stealth concept not discussed so far is that of plasma stealth. This concept is based upon the scientific fact that plasma, which is a fully ionised quantity of air with low density that comprises roughly equal positive and negative ions[50], has the property of being able to interact with incident EM energy. If an aircraft were enclosed in a covering, or envelope, of plasma, incident radar energy would interact with the plasma and be attenuated; in fact to such an extent that there would be no effective return of the radar energy towards its source as if the plasma cloaked aircraft was invisible or not there at all. The attenuation of radar energy by plasma is very different from the effects achieved through shaping of the aircraft. Shaping does not attenuate the radar energy per se but directs it away from the hostile radar. Plasma through interacting with incident radar energy does not direct it away from the radar but attenuates to a large extent it by interacting with it. Hence, a stealth system based upon plasma would be less susceptible to being defeated by bi-static or multi-static radar systems. This attenuation effect is greatest at higher radar frequencies while very low frequencies may even be reflected by the plasma. Fortunately most radars that aircraft require to defend against operate in the centimetric wavelength bands that fall in the classification of X band radars with frequency of 8 to 12 Gigahertz (GHz) and Ku band radars of frequency 12-18 GHz. This physical property of plasma is not, as of now, seen to be applied in any current aircraft. The concept at time of this writing remains just that, a concept. Plasma stealth if practically achievable would act like a radar energy sink able to effectively hide aircraft from radars very efficiently. There are random reports of trials on plasma based stealth being carried out in Russian research laboratories. Therefore, while not much more can be said at this stage about this purported technique for achieving stealth, it is quite reasonable to expect an aircraft that relies upon plasma stealth for low observability to retain very high basic aerodynamic performance characteristics as it would rely not upon shape alone (aircraft shape modification to increase low observability often detracts from pure performance needs) but upon the added on plasma generation system for stealthiness. This makes plasma stealth an interesting concept worth exploring further by all technologically advanced nations. Through the ability to interact with and greatly attenuate radar energy plasma stealth could potentially deliver

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[50] Andrew Zimmerman Jones, "Plasma", http://physics.about.com/od/glossary/g/plasma.htm, Accessed September 02 2013.

RCS values more closely approaching zero unlike the techniques described so far.

The main learning and take away from this section is that several techniques that include shape of the aircraft, construction materials used in manufacture and the internal structure of the aircraft body have reduced the RCS of aircraft manifold to the extent that aircraft that are quite large physically such as the B-2 "Spirit" and the F-22 "Raptor" have RCS values that are assessed to be lesser than those of birds and even of some insects. This fact should not mask the fact that all these techniques of RCS reduction have been unable to make aircraft truly invisible to radar. The techniques used have been able to reduce but not eliminate the aircraft's radar signature. Stealth aircraft of today do have a detectable radar signature despite the application of the many technological fixes described in the section above. Here it is pertinent to remind the reader that these RCS reduction techniques have come at very high cost. A single F-22 "Raptor" is reported[51] to cost $412 million. The US Government has capped the purchase of F-22s at 187 aircraft[52] due to their very high cost. B-2 "Spirit" stealth bombers cost between $ 1 billion per piece in 1997[53] to $2.2 billion in about 2009[54]; a fact that forced the US to stop buying B-2s after building just 21 aircraft[55] . This point is laboured over here as the cost of stealth aircraft is likely to have an effect on the conduct of aerial warfare in addition to the affect of the stealth technologies themselves. The capability versus quantity issue comes into play at this stage. This will be discussed in detail in a later section.

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[51] Ralph Vartabedian and W.J. Hennigan, "F-22 Program Produces Few Planes, Soaring Costs", http://www.latimes.com/business/la-fi-advanced-fighter-woes-20130616-dto,0,7588480.htmlstory, Accessed August 04, 2013).

[52] Michael Auslin, "These Fighter Numbers Don't Add Up", http://www.american.com/archive/2009/july/these-fighter-numbers-dont-add-up/, Accessed August 05, 2013).

[53] Joel Baglole, "The B-2 Spirit Stealth Bomber", http://usmilitary.about.com/od/bomberaircraft/a/B2.htm, Accessed October 03, 2013).

[54] *Robert S. Dudney,* "The Real B-2 Mistakes", http://www.airforcemag.com/MagazineArchive/Pages/2009/November%202009/1109edit.aspx, (Accessed October 03, 2013).

[55] Tom Harris, "How Stealth Bombers Work", http://science.howstuffworks.com/stealth-bomber4.htm, (Accessed August 04, 2013).

STEALTH AND INFRA-RED (IR)

A large variety of detection and tracking systems operate in the IR band of the EM spectrum, as do several anti- aircraft missiles. What makes the IR band more interesting from the military point of view is the fact that many IRST do not require actively transmitting themselves. They passively detect and track the target's involuntary and inherent IR emissions. So the detecting and tracking platform can maintain complete silence and carry out a stealthy and silent attack without warning the target that a sensor is searching for it, or that it has located it and is tracking it. This advertising of the actions being taken by the tracking platform perforce take place when using radars, except when using the latest LPI radars, as the target aircraft's radar warning receivers will indicate that a hostile radar is dwelling upon it in various modes of operation (from search to single target track and finally that missile guidance channels are also active). This relative stealthiness of search and tracking by IRST systems makes the IR band a high threat area of the EM spectrum, second only to radar, for military aircraft. Stealth design perforce requires addressing this band. Stealth technology also aims to reduce and minimise an aircraft's IR signature

The IR signature of an aircraft comes from two main sources. These are :-

- The heat of the engine and its exhaust gases (or jet efflux).
- The heating of the airframe due to air friction.

IR Signature of Engines and Exhaust Plume

Engines are the most powerful IR source aboard an aircraft. A typical jet engine burns Aviation Turbine Fuel (ATF), a form of refined kerosene; at temperatures, in the combustion chamber, of up to 2100 degrees centigrade[56]. The exhaust gases of modern jet engines while passing through the turbine blades can have temperatures as high as 850 to 950 degrees centigrade[57]. When reaching the free atmosphere outside the exhaust nozzle of the engine the exhaust gases, have typically

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[56] "Materials-Combustor", http://www.rolls-royce.com/interactive_games/journey03/ Accessed August 16, 2013

[57] Favorsky, O.N., "Jet Engine", http://www.thermopedia.com/content/901/, Accessed August 19, 2013).

travelled (at near supersonic speeds) about one to three metres from the turbines, and are only slightly cooler. The hot jet efflux behind the exhaust nozzles now spreads out in the shape of an expanding cone of hot gases behind the typically circular cross-section engine exhaust nozzles. As the ambient air mixes with the efflux, it starts to cool down. The speed of cooling and the mean temperatures of the air mass are a function of the rapidity of the intermixing of the hot jet efflux with the much cooler ambient air mass. While the exhaust plume is most prominent when viewing the aircraft from behind, parts of the plume can be seen even when viewing the aircraft from in front as the aircraft is relatively too small to be able to shield the much larger plume from view despite being placed between the viewer and the plume.

A small technical point of interest. All matter with temperature above absolute zero[58] radiates IR energy. The wavelength of the radiated IR energy is related to the temperature of the radiating body. A hotter body radiates shorter wavelengths (higher frequencies) of IR energy while bodies at relatively lower temperatures radiate longer wavelengths (lower frequencies) of IR energy. Hence, the IR radiation from different parts of the aircraft is not the same.

Most tail hemisphere only capable IR systems use the IR energy wavelengths given out by the hot parts of the engine itself that are visible from the rear when looking into the exhaust nozzles, such as the exhaust tunnel between the turbine blades and the exhaust nozzle and the turbine section, and the hot jet efflux. This choice of IR frequencies used was dictated by the easy availability of a large IR signature from the rear aspect as well as the then (1950s to 1970s) current technology that provided IR detectors best at detecting these IR frequencies/ wavelengths. The all aspect or front hemisphere capable missiles that were developed much later (late 1980s onwards) use the wavelengths radiated by the exhaust gases and also the longer IR wavelengths radiated due to airframe heating for their effective operation[59].

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[58] This is the coldest possible temperature in nature. It corresponds to (-) 273.15 degrees centigrade and is given symbol K. at 0° K there is no heat left in the body and no IR radiation.

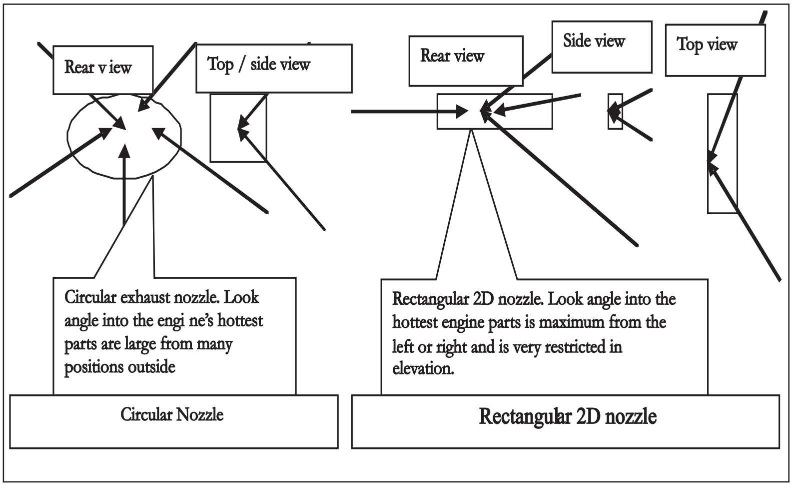
[59] Air Vice Marshal JR Walker, CBE, AFC, RAF. Air Superiority Operations. London : Brassey's (UK) Defence Publishers Ltd, 1989, pp.52-53..

The methods employed for reducing the IR signature in stealthy aircraft are discussed below:-

Use of Two Dimensional (2-D) Exhaust Nozzles

These exhaust nozzles are typically rectangular in cross-section with the width more than the height. . These thus restrict the "look angle" into the hot engine turbine from behind. With these nozzles, IR sensors get the best look angle into the hot engine parts from awkward narrow angles to the left or right with the available look angles in elevation being severely restricted. Such exhaust nozzles can be seen on the F-22 "Raptor". The F-22's exhaust nozzles are also movable to improve manoeuvring performance through thrust vectoring. This method of effectively 'hiding' the hot engine parts helps reduce the IR signature. The shape of the jet efflux from such an exhaust nozzle is not conical but has a roughly rectangular cross section and mixes faster with ambient air thus cooling down faster and reducing the IR signature.

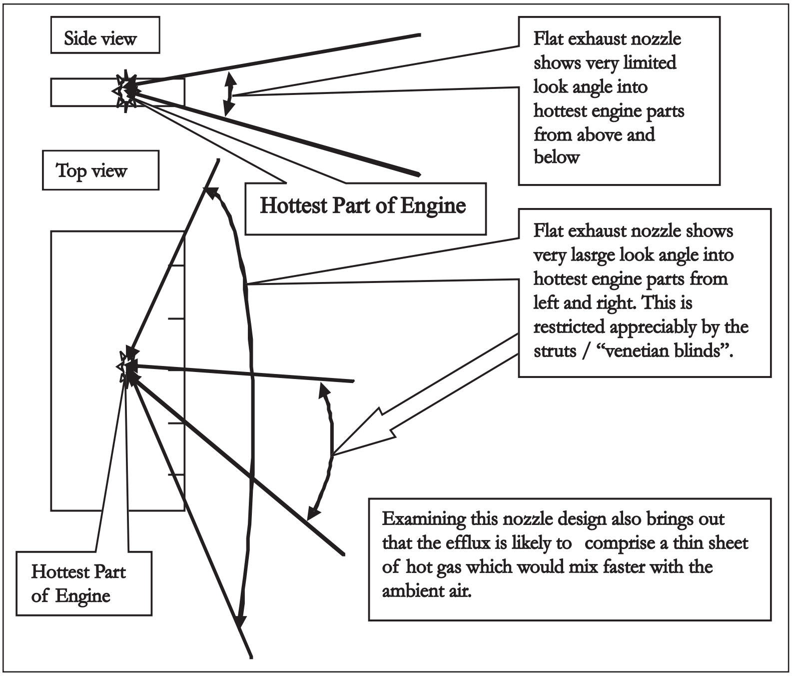
Fig 3.7 2D Engine Exhaust Nozzles



Flat Slit and Venetian Blinds Exhaust Nozzles

If the exhaust is made into a flat slit with "Venetian blind" partitions (these venetian blind partitions could also be likened to short vertical struts along the width of the exhaust) along its width the advantages mentioned in the last point would accrue to a greater extent as the "blinds" or "struts" would also restrict the horizontal view into the engine[60]. In addition, the exhaust plume would be in the form of a relatively thin sheet of hot gas. This would mix with the cooler ambient air faster than the expanding cone of hot gas from a conventional circular exhaust thus cooling down more rapidly and giving a reduced exhaust plume signature. By careful positioning of the exhaust it is possible to use vortices shed by airframe parts to promote even faster mixing of the exhaust plume with ambient air thus reducing the IR signature further[61]. The F-117's exhaust was designed in this manner. The F-22 and B-2 engine exhausts are also similar though to a lesser degree.

Fig 3.8 Flat Venetian Blind Exhaust to minimise IR (Advantage of Less Radar Look Angle Also)



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[60] The World's Great Stealth and Reconnaissance Aircraft,. Oriole Publishing Ltd, Hong Kong, 1991, pp. 163-172.

[61] Bill Sweetman. Advanced Fighter Technology The Future of Cockpit Combat., Airlife Publications Ltd, London,1988, p.126.

Thermal Insulators and Air Mixing

Positioning of suitable thermal insulators in and around the engine can help hide its thermal signature from prying sensors. These insulators could be in the form of ceramic tiles/ plates / blankets or even ducted cooler air. The mixing of cooler air with the post combustion hot exhaust gases, as is done in bypass jet engines, also helps cool down the exhaust efflux thus reducing the IR signature. In order to cope with the very high temperatures at the turbine some engines are designed to have small air channels running along the turbine blades under the turbine blades' skin. Cooler air is passed through these air channels and this helps cool down the turbine blades so as to reduce thermal stress and thus avoid material failure[62]. The same technique through lowering of temperature also provides IR signature reduction and is used in the exhaust ducts of several jet engines.

Shielding

Location of the exhaust so that it is shielded from hostile view by airframe parts also contributes towards the reduction of the IR signature. For instance the **S**ociété **E**uropéenne de **P**roduction de l'Avion d'**É**cole de **C**ombat et d'**A**ppui **T**actique, which translates as "the "European company for the production of a combat trainer and tactical support aircraft", (SEPECAT) Jaguar and McDonnell Douglas F-4's engine exhaust nozzles are partially shielded from view at some angles by their relatively large and drooping tail-planes positioned just above and behind the exhaust nozzles.

Use of Reheat

Reheat, or afterburner, systems were designed to increase the thrust of jet engines for phases of flight of relatively short duration. These systems involve injection of fuel into the combustion reside air mass after it passes through the turbine. This combustion reside air mass contains an amount of unburnt oxygen. The fuel added to this air with operation

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[62] Je-Chin Han and Lesley M. Wright, "Enhanced Internal Cooling of Turbine Blades and Vanes", http://www.netl.doe.gov/technologies/coalpower/turbines/refshelf/handbook/4.2.2.2.pdf, (Accessed August 21, 2013).

of a suitable ignition system leads to further combustion aft of the combustion chambers and turbine assembly and gives an appreciable increase in thrust albeit at the cost of an increase in fuel consumption[63]. The use of reheat leads, on the average, to an increase in the size of the detectable hot exhaust plume by a factor of five. The exhaust gas temperatures are also now higher. Therefore, for IR stealth the use of reheat would be counterproductive[64]. This is why earlier stealth aircraft, the F-117 "Nighthawk" and B-2 "Spirit" were subsonic machines without reheat systems and most high performance stealth fighters such as the F-22 "Raptor" and F-35 "Lightning-II" include the ability to avoid use of reheat and supercruise[65] through use of very powerful new technology jet engines. The exception to these was the USA's Lockheed A-12/SR-71 "Blackbird" that compensated for use of reheat by flying at heights of 80,000 to 100,000 feet above mean sea level at above Mach[66] 2.8-3.0; utilising an operational envelope that few hostile weapons could approach, thus achieving safety in its long service life of missions over hostile territory (the Soviet Union and Peoples Republic of China (PRC)).

Airframe Heating

The heating due to skin friction is a function of the Mach number. Appreciable heating occurs at fairly high Mach numbers. The wavelength of IR energy given out due to this heating is about 8.6 x 10^{-6} metres

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[63] For instance the Klimov RD-33 engine that powers the MiG-29 fighter and in developed variants the South African Cheetah, Chinese JF-17 "Thunder" (FC-1 "Fierce Dragon") has a non-reheat thrust of 5040 kilogram force static thrust (kgfst) which increases to 8300kgfst with afterburners. The RD-33's specific fuel consumption (SFC) in afterburner settings is about 2.0 kg/kgfst/hour and in max dry power the SFC is about 0.7. The twin engine MiG-29 burns up to 554 kilograms 2 x (2 x 8300/60) =276.66666666 kg) of fuel per minute with afterburners on while a JF-17 which has a single engine burns about 277 kg of fuel per minute in reheat settings.

[64] Knight. op. cit., pp. 93-94.

[65] Supercruise refers to the ability of an aircraft to carry out sustained flight at supersonic speeds in dry or non-reheat power settings. This obviously requires engines that are able to deliver non-reheat thrust output comparable to the thrust delivered in reheat settings by earlier engines.

[66] Mach number is a ratio of the true air speed the aircraft to the local speed of sound.

(m). This wavelength is absorbed by atmospheric gases and minute suspended particles. Its transmittance increases at higher altitudes as the density of the air reduces. Thus, this IR signature is of greater importance at higher altitudes and high Mach numbers[67]. The airframe heating due to friction increases as the speed of the aircraft increases. In earlier times due to relatively lower speeds of aircraft and the then less sophisticated IR seeker technology this heating was ignored. However, with development of more advanced IR detectors and seekers that are able to pick up the longer IR wavelengths emitted by airframe heating and the increase in aircraft speeds of operation it has become necessary to address this aspect of the IR signature also.

All parts of the airframe do not heat up uniformly. It has been found that maximum heating occurs on the sharper parts of the aircraft that face into the airflow such as wing leading edges, air intake lips and sharp nose sections[68]. One way of reducing this signature is by careful design to eliminate potential heating hot spots. Requirements to design in adequate manoeuvrability are likely to impose limits on the amount of elimination of heating hot spots that would be possible through re-shaping of the aircraft. Another method is to conduct heat away from hot spots giving a more uniform and lower temperature over the airframe and thus pushing the IR wavelengths higher. Fuel flowing in a network of fine pipelines below the skin of the aircraft in hotspots[69] may be used for this purpose as may Radar Ablative Paints, which by their nature are able to conduct heat, and some composite materials[70]. The Lockheed A-12/SR-71 "Blackbird" at its highest speeds, of close

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[67] Air Vice Marshal JR Walker, CBE, AFC, RAF. Air Superiority Operations. Brassey's Defence Publishers Ltd, London,1989, pp.53-54.

[68] Bill Gunston and Mike Spick. Modern Air Combat. Salamander Books Ltd, London, 1983, p. 39.

[69] Ideally the fuel requires to be heated a little prior to its injection into the combustion chamber for best combustion efficiency. This makes the relatively cooler fuel stored in the fuel tanks the ideal cooling fluid to absorb and conduct the heat away from hotspots.

[70] Bill Sweetman. 'Stealth'. International Defence Review Special Electronics No. 2/1984. P.11.

to Mach 3.0, subjected its airframe to temperatures as high as 500° C. In this aircraft fuel flowing in pipelines running under the skin was used to conduct heat away from its friction heated surface in addition to radar ablative paints[71] in order to reduce the heating and the IR signature[72].

ACOUSTIC, VISUAL SIGNATURE AND STEALTH

Acoustic Signature

Aircraft noise is another means of its detection[73]. Aircraft engines are the primary source of this signature. Application of civilian technologies, driven by noise pollution laws, to military aircraft may serve to reduce the acoustic signature. This is already underway as seen in the shift in military jet engines from pure turbojets to turbofans with ever increasing bypass ratios. Other design changes to reduce noise are also finding their way from civil engines to military engines. Jet engine noise is caused primarily by the high speed movement of high pressure air. Attempts to shape the engine's air flow passages to reduce this noise are underway. Control of the pressure distribution inside the engine as well as the redesign of the jet nozzles is reportedly to be a promising way forward[74]. Experiments in the US have led to the discovery that making the exhaust nozzle lip in a saw tooth shape, referred to as cutting chevrons in it, contribute to jet engine noise reduction[75].

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[71] The black colour of the SR-71, which in turn gave it its "Blackbird" name, is attributed to the use of radar ablative paint. This paint is reported to change colour to blue at high temperatures when the aircraft was operating at high mach numbers.

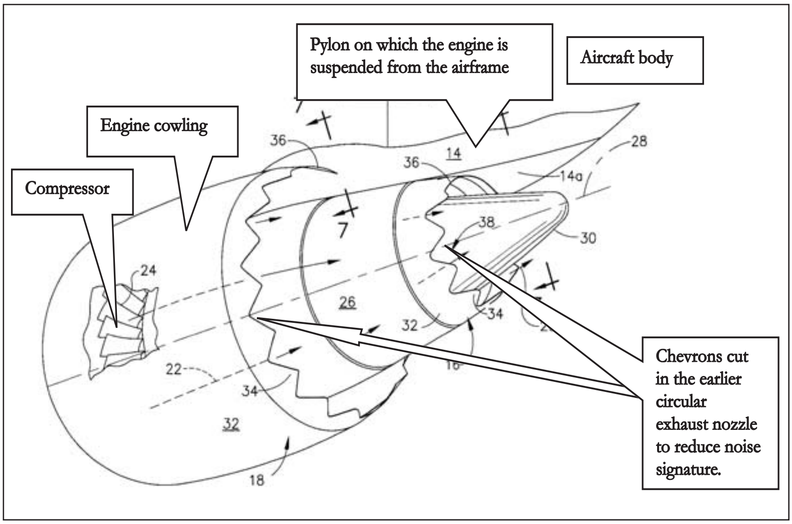
[72] *The World's Great Stealth and Reconnaissance Aircraft*, Oriole Publishing Ltd, Hong Kong 1991, pp. 19-30.

[73] Knight. op. cit., p. 89.

[74] "Reduction of Advanced Military Aircraft Noise", http://www.serdp.org/Program-Areas/Weapons-Systems-and-Platforms/Noise-and-Emissions/Noise/WP-1583, Accessed September 16, 2013.

[75] "Playing Skilfully With a Loud Noise", http://www.insidescience.org/content/playing-skillfully-loud-noise/771, and Anlage A , "Noise Aspects of Future Jet Engines", http://www.mtu.de/en/technologies/engineering_news/others/Traub_Noise_aspects_en.pdf (Accessed October 04, 2013).

Fig 3.9 Jet Exhaust Design to Reduce Noise, Cutting Chevrons in Exhaust Nozzle



Another source of noise is the sonic footprint of an aircraft flying at supersonic speeds. The "sonic bang" is the noise heard as the pressure discontinuity which is the shock wave caused by supersonic flight crosses over the observer's position. With adequate listening posts deployed it could be possible to track an aircraft in supersonic flight through this noise signature alone, especially as the sonic shock waves are directional. A stealthy aircraft would usually operate at subsonic speeds. Its supersonic capability, if any, would be reserved for the escape or die / kill situations where survival or the need to secure a victory in combat over an opponent outweighs the need for stealth. Both the B-2 "Spirit" and F-117A "Nighthawk", the two longest in service stealth aircraft, are definitely subsonic. Newer designs such as the F-22, F-35, J-20, J-31 and PAK FA have supersonic capability (this supersonic capability is expected to be coupled with very high agility for success in tactical engagements). High performance stealth aircraft have the ability to use supersonic flight only when considered necessary thus retaining the desired level of stealth in the acoustic domain for the mission concerned.

Visual Signature

Visual detection was all that was available to detect aircraft in the infancy of the military use of aircraft in WW-I. Detection of an aircraft by the human eye still remains important, especially at the close ranges typical of Within Visual Range (WVR) aerial combat and for use of lightweight Man Portable Air Defence Systems (MANPADS) such as the "Stinger", RBS-70, Mistral, and SAM-16 "Igla" anti-aircraft missile systems. This is because of the possibility that even a Beyond Visual Range (BVR) air combat may terminate in a WVR engagement. Additionally, in case sensors such as radar and IR fail to pick up an opposing aircraft it may, at closer ranges, be acquired and engaged visually. Several anti aircraft weapon systems also use optical tracking.

The main factors in the visual signature of an aircraft are :-

- Size and shape.
- Camouflage paints.
- Active camouflage.
- Contrails and exhaust smoke.

Size and Shape

The effects of size and shape are self explanatory. The smaller the size and the smoother the contours of an aircraft the less likely is its visual detection. The Gnat, MiG-21, and JAS-39 "Gripen" due to their smaller size compared to their contemporaries, are excellent examples of aircraft with low visual signatures[76].

Camouflage Paints

The aim of camouflage paints is to reduce the contrast between the aircraft and the background that it is viewed against. Another function of camouflage paints is to help break up the distinctive shape of the aircraft. Carefully selected paints are used to paint the aircraft surface with the aim that it matches the background that it is most likely to be viewed against. For instance over typical agricultural land areas and over forests a pattern comprising green and brown paints is chosen to paint typically low flying aircraft that are likely to be viewed by their

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[76] Bill Gunston and Mike Spick. *Modern Air Combat*. Salamander Books Ltd, London, 1983, pp. 188-189.

opponents from above in an attempt to make the painted aircraft merge with the background when viewed optically. Over desert terrain a sand brown colour is used while over the sea a dull blue-grey is most typically utilised. The under surfaces of these aircraft that would be viewed against the sky background are typically painted a dull sky blue or grey. These paints are given a matt finish to reduce reflectivity and thus try to control glint. The pattern used in camouflage painting is decided upon to break down the distinctive shape of an aircraft comprising a fuselage, wings and empennage and usually comprises uneven stripes or irregular shapes in different colours covering the main airframe parts. Many different patterns of painting have been experimented with and all have their relative merits and drawbacks. Camouflage painting is useful in visual signature reduction of aircraft at relatively close ranges. The latest trend globally is to paint military aircraft in a low contrast uniform grey colour sometimes referred to as "dove grey" (also air defence grey and low visibility grey) as a standard low visibility colour scheme.

Active Visual Camouflage

A little reflection will remind the reader that when scanning the skies to pick up aircraft the first visual acquisition of the aircraft is as a small dark speck against the sky and it is only later at much closer ranges that the actual aircraft can be clearly seen complete with its paint scheme. Obviously the delay in initial acquisition of this dark speck at a distance is desirable as only through this first step is the visual tracking of the aircraft maintainable. If not picked up early enough it may not be possible to acquire the aircraft visually in time to take necessary action against it. As the eye can not discern colours at large ranges, camouflage painting fails to address this problem. It is required to reduce the contrast between the dark speck and the background to conceal the aircraft from scanning eyes at large ranges. A technique dubbed "active visual camouflage" is being experimented with to achieve this aim. Active visual camouflage utilises a combination of photoelectric sensors and bright lights arranged around the airframe. The sensors and lights are linked through a central electronic processing unit. The photoelectric sensors measure the illumination on their side of the aircraft. This information is processed by the electronic processing unit which then commands the powerful lights set in the aircraft on the side opposite to the sensors to illuminate to give the same intensity as picked up by the diametrically opposed sensors. Thus, the airframe is lit up to match the ambient background illumination that it can be viewed against from all directions. This leads to a reduction in the contrast between the aircraft and the background. The dark speck seen earlier at large ranges would now be too dim to pick up due to active visual camouflage. Active visual camouflage is designed to be effective at larger ranges by day. The basic concept is to illuminate the aircraft by the use of these lights so as to match the background and thus present minimal visual contrast. However, there is no information on operationalisation of this technique and as on date, as far as is known in the public domain, it remains a research programme[77].

A new possibility in visual signature reduction comes from experiments in the laboratory wherein materials have been created[78] such that these have microscopic tubes or channels running through them. These channels have been made to enable a viewer to look through to the other side of an object, by conveying light photons through the channels, as if the object covered by the material were not there at all, thus making the intervening object practically invisible[79]. The current level of this technology is very rudimentary but over time development of this concept could lead to major reductions in visual and other EM signatures.

Condensation trails (Contrails) and Exhaust Smoke

Aircraft engines burn hydrocarbon fuels. The by-products of combustion of the fuel include carbon oxides and water vapour and these are ejected from the exhaust along with other waste gases. At certain ambient conditions the water vapour in the exhaust gases condenses into a thick cloud like white trail called a condensation trail

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[77] Knight. op. cit., p. 83-85.

[78]' Invisibility Cloak Successfully Hides Objects Placed Under It", http://www.sciencedaily.com/releases/2009/05/090501154143.htm, (Accessed September 08, 2013).

[79] "New Invisibility Cloak Closer to Working "Magic"", http://news.nationalgeographic.com/news/2011/01/110128-invisibility-cloak-magic-crystal-mit-barbastathis-science/, Accessed September 07, 2013).

(contrail)[80]. Two methods exist to avoid the formation of contrails. The first is to avoid flying between the minimum trail (mintra) and maximum trail (maxtra)[81] levels. This would in effect limit the operating envelope of an aircraft. The second method is to use chemical additives that change the size of water droplets present in the exhaust gases and thus prevent condensation with its betrayal of the presence and position of the aircraft[82].

Smoke

Smoke is present in the exhaust due to incomplete or inefficient combustion of fuel in the combustion chamber. Any power plant considered for use in a stealth aircraft would have to be smokeless. This can be achieved by electronic air-fuel mixture control and good combustion chamber designed for efficient combustion[83].

Compromises in Stealth Design

F-117 "Night hawk"

The F-117 was the first operational stealth aircraft. It was developed at the famous Lockheed Martin "Skunk Works" which had earlier turned out the A-12/SR-71 "Blackbird". The F-117 was a highly classified development programme and its existence was officially declared only in 1988 despite the development having commenced in 1976. The F-117 design comprised a faceted structure with flat surfaces aligned so as the reflect incident radar energy away from their origin. The F-117 owed its existence to the development of algorithms able to accurately predict the reflection direction of radar waves from flat plates. The most powerful computers then available to the designers were just

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[80] "Contrails", http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/cld/cldtyp/oth/cntrl.rxml, (Accessed September 15, 2013). also see "Contrail Science", http://contrailscience.com/, (Accessed September 16, 2013).

[81] The mintra level is the altitude at which the moisture in the exhaust gases of a jet engine will form a clearly visible trail of condensed vapour. The maxtra level is the altitude above which the condensation trails will not form. These levels are determined by prevailing meteorological conditions, especially humidity and temperature, and can be predicted with some accuracy.

[82] Ibid., pp. 85-87.

[83] Ibid., pp. 87-89.

able to carry out the calculations required for the F-117 design to be possible. There were at the time no algorithms available to accurately predict the reflection of radar waves from curved surfaces, and theF-117's design owes its faceted shape to this limitation. F-117's wing lacked flaps thus giving it a very high landing speed of 160knots (nautical miles (nm) per hour). Moreover, unlike other relaxed stability aircraft such as the F-16 and other fourth generation fighters, the F-117 was unstable along all three axes (pitch, roll and yaw). Aircraft with relaxed stability are usually built with stability relaxed only around the pitch axis to enable very rapid manoeuvre initiation. On board computers linked to the flight control system assist the pilot in preventing the aircraft from departing from controlled flight. In the F-117 the problem was much worse as the aircraft due to its unique LO design was unstable around all three axes. It required very powerful computers to provide basic flyability. As the shape of the aircraft suggests, stray postings on blog websites by erstwhile F-117 pilots indicate that it was not an agile aircraft and in fact had no aerial combat capability. The 'F' series based nomenclature (from the US trend of naming fighters with this prefix like the F-104, F-15, F-16,F-18 etc. and bombers with the 'B' prefix as B-52, B-1, B-2 etc.) and the "fighter" in its name were purposefully included in order to attract aircrew to fly it, as it was believed that pilots would be more willing to fly a fighter than a trainer. Thus, the only operational use the F-117 saw was for stealthy air-to-ground attack missions in Panama, in the Gulf War against Iraq, and in Kosovo. The F-117 demonstrated the compromise that had to be made between stealth and manoeuvrability. Through use of its advanced electronic flight control system the F-117 was usable as an effective ground attack platform especially at night. Night operations reduced the risk of the agility challenged F-117 being visually acquired and engaged by hostile fighters. In the F-117 stealth became the driving force in order to achieve which manoeuvrability and agility were sacrificed and the aircraft was tailored for the air-to-ground attack mission especially by night. The technological limitation of then being unable to predict radar reflection angles accurately from curved surfaces also played a part in the F-117 having low agility.

F-22 "Raptor"

The F-22 "Raptor" was conceived as a replacement for the F-15 "Eagle" which had been the USAF's prime air superiority fighter for many decades. In this design, due to the planned air superiority mission for the F-22, pure performance could not be sacrificed for stealth as had been done with the F-117. The F-22 design therefore explored means of retaining high aerodynamic performance while still reducing the RCS appreciably. The basic design was a compromise that leaned towards aerodynamic performance. The degree of stealthiness lost in the process was attempted to be recovered through more advanced stealth techniques. One such technique is the possible double layered surface skin that is tailored to reduce the intensity of reflected EM radar energy through active cancellation, described earlier in this monograph. Development and incorporation of such advanced stealth design and manufacturing techniques led to increases in cost and also in time over runs. Further in order to give the F-22 high performance without an enlarged infra red signature that afterburners would result in new jet engines that could provide very high thrust in dry power were developed. These bestowed the ability to "supercruise" or in other words to sustain supersonic flight in dry power. These powerful engines also provided a huge reserve of thrust to enable tight aerodynamic manoeuvres to be performed by the F-22. In order to overcome whatever sacrifices of manoeuvrability and agility that had been made in order to ensure stealthiness the F-22's engines were designed with vectored thrust 2D nozzles in order to provide even better agility through leveraging the ability to vector the engine thrust. These techniques make the F-22 probably the only stealth aircraft in squadron service with such high aerodynamic performance. The combination of high stealth and high performance has been achieved though at very high cost. The complete details of the advanced stealth techniques applied in the F-22 are not available for obvious reasons. However, stray news reports indicate that even the maintenance of the F-22 is a costly affair due to these very advanced stealth technologies being incorporated in the design.

The F-35 /Joint Strike Fighter (JSF) "Lightning-II"

The F-35 is probably the most challenging aircraft project ever conceived and executed. The F-35 was designed to replace the F-15 (air superiority), F-16 (multi-role but biased towards air-to- ground attack), A-10 (dedicated air-to-ground attack), F/A-18 (carrier based multi-role) and AV8B (operation from small restricted locations with vertical take off and landing ability) in US service. This single aircraft was supposed to replace capabilities spanning from dedicated air superiority fighters to dedicated ground attack aircraft through Vertical Take Off and Landing (VTOL) and aircraft carrier capable Short Take Off and Arrested Landing (STOBAR) aircraft. The F-35 airframe was to deliver capabilities found on the large list of disparate machines it was to replace and in addition to being stealthy. Understandably these requirements mean that this project has pushed the limits of technology almost as much as the F-22 has. In some areas the F-35 has pushed technological boundaries even more than the F-22 did. The F-35 has quite understandably, given the great complexity of tasks required of a single design, suffered several time and cost overruns. The aircraft which was planned to cost about $ 68 million per unit in 2001 has escalated to $144.89 million per unit in 2012[84]. The F-35 does make compromises also in its design. In order to ensure stealthiness its cockpit is flush with the fuselage sacrificing better visibility for the pilot as obtained on F-16s, F-18s, and Rafale etc. for stealthiness. Moreover in order to achieve VTOL performance it sacrifices internal weapons stowage (if more than two Laser Guided Bombs (LGBs) are needed to be carried, the third LGB onwards will require under wing hard point suspension thus compromising on the RCS) and internal fuel capacity (due to internal space being taken up by the vertical lift engine).

Compromises have been a part and parcel of aircraft design from the very beginning of modern aviation in 1903. This trend of compromises between different aspects of an aircraft's design requirements is continuing and as per currently discernible trends this system of compromises is likely to continue in future also.

Having seen the several different design features required for making an aircraft stealthy against radar, IR, and visual and acoustic sensors will now move on to an examination of how stealth technology affects aerial warfare.

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[84] Winslow Wheeler, "How the F-35 Nearly Doubled In Price (And Why You Didn't Know)", http://nation.time.com/2012/07/09/f-35-nearly-doubles-in-cost-but-you-dont-know-thanks-to-its-rubber-baseline/, (Accessed December 09, 2013).

EFFECT OF STEALTH ON AERIAL WARFARE

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A SIMPLIFIED WORKING CLASSIFICATION OF AIR MISSIONS

Air Power can be called upon to perform a variety of missions in war and peace. These missions are classified into several very logical categories by texts written on Air Power theory and practice. Based upon the environment in which aircraft would have to operate and survive, in this monograph two very simplified classifications have been used for all air missions. These two classifications are, firstly, offensive operations; which will include all missions that require flying into airspace that is under control of the enemy. These will include reconnaissance (in peacetime as well as during war), Air Interdiction (AI), strategic strikes, all offensive Counter Air Operations (offensive CAO), and Battlefield Air Interdiction (BAI). BAI is conducted up to relatively shallow penetration depths behind the Tactical Battle Area (TBA). BAI is meant to attack enemy surface forces that have arrived within the land battle area but have not yet been moved to make direct contact with our own troops. Thus, BAI missions are flown to destroy targets in the TBA but against enemy targets that are not in direct contact with friendly forces (this leads to lesser problems of identification etc. and lower probability of fratricide). Battlefield Air Strike (BAS), which was earlier called Close Air Support (CAS), on the other hand comprises attack missions against enemy forces that are engaged in direct combat with friendly troops. In the case of BAS identification of targets is more difficult and chances of fratricide increase due to the close proximity of enemy and friendly forces[85]. The second classification that I will use is defensive operations. This term may be a bit of a misnomer (for air power purists) as I will include in this classification all missions that do

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[85] John Warden III, Col USAF, *The Air Campaignt*, Permagon Brassey's International Defence Publishers, London,1989, pp. 86-97. and *Basic Doctrine of the Indian Air Force 2012*, Indian Air Force, New Delhi, 2012, pp.57-68.

not require crossing over from airspace controlled by own aircraft into airspace controlled by enemy forces. Some missions that are essentially offensive in nature but most often conducted from within friendly airspace, such as Airborne Warning and Control System (AWACS), In Flight Refuelling (IFR), and Stand Off Jammer (SOJ) support to own strike forces will fall in this classification as will all defensive CAO missions. These two classifications are made in order to reduce complexity as all aircraft operating in enemy controlled airspace face similar dangers and difficulties and hence the affect of stealth on their conduct is similar as is the case for all aircraft operating within friendly airspace. BAS due to its nature would straddle both these simplified classifications and will therefore be discussed separately.

STEALTH AND OFFENSIVE OPERATIONS

In the context of this monograph offensive operations comprise all air operations that involve friendly aircraft crossing into enemy controlled airspace, that is, airspace in which the enemy has the ability to effectively apply force. Thus, offensive operations include Strategic Bombing, Interdiction, Offensive Counter Air (OCA) Operations (Airfield and Air Power Infrastructure Strike), BAI fighter escort missions, fighter sweep missions and airborne operations including airborne assault and special heli-borne operations. The rationale for this clubbing together is that the perils or threats that aircraft indulging in such operations face are similar. Therefore, the self defence and survival measures that need be taken will be similar. The operations listed above all involve the penetration of enemy airspace or at least entry into the enemy's air defence envelope. Thereafter, the desired target has to be acquired and attacked successfully. While this is being done the aircrew have to be aware of the air situation around them so as to keep the enemy defences at bay. What is of importance here is that ideally aircrew have to be relatively free from enemy anti-aircraft threats during the crucial target detection, tracking and attack phase of flight so as to be able to effectively carry out their primary task of destroying their designated targets. Next in line to be elaborated will be the threats that aircraft on offensive missions face. This will help put the effect of stealth on offensive operations, which will be examined a little later, in proper context.

THREAT SPECTRUM IN OFFENSIVE OPERATIONS

The idea of aerial bombardment and the raining down of weapons of destruction from the air was the province of science fiction in the late nineteenth century. The potential for such action had been foreseen by military thinkers at least a century earlier. The popular press of the time built up the bomber threat, with images of death and destruction raining down from the skies, to such an extent that the bomber was as feared then as the nuclear tipped ballistic missile is today. In the infancy of military aviation the roles first developed for aircraft were exclusively supportive of the land battle in nature. These involved aerial reconnaissance of the battlefield, spotting of enemy forces and their deployments and the direction of friendly artillery fire. The offensive potential of the aircraft, however, was not entirely ignored and such early proponents of air power as Hugh Trenchard in Britain, Brigadier (Brig.) "Billy" Mitchell in the USA and Brig. Giulio Douhet in Italy went beyond the technology of the day and foresaw capabilities much beyond the ability of the nascent air power of the time. In the context of the level of technology available in the early twentieth century, they exaggerated the destructive potential of the bomber and its invulnerability. The bomb load the early machines could carry was limited, as was their navigation capability and weapon delivery accuracy. The German Zeppelin and Gotha bomber raids over England in World War I did not achieve much militarily but did demonstrate the arrival of air power with its ability to circumvent ground defences and strike the enemy's heartland[86]. The effect of these raids on the morale of civilians forced nations to take up the task of air defence seriously. At the time visual sighting or hearing the engine noise were the only means of detection of an enemy aircraft. Detection range by these means being limited, by the time an enemy aircraft was detected it was too late for friendly fighters to take off and effect an interception. If these fighters got airborne they could not locate the enemy beyond visual ranges. There were no means, such as radar and radio, to track the enemy machines and guide fighters towards them. Combat air patrols along likely ingress routes and use of searchlights to illuminate the bombers were tried out with very limited success. This situation led to

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[86] Knight. op.cit., pp. 2-8.

the widely held belief that the bomber would always get through, a belief that persisted well into World War II.

Since the invention of radar the threat faced by the bomber or the attack aircraft has increased tremendously. Modern air defences comprise large, complex and highly integrated systems. They employ a variety of integrated sensors and weapon systems. These defensive systems provide a layered detection and destruction system capable of bringing several weapons to bear on the intruding aircraft at each stage of its ingress. With the fielding of such systems the balance has seemed to shift towards the defender and the trend has been such as to negate the belief that the bomber would always get through[87]. In World War II this was evident from the heavy losses suffered by the German Luftwaffe's bombers over the skies of Southern England and by the RAF and Allied air forces' bombers over Germany. The United States Army Air Force (USAAF) daylight bomber raids, most notably the raid on the German ball bearing industry at Schweinfurt on October 14, 1943, re-enforced the fact that the balance was shifting in favour of the defender[88]. The weapons used for air defence in World War-II were radar for detection, supplemented by some acoustic direction finding stations and visual observation posts. These fed data into central command posts. From these command posts the battle was actually fought with fighters being directed to intercept intruders and terminal defences provided by optically aimed anti-aircraft artillery which was supplemented, in much smaller numbers, by radar guided anti-aircraft artillery.

Modern attack aircraft have greatly increased destructive potential. This has led to even more importance being given to air defence. An Air Defence force's objective involves denial of effective weapon delivery to the attacker. It is important to understand that the operative term here is "effective weapon delivery". It may not be feasible or possible to destroy all intruding aircraft, but if they could be denied accurate weapon delivery, or forced to jettison their weapon load before reaching

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[87] Group Captain MB Elsam, FBIM, RAF. *Air Defence* , Brassey's Defence Publishers Ltd, London, 1989, pp. 1-5.

[88] Air Vice Marshal JR Walker, CBE, AFC, RAF. *Air to Ground Operations*, Brassey's ,Defence Publishers Ltd, London, 1987, p.118.

the target, the aim of air defence would be achieved just the same. The term "hard kill" is used for the physical destruction of the target or aircraft and "soft kill" for means of negating the effectiveness of the enemy weapon system short of its physical destruction, or the denial of effective weapon delivery in this case. Both are effective means of countering attacking aircraft.

Components of a Modern Air Defence (AD) System

An opposing weapon system can be defeated by attacking its component parts each of which is necessary for the whole to function. As both conventional and stealthy aircraft, in offensive missions, require surviving against enemy AD Systems while carrying out their own missions effectively it is pertinent to examine a representative AD system in order to understand how the introduction of stealth affects aerial warfare. The component parts of a modern air defence system are as below:-

Early Warning, Detection, Tracking and Direction

Early warning of the attack is provided by means of radar stations deployed at suitable locations to cover the likely ingress routes. These form the eyes of the system. The curvature of the earth imposes a limitation on the radar detection range against low-level targets. This is usually countered by the deployment of low level radars to cover the gaps in the radar cover or elevating the radar antenna, in modern times through deployment of Aerostat[89] radars and AWACS[90]. The radar systems are supplemented by visual observation posts that supplement the radar chain. The early detection radar chain is backed up with Ground Controlled Intercept (GCI) radars and tracking radars that feed accurate target parameters to direct the designated weapon systems fielded against the intruding aircraft.

Interceptors

The first line of defence is the interceptor, which is usually the first weapon system that is brought to bear on the attacker. The interceptor

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[89] Aerostats are large multi-cell helium filled tethered balloons that carry aloft a radar antenna system and thus increase the low level coverage of that radar.

[90] Elsam. op.cit., pp. 17-18.

is typically a highly capable aircraft optimised for air-to-air combat. Most of these have Airborne Intercept (AI) radar, Look Down Shoot Down (LDSD) capability and compatible radar guided missiles. The engagement envelopes of such systems typically extend in altitude from 30 m to 25 km. They also carry IR passive homing missiles and one or more cannon(s). Accurate employment of the IR missiles and cannon also depends upon the use of radar or other sensor operating in the EM spectrum to track the target, derive its flight parameters accurately, and to compute viable firing solutions. Most interceptors are very agile and able to best their adversaries in close combat. They are flexible and can be brought to bear in force in any area on the availability of adequate warning. They rely on the Ground Controlled Intercept (GCI) stations and on their AI radars for successful interception. Some also have IR Search and Track systems (IRST) to supplement their radars[91]. The reliance on radar and IR based detection and steady tracking for successful employment of the air defence interceptor fighters is noteworthy.

Surface to Air Missiles (SAMs)

In the last 50 years there has been considerable development in this field. SAMs that are available today range from large range area defence weapons, such as the Russian S-400 SAM system with engagement ranges of up to 400 km[92], to short range point defence systems, such as the Russian 9K33 OSA or "OSA AK" with a range of 10 km[93]. The detection and tracking of high-speed targets presents great difficulty. All SAMs rely on radar for long range detection of threats and for their tracking. Short-range detection can also be achieved by using other parts of the EM spectrum[94]. Long-range area defence weapons are basically radar guided. Several short-range SAMs are also radar guided;

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[91] Ibid., pp. 36-54.

[92] Dr Carlo Kopp, "Almaz-Antey 40R6 / S-400 Triumf Self Propelled Air Defence System / SA-21", http://www.ausairpower.net/APA-S-400-Triumf.html,(Accessed October 16, 2013).

[93] "9K33 OSA", http://weaponsystems.net/weapon.php?weapon=EE05%20-%20SA-8%20Gecko, (Accessed October 17, 2012).

[94] Rupert Pengelley. 'Ground Defence Sensors for the 1990s; Technologies Enter Gradually'. International Defence Review, 12/1987, pp. 1619-1625.

however, some rely upon IR or electro-optical means for target detection and tracking. The missile guidance may also be in the radar, IR or visual part of the EM spectrum[95]. The EWS discussed previously feeds data from its sensors to SAM sites.

Air Defence Artillery

Air defence artillery guns ranging from 7.62 mm to 100 mm or more in calibre are available in large numbers. Expected to be deployed from the TBA to areas in depth, their function is to provide point defence to vital targets. Radar is used as an early warning sensor. This gives adequate warning for the weapons to be brought to a high state of alert and also makes known the sector of approach of the enemy aircraft. The anti-aircraft guns make use of radar or electro-optical means to track the target aircraft and so enable the laying of accurate salvos on it. For sheer volume of fire the anti-aircraft gun is a very potent weapon. It is to be noted here that this weapon also relies upon radar, IR or the visual part of the EM spectrum for its efficient functioning.

Integration

EW forms a part of all the components discussed above. The data from detection systems is fed to centrally located operations centres where it is integrated, analysed and defensive measures initiated. These operations centres form the nerve centres of the air defence system. The essence of a well developed air defence system is the effective integration of sensors and weapons so that the intruding aircraft is under surveillance from before it enters the defender's airspace. The attacker would be subjected to successive layers of defences that bring to bear all the weapons of air defence in turn[96].

The direction and control of weapon systems depends upon secure and effective communications[97]. It has been seen that all these weapons

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[95] Air Vice Marshal RA Mason, CBE, MA, RAF. Air Power an Overview of Roles. Brassey's Defence Publishers Ltd, London, 1987, pp. 37-38.

[96] Bill Sweetman. *Advanced Fighter Technology The Future of Cockpit Combat*, Airlife Publications Ltd, 1988, London, p. 31.

[97] Elsam. op. cit., pp. 67-74.

rely on detection for their effective functioning. The only available means of effective long-range detection is radar. IR, TV, and visual/acoustic observation and other electro-optical means supplement this. If the defensive weapons are denied detection and accurate tracking of the target they would be in effect defeated.

Analysis of the Progressive Development of Attack Doctrine

Tactical doctrine in World War I and World War II was for massed attacks from medium and high altitudes. The force level of bombers per raid at times reached 1000 bomber aircraft[98]. Where possible, fighter escort was also provided. With the increasing lethality of air defences in the 1950sand 1960s the low-level high-speed approach gained favour. The aim of this choice was based upon delaying detection of the attacking force by enemy radars, thus achieving surprise, by masking the attacker's approach through exploiting the limited radar horizon at low altitudes. The limited low-level detection capability of the radar due to the curvature of the earth was exploited for delaying detection. Even so, detection could not be denied to a defender with the resources and will to deploy a large number of radars and other sensors. Therefore, to guarantee a reasonable degree of success to the mission a large number of support aircraft were needed. These were to carry out missions such as Suppression of Enemy Air Defence (SEAD), Fighter Escort, AWACS, In Flight Refuelling (IFR), and ECM[99]. There have been instances where the support aircraft have outnumbered the actual attackers by a ratio of 5:1[100]. Despite this very large force packaging, the probability of destroying the designated target has not historically been very high and repeated attacks have often been required. The reason for this is that aircrew and the weapon system require at least a few minutes of straight undisturbed run for target acquisition and accurate tracking immediately prior to weapon delivery. It must be

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[98] "The Thousand Bomber Raid", http://www.historylearningsite.co.uk/thousand_bomber_raid.htm, (Accessed October 18, 2013).

[99] Air Vice Marshal JR Walker, CBE, AFC, RAF. *Air to Ground Operations*, Brassey's Defence Publishers Ltd, London,1987, p.50.

[100] Richard G. Davis, "Decisive Force Strategic Bombing in the Gulf War", http://www.afhso.af.mil/shared/media/document/AFD-100526-020.pdf, (Accessed October 17, 2013).

kept in mind that the attacker has been constrained to penetrate the defences at low-level. This profile makes navigation and target acquisition more difficult. The pilot has lesser margin for error even as regards basic flying of his machine, and the penetration of successive layers of defences add to the stress that he is under and workload he is dealing with. Defences that threaten the attacking aircrew in this terminal attack phase reduce his concentration on weapon delivery by necessarily shifting more of his attention towards survival in the face of enemy fire and hence the weapon delivery accuracy suffers[101]. The defender does not even have to launch a weapon to achieve this. If an attacker finds that hostile fire control radar has locked onto his aircraft he may be forced to initiate defensive action to the detriment of weapon delivery accuracy.

The problems of co-ordination between the various elements of the large attack packages also continue to grow. To be effective large composite strike packages that mix several different types of aircraft and different roles and missions require that each element carries out its task at precise pre-determined points of time for the overall mission to succeed. The concept of large attack packages aims also at saturating the enemy defences through presenting the defenders too many targets for them to be able to effectively deal with[102]. Here the philosophy is that the defender would have to spread out his weapons to cover near simultaneous multi-layered attacks from several different directions. The available weapon density that each attacking element faces would, therefore, reduce. The force levels in such very large force saturation raids are worked out on the assumption that even if several attackers are shot down and some others are denied accurate weapon delivery, at least a reasonable number would still be able to deliver their weapons on the target. This is by no means a cost effective solution. The fielding of a large air force would mean very little if that air force could deliver just a handful of attacks per day, and that too with heavy attrition.

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[101] Bill Sweetman. *Advanced Fighter Technology The Future of Cockpit Combat*, Airlife Publications Ltd, 1988, London, p. 32.

[102] Air Vice Marshal JR Walker, CBE, AFC, RAF. *Air to Ground Operations* Brassey's Defence Publishers Ltd, London, 1987, pp.50-51.

EFFECT OF STEALTH ON OFFENSIVE OPERATIONS

A simple analysis of the typical AD system described above makes it clear that all the sub-systems of a modern AD system are made less effective by an enemy challenging it with aircraft equipped with stealth technology. The detection of a stealth aircraft is delayed as compared to a conventional aircraft due to its much lower RCS. Hence, the time available to the defender to engage the intruding stealth aircraft is also reduced with interceptions being initiated only after the stealthy threat has penetrated further into the defenders territory, thus coming close enough to defensive radars for them to be able to acquire its low RCS. Interceptors that are directed towards the stealthy intruder would also be able to acquire the stealthy intruder at much closer ranges than desired, if at all. This delayed detection could make the interceptor itself vulnerable to anti-aircraft weapons fired from the stealthy intruder or at best make the interceptor's attack on the stealthy intruder ineffective. SAMs would also have greatly reduced pick up ranges on the stealthy intruder making its destruction less likely. Terminal defence systems comprising short range missiles and anti-aircraft guns that utilise parts of the EM spectrum to acquire and track targets would also be much less effective against stealthy intruders. The net effect of the intruder being a stealth aircraft is that the likelihood of its being able to successfully penetrate even well organised and equipped defences would be very high. The survivability of such a stealthy intruder would also be high and it could be reasonably expected to achieve its mission objective and return safely to its base. This indicates a return to the situation that prevailed in the early part of the twentieth century, during World War-I when the "bomber would always get through". Much as the then absence of air defences allowed German Gotha bombers to reach as deep as London itself, stealthy aircraft render modern air defences less effective and can successfully penetrate deep within enemy airspace. The situation would be similar to that of a century ago and indicates a tilting of the Offence/Defence balance in favour of the offensive again despite the major advances that have taken place in development of effective integrated AD systems.

Stealth takes the offence-defence relationship back to that prevailing in the early part of the twentieth century. The detection of an attacker would be delayed to the stage where he could not be intercepted or engaged effectively by surface based weapons. This would be achieved by the careful incorporation of the stealth technologies discussed earlier. The end result would be that the stealthy attacker would be able to penetrate hostile defences with near impunity.

The effect of stealth on offensive operations is best illustrated through a simple but educative example. If an attacker has to be within 10 km of a target to deliver his weapon (weapon release distance), then the defender must destroy him latest by this distance from the target being defended in order to achieve the defender's aim of providing effective AD. Let us assume that the following situation:-

- The defender's early warning/GCI radar is positioned at the target.
- This radar has a max detection range of 200 km.
- The attacker flies at 1000 kmph.
- The defender's interceptor can fly at 1,200 kmph.
- The interceptor takes two minutes to accelerate to 1,200 kmph after it gets airborne. The horizontal distance covered during this acceleration is 10 km.
- From the time of detection of the intruder the defender's interceptor takes five minutes to get airborne.
- The fighter requires two min from interception completion to destroy the target (combat time).

In the time elapsed between the detection of the intruder and the interceptor getting airborne the attacker would travel 83.33 km (1000 kmph X 5/60 minutes = 83.33 km). The defender takes two minutes and a ground distance of 10 km to achieve his maximum speed. In this time the attacker would travel a further 33.33 km. The fighter requires two minutes to destroy the attacker. In this time the attacker would cover another 33.33 km (combat distance). The minimum line of interception is the sum of the weapon release distance and the combat distance. This is 43.33 km in this example. The distance that the fighter has to fly out to the intercept point after achieving maximum speed is 33.33 km (43.33 km –10 km). This will take 1.665 minutes and in this time the attacker will travel 27.775 km. The closest distance from the target by which the attacker must be detected for a successful interception is, therefore, 144.435 km (27.775 + 83.33 + 33.33 km).

This is seen to fall within the capability of the radar/ interceptor combination described and assumed above. An interception would be possible with all the components of the air defence system working optimally and a small margin for error is seen to exist. Now if the attacker was to use stealth techniques to reduce his RCS by a factor of 10 then the radar detection range for such a target would be the detection range for the non-stealthy target (200km) divided by 1.78[103]. In this stealthy attacker example the target would now be detectable at 112 km (200 km divided by 1.78). However, we have seen above that the interceptor and radar combination used in the example require a detection of the attacker by 144.435 km for a successful interception. The given radar/ interceptor combination would thus now be unable to intercept this stealthy attacker. By the time the interceptor gets airborne and vectors towards the attacker, the latter would have delivered its weapons.

ANALYSIS OF EFFECT OF STEALTH TECHNOLOGY ON OFFENSIVE OPERATIONS

Fighter class jet aircraft developed in the 1950s through the 1970s have traditionally had a RCS of close to 3 m^2 to 5 m^2 with bombers in the 10 to 100 m^2 class. These are average figures. Even for the same aircraft the RCS can vary enormously at different aspects. Open literature in aviation journals seems to confirm that very low RCS values, in the region of 0.7 to 0.005 m^2, have been achieved by fighter-bomber aircraft. Well designed stealthy fighters should then be able to present a RCS between 0.1 and 0.0001 m^2. With such reductions in the RCS the range of detection of stealth aircraft can be expected to reduce to the extent where even very powerful radars are unable to see these aircraft till they are within a few km of the radar. The effect on the SAM systems' radars would be similar but more exaggerated. These radars are not as powerful as the search and GCI radars. They also need to acquire the target at a range adequate for the system to react, track and fire its weapon. The shrinkage of the effective engagement envelopes of SAMs could well make their use impossible. By the time the SAM

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[103] Air Vice Marshal JR Walker, CBE, AFC, RAF. Air Superiority Operations. Brassey's Defence Publishers Ltd, London,1989, pp.74-79.

radar sees the stealth aircraft, if at all, the aircraft could be entering the minimum launch range of the system. Moreover, the reduction in the SAM radar envelope in elevation against a stealth aircraft, compared to that against a conventional aircraft, would enable the stealth aircraft to avoid the system altogether by flying above its limits of detection. Reduction in the IR, visual and acoustic signature would help in defeating weapon systems that use multiple sensors by shrinking the detection and engagement envelopes in these bands also.

Relatively safe from these threats the stealth aircraft would be able to operate with ease even at medium and high altitudes. This would help increase the range, reduce navigational problems and make target acquisition easier. In this scenario the stealth aircraft would not need the large number of support aircraft that go into a conventional attack package. Strike missions could reduce the number of aircraft in a package from the peak of more than 56 to 72 F-16 and other aircraft including F-111s for the Package 'Q' strike on Bagdad on January 19, 1991[104] to as few as one or two aircraft. These aircraft shed from the strike package could be used for other tasks. Thus, a force multiplier effect would be achieved by the air force using stealth aircraft. The investment in expensive ECM systems would also be expected to reduce. The complexity of the ECM system carried by an aircraft depends upon the potency of the threat posed to it. This threat has been seen to be mainly dependent upon the EM signature of the aircraft itself. For a stealth aircraft, as the signature required to be protected would be small, a less complicated system would suffice to mask its lower RCS from enemy sensors. This is a result of the range of detection and tracking by hostile weapon systems reducing appreciably. If the stealth aircraft were carry stand off precision weapons then it would be even more effective, while being even safer from enemy weapons. This combination could have the ability to achieve with a handful of aircraft what otherwise could take an entire air force[105].

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[104] "Target for Today Baghdad", http://www.lucky-devils.net/baghdad.html, (Accessed October 06, 2013).

[105] Bill Sweetman. 'F-117 Excels in "Desert Storm"'. Jane's Defence Weekly, January 26, 1991. p. 104.

What stealth achieves for offensive operations is the virtual blinding of the opponent. Great holes are created in the defensive arrangements of the defender[106]. These gaps can be used to operate with relative fearlessness in hostile airspace, with the enemy being attacked at will. Stealth is thus seen to have a very beneficial effect on offensive operations[107].

ANALYSIS OF STEALTH AND BAS

Aircraft engaged in BAS missions perforce operate over both own and enemy troops. Given technical issues with even the most modern Identification Friend and Foe (IFF) systems, such aircraft face the fury of enemy as well as friendly anti-aircraft weaponry. Moreover, the hostile air-defence environment over the TBA detracts from the pilot's concentration on target acquisition and attack as he must simultaneously evade the anti-aircraft weapons in the area while detecting, identifying and attacking legitimate targets in the TBA. Stealthy aircraft if available for use on BAS missions would reduce the pressure on pilots tasked for BAS missions to a great degree, through rendering a greater level of safety from guided anti-aircraft weapons, thus increasing the effectiveness of such missions through enabling greater aircrew concentration on target acquisition and attack. However, given the very high cost of stealth aircraft, such deployment is unlikely for most Air Forces and wartime scenarios. Moreover, the TBA is teeming with unguided weapons ranging from optically aimed machine guns of various calibres to even personal small arms. These weapons' presence in large numbers detracts from the possibility of even stealth aircraft being very effective in the TBA. The TBA demands expensive [precision guided air-to-ground weaponry with stand off delivery capability more than any other area for employment of aerial assets. Such precision weapons if deployed with designation of targets by surface forces could prove very effective even without deployment of stealthy aircraft.

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[106] Bill Sweetman. Advanced Fighter Technology The Future of Cockpit Combat. Airlife Publications Ltd, London, 1988, p. 75.

[107] James W Canan. 'The Future is Stealth'. Air Force Magazine, January, 1991. p. 14.

STEALTH AND SPECIAL ROLE MISSIONS

Analysis of Effect of Stealth on Reconnaissance

Study of military history reveals that surface warfare has always been a matter of guessing the enemy's force deployment and strategic and tactical intentions. Based on this assessment of the enemy counters are developed that in the best case scenario lead to his surface forces being outmanoeuvred and defeated. Observation of the surface battlefield and the enemy's rear areas has, therefore, always been of prime importance in surface (land and sea) warfare. An aerial vehicle provides an eminently suitable platform for this observation of surface forces and their deployments. The first recorded military use of an airborne platform was in reconnaissance[108]. There is some evidence that the Chinese used large man carrying kites for this purpose in the past[109]. Tethered balloons were used as reconnaissance platforms during the nineteenth century in Europe and even during the US civil war[110]. The availability of the aircraft led to this machine also being used for this purpose. The aircraft has proved to be a very flexible reconnaissance platform. With the passage of time the visual observation of the battle area has given way to the use of dedicated sensors operating across almost the entire EM spectrum. The data so obtained is recorded on appropriate storage media and if digitised is available for analysis almost instantaneously through near real time data downloads from airborne sensors to ground exploitation stations equipped with high bandwidth datalinks[111]. The artificial Earth satellite is logically the ultimate platform for observation of the planet's surface. However, the current state of technology does not allow the same degree of flexibility and detail

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[108] Air Vice Marshal RA Mason, CBE, MA, RAF. Air Power An Overview of Roles. Brassey's Defence Publishers Ltd, London, 1987, p. 77.

[109] M. Robinson, "Kites On The Winds of War", http://www.kitehistory.com/Miscellaneous/Warkites.htm,(Accessed June 03, 2013).

[110] "Balloons in the American Civil War", http://www.civilwar.com/weapons/observation-balloons.html, (Accessed June 03, 2013).

[111] S.A. Horn and A. Zegers, "Near Real-Time Multi-Sensor Fusion for Cued Reconnaissance Operational Analysis of Operation Driftnet 2009", Near Real-Time Multi-Sensor Fusion for Cued Reconnaissance Operational Analysis of Operation Driftnet 2009, Accessed September 18, 2013). pp. 7-11.

with use of satellites that an aircraft (manned or unmanned), flying at a much lower altitude and with very high revisit capability, provides[112].

For obtaining the required information the reconnaissance aircraft may well have to operate in the enemy's airspace, both in war and in peace. While the quest for information on the enemy is pursued vigorously, attempts have to be made to deny the enemy similar information. This makes the reconnaissance aircraft a highly valued target. Today specialist aircraft, belonging to many nations, are suspected to carry out covert reconnaissance over-flights of their likely adversaries' territory in peace. In times of war the frequency of such flights would only increase. The loss of an aircraft engaged in such peacetime clandestine activity during peacetime is a major diplomatic disaster, as was the 1960 shooting down of the American U-2 piloted by Gary Powers over Soviet territory[113]. In times of war loss of these aircraft means the loss of scarce resources. Aircraft designated for reconnaissance duties would benefit enormously from the application of stealth technology. With reduced signatures these aircraft would be able to carry out their tasks unhampered. They would be able to penetrate deep into enemy airspace without being detected by the enemy's air defence system. This would give great flexibility in operations in peace and war. The probability of loss to enemy defences would be reduced to the chance encounter with a hostile fighter or the inadvertent over-flight of an alert anti-aircraft site that is equipped with such powerful sensors that they can acquire and track even stealth aircraft effectively. The first stealth aircraft to be developed, the US A-12 / SR-71 "Blackbird", was used for reconnaissance, highlighting the importance of stealth in this mission. The US deployed the SR-71 Blackbird strategic reconnaissance aircraft in the 1960s. This was the world's first, and only, stealthy Mach 3.0 capable jet aircraft. Its success can be gauged from the fact that in the several decades of its operation it was never detected and intercepted

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[112] Ibid., pp. 77-79.

[113] "U-2 Overflights and the Capture of Francis Gary Powers, 1960", http://history.state.gov/milestones/1953-1960/U2-incident, Accessed June 03, 2013).

by hostile forces[114]. This machine, despite being finally retired from active service in April 1998[115], remains highly classified even today[116].

Remotely Piloted Aircraft (RPAs) earlier called Unmanned Aerial Vehicles (UAVs) are finding increasing application for reconnaissance[117]. The small size and inherently low signature of these vehicles makes them ideally suited for the application of stealth techniques as even moderate degrees of added stealthiness can make them virtually invisible. The US is developing the stealthy RQ-170[118] RPA while France is developing the stealthy Neuron[119] UAV and Britain is developing the Taranis[120]UAV. India is working on the Rustam-I and Rustam-II and developing the Autonomous Unmanned Research Aircraft (AURA) stealthy unmanned aircraft that is eventually intended to be developed into a stealthy Unmanned Combat Air Vehicle (UCAV)[121].

ANALYSIS OF EFFECT OF STEALTH ON EW

Electronic Support Measures (ESM)

The EM spectrum is vitally important for military operations today. It is a truism that the side that wins the electronic battle will win the war.

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[114] *The World's Great Stealth and Reconnaissance Aircraft* Oriole Publishing Ltd, Hong Kong, 1991, pp. 20-29.

[115] "The SR-71 maintained an excellent operational service record during its Cold War tenure, though a dozen were lost to accidents", http://www.militaryfactory.com/aircraft/detail.asp?aircraft_id=84, (Accessed September 05, 2013).

[116] "Cold War: Lockheed SR-71 Blackbird", http://militaryhistory.about.com/od/militaryaircraft/p/Cold-War-Lockheed-Sr-71-Blackbird.htm, Accessed June 03, 2013).

[117] Air Vice Marshal RA Mason, CBE, MA, RAF. *Air Power An Overview of Role*. Brassey's Defence Publishers Ltd, London, 1987, pp. 84.

[118] Joe Pappalardo, "Air Force Acknowledges Secret Stealth UAV", http://www.popularmechanics.com/technology/aviation/military/4339138, (Accessed September 20, 2013).

[119] Michael Rundle, "Neuron, Europe's First Stealth Drone 'Killer Robot', Makes Test Flight", http://www.huffingtonpost.co.uk/2012/12/03/neuron-europes-first-stealth-drone-test-flight_n_2230316.html, Accessed September 21, 2013).

[120] Richard Gray, "British stealth drone to undergo first test flight", http://www.telegraph.co.uk/news/uknews/defence/9797738/British-stealth-drone-to-undergo-first-test-flight.html, (Accessed September 03, 2013).

[121] "EXCLUSIVE: What India's Stealth UCAV 'AURA' May Look Like", http://www.livefistdefence.com/2012/02/exclusive-what-indias-stealth-ucav-aura.html, Accessed October 04, 2013).

For effectively prosecuting the electronic battle knowledge about the enemy's electronic capabilities is required. This is the province of ESM, a branch of EW. Aircraft are an important platform for obtaining this information. It will be evident that the ESM aircraft has to enter the radiation envelope of the enemy weapon system to obtain and record useful information, such as detailed electronic fingerprints of hostile emitters as well as their locations. Closer proximity to a hostile emitter yields information of higher quality. The accuracy with which the locations of hostile emitters can be determined would also be greater if fixes could be taken from a lesser distance. As most of the ESM work has to be done in times of peace, covert penetration of the enemy's airspace could be required. This is not usually possible due to the high probability of detection and destruction by the enemy. With stealth aircraft the probability of detection would reduce appreciably. Covert penetration of the potential enemy's airspace to obtain vital ESM information would now be possible. This would yield valuable information that could prove crucial in the event of open war. In war the survivability of support aircraft engaged in ESM activity would increase.

ECM

ECM are the offensive arm of EW. With the proliferation of weapon systems that make extensive use of the EM spectrum for target acquisition, tracking and destruction, this branch of warfare is becoming increasingly important. This is so much so that highly capable and expensive ECM systems are becoming the standard fit on modern fighter/attack aircraft. Even so, these aircraft are deficient in EM self protection and dedicated ECM escorts are required. The basic reason for this ECM effort is that the aircraft can be acquired by a variety of sensors operating in the EM spectrum. With the reduced signature that a stealth aircraft would have, its probability of detection and the range at which detection does finally take place would reduce appreciably. The threat that has to be countered by ECM would now be much lesser[122]. Thus, the power and complexity of the ECM suite on board, a stealth aircraft would reduce with consequent savings in weight, space,

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[122] Bill Sweetman. 'Stealth'. *International Defence Review Special Electronics* (2), 1984. p. 12.

size and cost. In a very stealthy aircraft provision of an ECM suite could conceivably even be entirely dispensed with.

SEAD

SEAD is a specialist mission that uses soft kills (use of ECM) and/or hard kills to degrade and/or destroy hostile anti-aircraft systems. The existence of a stealthy strike force would reduce the requirement for dedicated SEAD missions, aimed at enabling penetration by the actual strike package. If such missions were still to be required, the use of stealth aircraft would make them more effective as the SEAD package would then not require protection for itself to the same degree as required by conventional SEAD aircraft. If the strike package is also stealthy, then the degree of suppression required would also be less as these aircraft by their nature would shrink the enemy's weapon envelope.

ANALYSIS OF APPLICATION OF STEALTH TO TRANSPORT AIRCRAFT

Transport aircraft are used for a variety of operational roles in peace and war. During peace they could be used to covertly insert Special Forces into enemy territory. In war airborne assault operations and air to air refuelling are worth mentioning. In these roles the evasion of notice by the enemy is important, especially as, being inherently large and relatively slow, transport aircraft are extremely vulnerable to enemy action. Incorporation of stealth in the design of transport aircraft would contribute to the success of the operation; it would also increase the degree of surprise achieved and reduce the supporting forces required; these erstwhile supporting forces could then be utilised more effectively elsewhere. However, there is as yet no known stealthy transport/utility aircraft. The US apparently has at least one utility helicopter variant of its popular UH-60 "Blackhawk" that has been modified through application of stealth technologies. These were, as per news reports, used in the US raid to kill Osama Bin Laden at Abbotabad, Pakistan in 2010[123]. With the technologies for stealth fairly well understood,

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[123] Tom Geoghegan and Sarah Shenker, "'Stealth helicopters' used in Bin Laden raid", http://www.bbc.co.uk/news/world-us-canada-13297846, (Accessed 19 October 13, 2013).

especially in technologically advanced air faring nations, making stealthy transport aircraft is just a matter of expression of an operational requirement, engineering and provision of adequate funding.

STEALTH AND AIR DEFENCE

Analysis of the Effect of Stealth on AD

AD implies, in simplest terms, the protection of ones own vital targets from effective enemy attack. The operative word here is "effective". This is because there is a great possibility that all attackers heading for a particular target cannot be stopped[124]. What can be achieved in such a case is that the number of attackers that get through are reduced to so few that they are unable to deliver the weight of attack required to destroy or appreciably degrade the target being defended. Of the attackers that do get through, keeping them under the constant attack can greatly reduce the efficiency of their weapon delivery. The components of an air defence system have already been discussed earlier. Before proceeding to the effects of stealth on this function of air power it would be in place to examine the package that has to be tackled by the air defence forces.

Modern air forces field a large number of specialised and multi-role aircraft. Examples of specialist aircraft are dedicated ground attack aircraft such as the Jaguar, Tornado Interdictor / Strike (IDS), MiG-23BN, and MiG-27 and specialist air superiority aircraft such as the F-15C and MiG-29. The F-18, F-16 and Mirage-2000 are excellent examples of relatively modern multi-role aircraft[125]. In view of the dense air defence environment expected in today's air battle any air strike would comprise a mix of dedicated strike aircraft, air superiority fighters for providing air defence escort to the strike aircraft, SEAD aircraft, ECM escorts and, possibly, AWACS and Air to Air Refuelling (AAR). While all these elements form part of the target complex for the air defence battle, this discussion will be restricted to the first two.

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[124] Robert L Shaw. *Fighter Combat the Art and Science of Air-to-Air Combat.*, Patrick Stephens Limited, Wellingsborough, Northamptonshire 1988, pp. 331-332.

[125] Bill Gunston and Mike Spick. *Modern Air Combat.* Salamander Books Ltd, London,1983, pp. 80-171.

This is because the other elements of the package are expected to be operating either deep inside enemy territory, or anyway fall into the category of strike aircraft in the case of the SEAD and ECM elements. Another factor to be borne in mind is that the strike aircraft, if of the multi-role type, may themselves be capable of defending themselves with their integral air to air capability. This is best exemplified by the F-18's much advertised air to ground / air to air role change with the flick of a button; with a, claimed, lack of degradation of the offensive potential of the weapon system.

The prosecution of the steps of detection, identification and interception are assumed to follow their course successfully. In the later part of the interception, depending upon the intercept geometry and the warning given to the strike package by their integral radar illumination warning devices or their AWACS, the air defence escorts integral to the strike package would strive to carry out their assigned function of protecting the strike force. These aircraft would have their own AI radars and would be capable air combat machines with suitable weapon systems. For example, the MiG-29 has an advanced Pulse Doppler radar and an integrated Infra Red Search and Track (IRST) system. These are backed up by very capable Beyond Visual Range (BVR) and IR close combat missiles. The radar can search a large volume of airspace and pick up aircraft at ranges out to more than 75 to 100 km. These aircraft can be tracked and weapons launched at them at ranges as large as 50 km. alternatively, the strike aircraft themselves, if of suitable performance and with advanced weapon systems, could threaten the interceptors. This threat takes on importance in the context that once the interceptor has been picked up by the escorts' radar the element of surprise is lost and the advantage of the interceptor operating under GCI control negated to some extent. The aircraft with the better sensor/weapon combination and the pilot with better situational awareness would come out the victor in such an engagement. Apart from the fact that the escort fighters would be capable of picking up the interceptors at large ranges on their radar, the radar emissions from the interceptors would also be a sure give away of their presence and direction of approach. It could well be that the interceptor suffers the insult of being shot down in its own territory in addition to the injury of the strike getting through. This would be the direct result of the strike package being able to use their radar, or passive means, to detect the presence of the interceptors.

The interceptor relies, for its success, on approaching the victim undetected[126]. This allows the interceptor to carry out a fast and focussed attack on the strike package and to repeat the attacks till the desired result is achieved. An interceptor built with the incorporation of stealth features would be difficult to detect. The range of his detection would be a function of the degree of stealth achieved. This would help negate the elaborate defensive arrangements that a modern strike package undertakes to achieve the required degree of penetration. An AWACS if being used to warn the strike of the approach of interceptors could also be effectively blinded and fail to warn the strike about the approach of the stealthy interceptor. The escort fighters with AI radars would be rendered ineffective and the strike package would come under attack from an unseen enemy with no warning. The situation would be akin to, but more exaggerated than, that faced by the USAF aircraft intercepted by the relatively smaller, difficult to detect MiG-21s over North Vietnam[127]. This would be even more so if the stealthy interceptor had a LPI radar or an IRST system. The strike would now face potentially heavy losses. The uncertainty of the time of the next "invisible" attack would help to degrade the combat effectiveness of the surviving members of the strike package. Thus, the defensive air battle also stands to gain substantially from the incorporation of stealth features in aircraft used for air defence.

ANALYSIS OF THE EFFECT OF STEALTH ON THE OFFENCE DEFENCE BALANCE

In the last discussion so far the effect of stealth on offensive, special and defensive operations has been seen. In these discussions the asymmetric use of stealth has been examined. Here it was found that the possession of stealth technology by one adversarial side in a conflict gives that side an appreciable advantage. The other side was effectively reduced to fighting blindfolded. However, the question arises whether this technology, if available to both the sides involved in a conflict, tilts the balance in favour of the defender or the attacker.

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[126] Bill Gunston and Mike Spick. op. cit., p. 187.

[127] Air Vice Marshal JR Walker, CBE, AFC, RAF. *Air Superiority Operations*, Brassey's Defence Publishers Ltd, London, 1989, p. 126.

Paradoxically the pursuit of this answer takes us back to the infancy of aviation, when the technology available was truly primitive. This is because stealth technology brings the clock back to zero or the teams involved back to the start line. In the early years of aviation there was no radar or other electro-optical means to detect aircraft. Detection relied upon visual observation of the skies and crude acoustic direction finders. Acquisition of an aircraft was more a matter of chance than anything else. Even if a hostile aircraft was detected, there was no means of keeping track of its position for any length of time. Thus, if an interceptor was to be launched, or an airborne aircraft diverted, to intercept the intruder, the pilot of this machine would be searching for the proverbial needle in a hay stack. The enemy machine could have travelled a large distance in any direction since the last observation of its position. The aerial combat engagements that did ensue in these early years could be put down to luck, desire for "adventure and glory" and naivety about the basics of air warfare[128]. These engagements, for the most part, took place over the static battlefields imposed by the concept of trench warfare. Missions flown deep into enemy airspace, in contrast, did not face any threat of interception. The German Gotha bomber raids on London and Zeppelin air raids on Paris, Antwerp, King's Lynn and Great Yarmouth are a glaring example of this, as are the raids by the British Royal Flying Corps. (RFC) on the Zeppelin launch bases[129]. Air operations in the first half of the twentieth century fed the belief that the "bomber would always get through", as indeed it did in this period[130].

The bomber continued to "get through" without any major opposition till the invention of radar. This invention served to put an end to the "stealthy" approach of the bomber and evened out the balance between offensive action and defensive action. The bomber could now be picked

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[128] Bill Sweetman. *Advanced Fighter Technology The Future of Cockpit Combat*. Airlife Publications Ltd, London,1988, pp. 171-172.

[129] Karen S. Gavin, "British Air Raids on Zeppelin Sheds Septermber to December 1914", http://www.academia.edu/3202752/British_Air_Raids_on_Zeppelin_Sheds_September_to_December_1914,(Accessed October 04, 2013). pp 3-5.

[130] Air Vice Marshal JR Walker, CBE, AFC, RAF. *Air Superiority Operations*. Brassey's Defence Publishers Ltd, London, 1989, p. 15.

up well in time and interceptors launched to shoot it down while the terminal defences were alerted. The bomber would still reach its target in most cases, but at the cost of insufficient weight of attack and heavy casualties not to mention the degradation caused by the interference it faced[131]. In order to achieve the weapon load on target, or weight of attack required to achieve the desired destruction or degradation of the target a large number of aircraft had to be launched. This allowed the required bomb load to be delivered at the target despite aircraft losses and operational degradation. The cost of such operations continued to rise in terms of losses and wasted effort and the balance was seen to be shifting in favour of the defender[132].

Stealth technology serves to again mask air operations in the shroud of secrecy that prevailed in the infancy of aviation. In doing so it serves to place the advantage in the hands of the aggressor and the balance tilts in favour of offensive action. Looking in the not too recent past, the Falklands War of 1982 between Britain and Argentina also demonstrates the effect of stealth. In this case the stealth referred to was the result of the lack of adequate early warning capability with the British Fleet. Radar picket ships were unable to give effective warning of the approach of low level Argentine intruders. The range of cover from the heart of the British Fleet was also limited. This gave the attacking Argentine aircraft a stealthy approach by default. If they had possessed stealthy aircraft the effect would have been the same as regards the approach to the targets evading the enemy's notice. The anti-ship strikes were remarkably successful, and would have resulted in far greater losses than those actually caused to the British if the Argentine weapons had been better fused[133]. The heavy losses that the Argentine aircraft suffered in these anti-ship strikes were a result of their operating at the limits of their radius of action. This denied them the fuel for even basic defensive manoeuvring; hence they could be acquired in the vicinity of their targets, pursued by the British Sea Harriers

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[131] Elsam. op.cit., pp. 1-5.

[132] Air Vice Marshal JR Walker, CBE, AFC, RAF. Air to Ground Operations. Brassey's Defence Publishers Ltd, London,1987, pp.125.

[133] Norman Friedman, "The Falklands War, 30 Years Later Hard lessons from a small war", http://www.defensemedianetwork.com/stories/the-falklands-30-years-later/, (Accessed October 19, 2013).

and shot down. The anti-shipping strikes using stand off weapons, the French made Exocet missiles, did not suffer any losses.

Stealth with both the adversarial sides would confer the advantages discussed earlier in this work to both the attacker and the defender. It has been seen that the defender has to acquire the enemy for defence to be effective. Thus, for the defender incorporating stealth is not as important an attribute as the ability to detect the intruder. For the attacker the most important requirement is to be able to avoid being detected. This confers greatly increased survivability and enhances the accuracy of weapon delivery by reducing the pressure on the pilot. A stealthy aircraft would be better able to use its stealthiness in the attacking role. Incorporation of stealth in the attacker's aircraft would thus give great advantages. The possession of an asymmetric stealth capability would definitely place the advantage in the hands of the contestant who has the stealth advantage[134]. This advantage would be more evident in the offensive role. In case the adversarial sides possess symmetric stealth technology, the basic characteristics of this technology would again be seen to give the upper hand to the side indulging in offensive operations.

The balance between offensive action and defensive action is thus clearly seen to tilt in favour of the offensive in case of possession of stealth technology by both adversarial sides. In case of asymmetry in stealth capability the side with stealth can be seen to have the edge, but again this edge would be more apparent in offensive action rather than in defensive action.

THE IMPERATIVE TO INDUCT STEALTH AIRCRAFT

Any Air Force that aims to remain effective at carrying out its offensive tasks in the near to medium term future requires to invest in stealth aircraft for the reasons discussed above. Additionally, in the past aircraft on offensive missions were able to exploit the low and fast regimes of flight to reduce detection ranges of enemy AD systems and thus achieve surprise adequate for them to successfully execute their missions. The advent and proliferation of AWACS makes this tactic obsolete as

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[134] Bill Sweetman. Advanced Fighter Technology The Future of Cockpit Combat. Airlife Publications Ltd, London, 1988, p. 173.

AWACS is able to detect even low flying conventional aircraft out to ranges of more than 300 to 450 km. Stealth thus becomes an inescapable necessity for aircraft required to be tasked for offensive missions especially against an adversary who posses AWACS and Aerostat radars. USAF fields three stealth aircraft the B-2 "Spirit", F-22 "Raptor" and F-35 "Lightning-II", the F-117 "Nighthawk" having been retired in March 2008[135]. Russia is developing the **P**erspektivny **A**viatsionny **K**ompleks **F**rontovoy **A**viatsii (PAK FA) translated roughly as Prospective Aircraft Komplex [for] Frontal Aviation from the Sukhoi T-50 prototype[136] while China is developing its indigenous J-20 and J-31. India is participating in the PAK FA project with Russia to meet its requirements of stealth aircraft[137] while also progressing the indigenous AMCA stealthy fighter project[138].

Analysis of Stealth and Future Trends

Stealth aircraft are designated Fifth Generation Fighter Aircraft (FGFA) by the advanced Western nations that drive such terminology. It could be argued that it may be prudent to skip the expensive fifth generation equipment and move directly towards sixth generation one. There is no sixth generation aircraft in service yet. However, it is quite likely that the sixth generation may comprise unmanned stealthy drones with or without a man in the loop. The French Neuron, British Taranis, American X-47 and other such experimental craft appear to be the forerunners of the sixth generation of warplanes. India is also reportedly developing its AURA stealthy drone. China flight tested a stealthy drone,

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[135] "F-117A Nighthawk Stealth Fighter, United States of America", http://www.airforce-technology.com/projects/f117/, (Accessed September 09, 2013).

[136] David Cenciotti, "Up close and personal with Russia's 5th generation stealth fighter: first close-up pictures of the PAK-FA", http://theaviationist.com/2013/09/03/pak-fa-close/#.Ul9kv9JmC9I, (Accessed September 13, 2013). http://www.indiastrategic.in/topstories821_India_Russia_sign_fifth_generation_stealth_project_fighter.htm, (Accessed September 15, 2013).

[137] Gulshan Luthra, "India, Russia sign Fifth Generation stealth fighter project",

[138] Vladimir Karnozov, "Indian 'Home-Grown' AMCA, An Alternative To FGFA", http://www.ainonline.com/aviation-news/paris-air-show/2013-06-13/indian-home-grown-amca-alternative-fgfa, (Accessed September 17, 2013).

named "Sharp Sword", recently[139]. It is not as yet certain what the sixth generation of warplanes will look like exactly. However, reasonable projections could be made to say that these will be autonomous drones with stealthy airframes in view of the large number of such development programmes underway in America, Europe and Asia. All these programmes include stealth technology in the new drone development projects. The fifth generation of warplanes appears to be leading into the possible sixth generation while carrying its technology along into the next generation. Hence, skipping the fifth generation seems to be infeasible.

A possible alternative strategy to developing fifth generation stealth aircraft in a big way could be to invest the minimal amount of resources in fifth generation stealth technology manned aircraft to enable effective incorporation of this technology in developing sixth generation aircraft.

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[139] "China Tests New Stealth Drone", http://www.popsci.com/article/technology/china-tests-new-stealth-drone, (Accessed November 22, 2013).

COUNTERS TO STEALTH

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Given the major advantage that stealth fighters convey to an air force it is but natural that efforts would be directed towards finding counters to stealth technology. The starting point for these anti-stealth measures is determining how the currently available stealth technology works. Once again, as radar is the most potent and dangerous sensor in the aerial warfare arena, anti-stealth technologies look first towards negating the measures used by stealth aircraft to reduce radar's effectiveness. There are many techniques talked about in aviation journals for defeating stealth in the radar part of the EM spectrum. A few more relevant and feasible techniques are elaborated upon below.

BI-STATIC RADARS

The mono-static assumption of radar is fundamental in designing anti-radar stealth. It was mentioned while describing how stealth defeats radar that the concept of mono-static radars is used in designing aircraft to evade radar. That is to say that the radar transmitter and receiver to be defeated are assumed to be co-located as is the case for most military radar systems and airborne radars on aircraft. Stealth aircraft designs aim to direct radar energy incident upon them in directions away from their origin, where the enemy radar receiver is assumed to be located. In addition to attenuation of the incident radar energy this technique is adequate to defeat most radars of interest. A possible anti-stealth solution is obviously to design and field bi-static radars. These radars would comprise a transmitter widely separated in space from its receiver antenna array. Through suitable location of these bi-static radars in the area to be defended, it should be possible to acquire the radar energy directed away from its point of origin by the stealth aircraft and to triangulate its origin (which would be that of the object that directed it towards the receiver) fairly accurately. Use of a larger number of such radars would give greater accuracy and redundancy. OTH-B radars are bi-static by design but are optimised for very large ranges. Design of tactical radars with bi-static antennae is thus one possible solution to detect stealth aircraft. Bi-static radars may present difficulties in application on board fighter aircraft. Even location of the transmit and receive antennae on the most widely separated parts of the fighter's airframe may not give the required separation between these antennae for acquisition of the radar energy directed away by a stealth aircraft. Here a solution could be to utilise a formation of fighters that fly very widely separated from each other. A few of these fighters could carry radar transmitters while others carry just radar receivers. This could translate to a multi-static radar arrangement with greater flexibility than a purely bi-static arrangement. Co-ordination between the fighters could be achieved through use of the air-to-air and air-to-ground high bandwidth datalinks that are already in widespread use in several air forces. Another advantage of this possible solution with on ground bi-static and airborne multi-static arrangements would be that these would utilise technology that has been in use for several years, is well understood and is relatively low cost. The absence of serious technological challenges reduces the possibility of time and cost over runs in development of such anti-stealth techniques.

LONG WAVELENGTH AND ULTRA WIDE BAND (UWB) RADARS

In the discussion on designing stealth aircraft to defeat radars it was emphasised that most radar stealth techniques are most effective against relatively high frequency or short wavelength radar signals. Most radars commonly used for attacking aircraft fall in this classification. Stealth techniques are optimised to defeat 'X' band radars. This is the radar band in which most modern aircraft tracking and fire control radars fall. Several stealth techniques are radar frequency specific or "narrow band". Use of radars that have much larger wavelengths or lower frequency could be a means of detecting aircraft trying to evade radar. Here the legacy Soviet radars from the early 1950s and 1960s that operated in the Very High Frequency (VHF) band of the EM spectrum are noteworthy as most stealth techniques are optimised to work against radars operating in the multi Gigahertz frequency region of the EM spectrum. Such VHF radars, however, have some drawbacks based upon their frequency. These give much lesser range than more modern radars and also lesser accuracy of target co-ordinate determination. 'L' band and 'S' band radars could be effective against radar stealth technologies meant to shield an aircraft from 'X' band radars. A USAF F-117 "Nighthawk" stealth fighter was shot down on March 27, 1999 by a legacy Soviet era Serbian SA-3 "Goa" SAM in Kosovo. The Serbian missile troops used a combination of techniques that melded use of the SA-3's old VHF band radars, intelligent appreciation of the situation, and visual observation to achieve the first ever SAM kill of a stealth aircraft. The range of the F-117 from the missile site when it was shot down was only 13 km. This close distance may have allowed the SAM radars to be close enough to detect the F-117's low RCS[140]. American sources speculate that at the time it was shot down the F-117 may have been opening its internal weapons bay to launch weapons thus also increasing its RCS temporarily[141]. All the factors in play in this instance irrespective, the point to be driven home is that stealth is far from being invulnerable to attacks by well trained and alert opponents. These drawbacks make old VHF radars usable but not the best option. Therefore, efforts are being expended upon development of radars that can operate simultaneously on a wide range of frequencies. Such Ultra Wide Band (UWB) radars would use too many frequencies for a stealth aircraft to evade and it should be picked up by some section of the energy transmitted. This though is cutting edge technology with risks inherent in its development.

PASSIVE DETECTION SYSTEMS

This concept does away with a transmitter but incorporates sensors alone to detect a stealth aircraft. A totally passive system, it would comprise an array of receivers situated in a pre-determined optimum pattern. The principle of operation is that these sensors will aim to pick up any transmissions from the stealth aircraft, such as the stealth aircraft's own on board radar, radio communication signals, radio altimeter and other navigation related transmissions. With an array of receivers such a passive system would be able to triangulate the origin

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[140] "How to Take Down an F-117", http://www.strategypage.com/htmw/htada/articles/20051121.aspx, and http://www.defenceaviation.com/2007/02/how-was-f-117-shot-down-part-1.html, (Accessed October 20, 2013).

[141] John A. Tirpak, "Two Decades of Stealth", http://www.airforcemag.com/MagazineArchive/Pages/2001/June%202001/0601stealth.aspx, (Accessed October 20, 2013).

of these signals and hence detect the presence and location of the stealthy target that it is looking for. One such in service passive system is the Czech VERA which reportedly has the ability to detect stealth aircraft. Countries that have shown interest in the VERA system include *Pakistan, China, Vietnam, Malaysia and Egypt. Of these Estonia and USA have obtained a system each for further examination*[142].

HIGH POWER RADARS

As was covered in the section on achieving radar stealth, no stealth aircraft available today has a RCS of zero. The RCS is reduced to a very large degree but it still exists. The fielding of very powerful conventional radars could theoretically pick up the much reduced RCS of even stealth aircraft. The increase of radar power output faces technical challenges regarding adequately powerful transmitters and increased cooling requirements. While these may be possible on the ground, increases of power output of airborne radars could prove more challenging.

DETECTION THROUGH SECONDARY EFFECTS

Stealth aircraft may be able to reduce direct radar returns appreciably but they still have to fly through the air and consequently create disturbances in the air mass that they fly through. Modern radars that are able to detect turbulence in the air mass could be used to detect stealth aircraft through the secondary effect of the disturbed air caused by their passage much like a ship can be detected and tracked through detection of its wake in the water.

ADVANCED IR DETECTORS

IR technology has made great strides in the past few years. Development of new materials as IR detectors, availability of cooling techniques for IR detectors etc have increased the sensitivity of IR detectors to a great degree. Modern IRST systems have an ability to pick up aircraft IR signatures at ranges of more than 50 km against a free space background.

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[142] "US to buy Czech Stealth-Detecting radar", http://www.abovetopsecret.com/forum/thread51905/pg1, (Accessed October 22, 2013).

Such capability as it matures further may enable detection of a stealth aircraft's low IR signature at tactically effective ranges[143].

The search for counters to stealth is ongoing and given the long history of mankind successfully finding counters to weapons developed by opponents it is but a matter of time before increasingly effective counters are developed. This weapon and counter dates back to the sword and shield in the antiquity of human warfare. More recently the advent of the IR homing air-to-air missile saw fielding of high intensity flares to decoy such missiles and then two colour IR seekers and other techniques to defeat flares going on to IR modulators etc. The development of new weapon technologies and counters to these new technologies, even in the IR missile field, is not yet over. All advanced countries that have the technical capability to develop stealth aircraft are doing so while at the same time researching methods and means to counter stealth aircraft. The importance of developing and nurturing a domestic high technology aerospace industry can not be over emphasised as quite often very high end technologies developed by other nations may not be available for export when required for myriad reasons.

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[143] "PIRATE IRST", http://defenseissues.wordpress.com/2012/10/30/pirate-irst/, (Accessed October 21, 2013).

OTHER ASPECTS OF STEALTH

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STEALTH AIRCRAFT COST VERSUS NUMBERS

It has been covered during the discussion on stealth technology and stealth aircraft that stealth comes at a high cost. The high cost of development of stealth aircraft as well as the high cost of manufacturing these aircraft has led even the US to curtail the numbers built. For instance the US built only 21 B-2 (20 aircraft for USAF service and one for test and evaluation) and has capped its F-22 purchase at just 187 aircraft. The cost of the F-35 has forced several nations that had originally intended to induct this aircraft to scale down, or even in the case of Canada cancel, their orders[144]. Stealth aircraft have been seen to be much more effective than conventional aircraft in successfully penetrating hostile airspace to achieve mission objectives. The reduction of force levels required for attacking each target with stealth aircraft also adds to the greater efficiency of stealth aircraft against conventional aircraft. The increases in efficiency and assurance of achieving mission objectives leads to the argument that with such an increase in capability fewer stealth aircraft will be able to achieve results that required larger numbers of aircraft earlier. In this line of thinking the higher cost of stealth aircraft which in turn leads to fewer numbers is not a major issue as these fewer numbers can now do more with greater success. However, numbers do matter. Even a stealth aircraft would be usable against one target system at a time. In modern warfare there are likely to be a large number of targets to be engaged. This requirement is likely to need larger numbers of platforms to be deployed. This is possibly why the US intends to induct over 2,456 F-35" Lightning-II" stealth fighters for the USAF, US Marine Corp. (USMC) and US Navy (USN). These numbers include 13 aircraft earmarked for research and

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[144] "DoD Says International F-35 Lightning II Sales Crucial; Italy Cuts Orders by 41", http://www.dailytech.com/DoD+Says+International+F35+Lightning+II+Sales+Crucial+Italy+Cuts+Orders+by+41/article24013.htm, (Accessed October 11, 2013).

development and 2,443 production aircraft intended for front line service in combat units. These numbers include 1,763 F-35s for the USAF and 680 F-35s for the USMC and USN[145]. Cost figures for other global stealth fighter projects are not as yet available and these programmes have yet to lead to induction into service of their aircraft.

Finally, the cost number balance will have to be determined by each concerned Air Force in view of its peculiar security situation and available funds for defence. Stealth technology is unlikely to be able to make up for numbers entirely and vice versa. Though, stealth aircraft technology is not a replacement for numbers per se, availability of stealth aircraft does enable an air force to do more with less especially in an offensive campaign. A balance will have to be determined based upon missions to be achieved, the prevailing environment including potential adversaries' technological capabilities, force levels and assessed intentions and capabilities. There would be no one size fits all result for this problem. The same has been true earlier in the history of technological development too. Introduction of jet fighters, supersonic fighters, air superiority fighters etc all saw the cost against numbers debate and at no time did technology enable numbers to be reduced drastically. The same is likely to be true in this case also. The IAF has, as per information available in the public domain, announced that it would induct over 250 FGFA but later these numbers were reduced to a requirement of 144 FGFA[146] in addition to the rest of its fighter force[147].

STEALTH IN LOW INTENSITY CONFLICT (LIC)

It has been opined that the bulk of conflicts in the twenty first century are likely to be LIC in nature. Examples of these abound. The most prominent is the US Global War on Terror (GWOT). In the non-superpower domain too LIC examples are not difficult to find. The

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[145] Jeremiah Gertlerm, "F-35 Joint Strike Fighter (JSF) Program", Congressional Research Service 7-5700 www.crs.gov RL30563, http://www.fas.org/sgp/crs/weapons/RL30563.pdf, (Accessed October 21, 2013).

[146] "Fifth Generation Fighter Aircraft (FGFA) Medium Combat Aircraft", http://www.globalsecurity.org/military/world/india/mca.htm, (Accessed November 20, 2013).

[147] Gulshan Luthra, "IAF decides on 144 Fifth Generation Fighters", http://www.indiastrategic.in/topstories1766_IAF_decides_144_fifth_generation_fighters.htm, (Accessed October 21, 2013).

current situation in Syria, the situation along Israel's borders with Arab areas and close to home the security situation in Jammu and Kashmir (J&K), the North East, and in Naxalite affected regions conform to this classification. Stealth was conceived for conventional warfare. In this context some experts question the rationale for investing in expensive stealth technology when the most likely conflict type could be LIC and not conventional warfare.

For Non State Actors (NSAs) shooting down a state owned aircraft through any means would be a major coup. Such an act by relatively weak NSA would also be a very major psychological victory for the NSAs while at the same time being demoralising for state forces. A closer examination of the LIC scenario in the world as well as in India brings out that the relatively easy availability of Man-Portable Air-Defence Systems (MANPADS) with NSA in most conflict regions makes use of conventional aircraft even in LIC operations fraught with danger. NSA have ad access to MANPADS since at least the early 1980s. A MANPADS can be very effective in the hands of suitably trained NSAs who are able to acquire their aerial target in time. Hence, even in LIC operations within one's own territory or outside the country's borders the use of stealth aircraft of different types is a useful capability to have if a situation requires their use. Here it should again be noted that for a NSA bringing down an aircraft operated by the much more powerful state forces would be a major achievement. Hence all efforts are required to be made to ensure that such an eventuality does not occur.

The requirement for avoiding losses of state owned aircraft to action by NSAs can not be overemphasised. However, it should be noted that in LIC operations the aircraft involved are likely to predominantly be helicopters. Such aircraft are inherently vulnerable to even small arms fire due to their relatively low speeds and low altitudes of operation. Indian helicopters supporting surface force operations against Maoists have been hit by small arms fire several times. In fact, in one such incident a Mi-17 helicopter carried out a precautionary forced landing after suffering hits from small arms fire[148]. The use of armoured

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[148] "Air Force helicopter makes emergency landing as Maoists open fire", http://articles.timesofindia.indiatimes.com/2013-01-19/india/36431186_1_crpf-jawan-anti-naxal-operations-paramilitary-jawan, (Accessed November 19, 2013).

and stealthy helicopters could reduce occurrence of such incidents. However, the weighing of the cost of such aircraft against other factors considered relevant by the state will have to be done to decide upon the cost benefit equation in such equipping and deployment decisions. These primarily political factors if put aside it can be seen that the use of stealthy aircraft even in LIC could have tangible benefits. The primary issue in this scenario would be that of cost and affordability. But then the cost and affordability issue plays a part in almost all such situations of force design and formation.

Global Stealth Aircraft Programmes

A look at the ongoing stealth aircraft programmes in the world necessarily needs to start from an examination of the America programmes as the US was the pioneer in this new technology and has the only in-service stealth aircraft; the first two stealth aircraft, designed for combat, to enter operational service, the B-2 "Spirit" and F-117 "Nighthawk[149], have been used extensively in combat in Iraq, Afghanistan, and erstwhile Yugoslavia.

US Stealth Aircraft Programmes

The first US stealthy aircraft to enter service was the Mach 3.0 capable Lockheed SR-71 "Blackbird". This was followed by the Lockheed F-117 "Nighthawk" stealth fighter (an aircraft optimised for stealthy penetration of enemy airspace and optimised for air-to-ground attack or bombing rather than aerial combat as the word "fighter" implies). The B-2 "Spirit" stealth bomber followed. These two led on to the F-22 "Raptor" stealth fighter and the F-35 "Lightning-II", earlier called the Joint Strike Fighter (JSF). The F-35 is intended to replace a large number of legacy aircraft in USAF, USN and USMC. This single platform has been designed to replace the F-16 "Falcon", A-10 "Thunderbolt-II", F/A-18 "Hornet" and AV8B "Harrier-II" in the US[150]. The US has the only operational fleet of stealth aircraft in active

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[149] The first stealthy aircraft to enter service was the SR-71 "Blackbird". This aircraft was intended and also actually used for reconnaissance alone and not for combat roles.

[150] "F-35 to replace most US combat aircraft by 2020", http://www.defencetalk.com/f-35-to-replace-most-us-combat-aircraft-by-2020-42557/, (Accessed October 21, 2013).

service. In addition many legacy aircraft have been subjected to the better understood and easier to retro-apply stealth technologies in order to reduce their detectability. These include the F-18 Hornet in its F-18E/F "Super Hornet" variant. The US had plans as reported in the media to develop a stealthy attack helicopter the RAH-66 "Comanche". This project was however, shelved[151]. In 2011 the US used a stealthy variant of its workhorse "Black hawk" helicopter[152].

Russian Stealth Aircraft Programmes

The Soviet Union broke up before any stealth aircraft could be developed by it. However, it was reported that the Soviets had two projects, one each from the Mikoyan and Sukhoi design bureaus at the design stage. These could not be progressed due to the financial distress the Soviet Union was under in its last few years. Russia, the inheritor state of the Soviet Union, shelved the Mikoyan Bureau stealth aircraft proposal, Project 1.44, and chose the Sukhoi design bureau's design for progressing towards full development and as the PAK FA program. The PAK FA is currently Russia's only stealth fighter project with its Sukhoi T-50 prototypes undergoing development trials[153]. Russia also has a stealth bomber project called the PAK DA under development in its initial stages[154].

Peoples Republic of China (PRC) Stealth Aircraft Programmes

The PRC has focussed upon self reliance in advanced technology from its very early years. Towards this end the PRC built up a domestic aircraft industry which has benefited from cooperation with Western companies in the civil field as well as from access to advanced Western

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[151] "RAH-66 Comanche, United States of America", http://www.army-technology.com/projects/comanche/, Accessed November 20, 2013).

[152] Christopher Drew, "Attack on Bin Laden Used Stealthy Helicopter That Had Been a Secret", http://www.nytimes.com/2011/05/06/world/asia/06helicopter.html?_r=0, (Accessed November 20, 2013).

[153] "PAK FA, Sukhoi", http://www.fighter-planes.com/info/pak-fa.htm, (Accessed October 21, 2013).

[154] "The Tupolev PAK DA stealth bomber is expected to replace the aging line of Tu-95 and Tu-160 bomber types." , http://www.militaryfactory.com/aircraft/detail.asp?aircraft_id=1108, (Accessed October 21, 2013).

equipment fielded by third countries. Gleaning the learning from these interactions PRC has ploughed back the results into its indigenous programmes. Where it was unable to develop or obtain a look at or examine advanced weaponry it has not hesitated to use espionage to obtain the secrets of advanced technology. PRC riding the tide of its economic success is suspected to have three stealth fighter[155] and one stealth bomber[156] projects underway at different locations within China. Chinese stealth fighter projects include the J-20 program underway at Chengdu Aircraft Corporation (CAC) and the J-31 programme at Shengyang Aircraft Corporation (SAC).

European Union (EU)

There is no known stealth aircraft project underway in the EU. There are two advanced fighters of the 4.5th + generation, the French Rafale and the multinational Eurofighter Typhoon, being fielded. Both these aircraft do display a degree of signature suppression, though not of the order of true stealth aircraft.

Indian Stealth Aircraft Project

India's Defence Research and Development Organisation (DRDO) is pursuing an indigenous stealth aircraft project called the AMCA[157]. This project is reportedly still at the design and wind tunnel model testing stages. India has also entered into a collaborative arrangement with Russia to partner Russia in development of the PAK FA from the Sukhoi T-50 prototype. The Indian stealth fighter variant developed from the Sukhoi T-50 prototype is to be known as the (FGFA)[158].

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[155] David Axe, "Questions Abound as China Unveils *Another*Stealth Jet", http://www.wired.com/dangerroom/2012/09/questions-abound-as-china-unveils-another-stealth-jet/, (Accessed October 21, 2013).

[156] John Reed, "Is This China's New Design for a Stealth Bomber?", http://www.foreignpolicy.com/articles/2013/06/11/is_this_chinas_new_design_for_a_stealth_bomber,(Aaccessed October 21, 2013).

[157] "New Design For Indian Advanced Medium Combat Aircraft", http://www.aviationweek.com/Article.aspx?id=/article-xml/AW_03_04_2013_p72-548182.xml, (Accessed October 22, 2013).

[158] Dave Majumdar, "India's FGFA stealth fighter set for 2014 roll-out", http://www.flightglobal.com/news/articles/indias-fgfa-stealth-fighter-set-for-2014-roll-out-375726/, (Accessed October 21, 2013).

7

CONCLUSION

Stealth is a catchy term for a potentially war winning technology. The basic concept of stealth itself is as old as warfare itself. With the advances in aircraft detection and tracking technology during the last 40 years or so, stealth as we understand it today in the realm of aviation, has come to the fore. This involves the reduction of the signature of the aircraft so that the machine is made more difficult to detect and engage by hostile weapon systems. Stealth can not as yet make an aircraft invisible. It can at best delay the detection of the aircraft. This technology is in fact an application of many different technologies that span the EM spectrum. Typically the radar, IR, visual and acoustic signatures of an aircraft are sought to be reduced by stealth technology.

Stealth is a revolutionary technology in that it has the potential to change the way air power is exercised. The applications that this technology has span the entire gamut of air operations. In offensive applications of air power stealth has the potential to reduce the vulnerability of aircraft. This has spin-offs in the reduction of support elements for strike packages and smaller strike packages. Air defence operations benefits from giving the interceptors an undetected approach to their targets. Special operations benefit from the 'evasion of notice' that stealth bestows upon them. This is particularly so in the case of special operations as these, by their very nature, are important but vulnerable operations. On the whole it can be seen that stealth bestows more advantages to offensive operations and the offensive use of air power than it does to defensive use of air power. The offence-defence balance is thus seen to shift towards the offence. This is particularly in case the adversarial sides have asymmetric stealth capability, but applies in case of symmetric stealth capability also. Almost all nations with a desire to maintain powerful military forces are pursuing stealth aircraft programmes, either indigenously or in collaboration with other technologically more advanced countries. Access to stealth technology is likely to be the key deciding actor in the relative effectiveness of air forces in the twenty-first century.

Stealth with both the adversarial sides would confer the advantages discussed earlier in this work to both the attacker and the defender. It has been seen that the defender has to acquire the enemy for defence to be effective. Thus, for the defender incorporating stealth is not as important an attribute as the ability to detect the intruder. For the attacker the most important requirement is to be able to avoid being detected. This confers greatly increased survivability and enhances the accuracy of weapon delivery by reducing the pressure on the pilot. A stealthy aircraft would be better able to use its stealthiness in the attacking role. Incorporation of stealth in the attacker's aircraft would thus give great advantages. The possession of an asymmetric stealth capability would definitely place the advantage in the hands of the contestant who has the stealth advantage[159]. This advantage would be more evident in the offensive role. In case the adversarial sides possess symmetric stealth technology, the basic characteristics of this technology would again be seen to give the upper hand to the side indulging in offensive operations.

The balance between offensive action and defensive action is thus clearly seen to tilt in favour of the offensive in the case of possession of stealth technology by both adversarial sides. In case of asymmetry in stealth capability the side with stealth can be seen to have the edge, but again this edge would be more apparent in offensive action rather than in defensive action.

Stealth is likely to be a useful capability to have even in conduct of LIC operations. The determining factor in use of stealth in LIC operations, as is the case in conventional operations also, is likely to be the cost of the equipment.

As has been the case throughout history, the advent of the new stealth technology has spurred efforts to find effective counters to this new technology. Efforts in this direction include more advanced radars,

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[159] Bill Sweetman. Advanced Fighter Technology The Future of Cockpit Combat. Airlife Publications Ltd, London, 1988, p. 173.

sensors based upon other arts of the EM spectrum as well as secondary means of detection and tracking. The development of technologies to counter stealth is in progress in almost all technologically advanced countries. The search for and development of effective counters to stealth is by no means over and in the years ahead we should see a plethora of anti-stealth technologies being fielded by military forces.

In aerial warfare technology has progressed rapidly from the frail and flimsy machines seen in the air in the first half of the twentieth century. In the jet age that started soon after World War-II military aviation initially expanded into higher speeds and multirole capabilities. In the early 1970s the concept of making military aircraft more difficult to detect gained the attention of design and development teams. Since then the world has seen the F-117 "Nighthawk", the world's first stealth or "low observable" fighter. This was followed shortly by the F-22 "Raptor" and F-35 "Lightning-II". The performance of the F-117 in the Gulf War of 1991 and in Kosovo made it clear that stealth was a revolutionary technology. Programmes to make stealth aircraft thereafter commenced in other parts of the world as well with the Russians developing the PAK FA and PAK DA, China working on the J-20, J-31, and "sharp sword" Unmanned Combat Air Vehicle (UCAV), and India working on the Advanced Medium Combat aircraft (AMCA), Fifth Generation Fighter Aircraft (FGFA) and Autonomous Unmanned Research aircraft (AURA). Stealth has been seen as practically invincible by the lay public. However, an understanding of how stealth technology works and an examination of the possible means of countering stealth aircraft help come to a more balanced understanding of this important technology. This monograph attempts to commence this task of explaining stealth technology, looking at possible counters to stealth and discussing the ways in which stealth technology changes the conduct of aerial warfare.

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