Assessment of Aircraft Radar Cross-Section for Detection Analysis

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Abstract

Hiding from and surprising an opponent are tactics that have been used in warfare throughout history. They were features that aircraft originally possessed when they were first used in military operations. However, development of military technology is an endless struggle between advances in technology and counter technology. During World War II this struggle led to the development of a new technology called radar, which was designed to detect sea vessels and aircraft at a distance and deny them the element of surprise. This laid the foundation for modern air defenses and simultaneously created a need for aircraft to penetrate such defenses. Central to the tactics and technological development that followed from the deployment of radar on the modern battlefield is the radar cross-section (RCS) of aircraft, which dictates the range at which aircraft can be detected by radar. In this thesis some aspects of the RCS of aircraft in radar detection are investigated. A combination of experimental measurement of aircraft and digital model development of the RCS of aircraft has been used.

From flight experiments, the uncertainty in aspect angle to a threat sensor, due to aircraft dynamics, is quantified for various aircraft. In addition, the RCS fluctuation behavior of a military jet trainer is investigated by dynamic in-flight measurement. The monostatic and bistatic RCS of an F-117 are modeled and findings show that spline interpolation provides superior accuracy when interpolating the RCS data. Smooth and conservative RCS models are suggested and a new RCS sampling scheme is presented. A model based on experimental data is suggested for determining the range of aspect angles that an aircraft is likely to orient towards a threat sensor, and experimental RCS data is compared to the classical Swerling radar target models.

Possible consequences for military operations and the design of military systems are discussed and considerations for modeling the interaction between air defenses and aircraft penetrating those defenses are given.

This thesis should be of interest to military actors and the defense industry, since the analyses of the ability to detect aircraft using radar are important for military operations and their planning.

Sammanfattning

Att kunna gömma sig för att sedan överaska sin motståndare är en taktik som har använts inom krigsföring genom historien, detta var också en möjlighet flygplan erbjöd när de började användas i militära samanhang. Utveckling av teknik för militära ändamål är emellertid en ständigt pågående kamp mellan framsteg inom det befintliga teknikfältet och utveckling för att kunna motverka sådan teknik. Under andra världskriget ledde denna kamp till utvecklingen av radar, en teknik som används för att upptäcka och följa fartyg och flygplan på stora avstånd, vilket kraftigt försvårade möjlighet att överaska motståndaren med hjälp av flygplan. Utvecklingen av radar är en hörnsten inom moderna luftvärnssystem, vilket också har skapat ett behov för luftstridskrafter att kunna motverka och penetrera sådana skydd. Centralt för den teknik och taktikutveckling som skede till följd av att radar introducerades på det moderna slagfältet är flygplans radarmålarea, som är avgörande för på vilket avstånd det är möjligt att upptäcka flygplanet. I den här avhandlingen undersöks aspekter kring hur flygplans radarmålarea påverkar detektionsmöjligheterna för en hotradar. Avhandlingen består av både mätningar på faktiska flygplan samt forskning kring digitala modeller av radarmålarea.

Flygförsöken gav kvantitativa exempel på hur stor osäkerhet i aspekt vinkel ett givet flygplan kan förväntas ha emot en hot sensor på grund av flygdynamik. Utöver detta så utfördes även en dynamisk mätning av radarmålarea på ett jetdrivet skolflygplan, för att undersöka fluktuationerna i radarmålarea. Både monostatisk och bistatisk radarmålarea har beräknats för en F-117 modell och resultaten tyder på att spline-interpolation ger den bästa noggrannheten vid interpolation. Vidare föreslås hur jämna och konservativa modeller av radarmålarea kan uppnås samt att en ny samplingsstrategi för radarmålarea presenteras. En modell som bygger på experimentell data föreslås för att uppskatta hur stor ändring av aspektvinkel ett givet flygplan kan förväntas ge emot en hotsensor, samt att mätdata av radarmålarea jämförs med de klassiska Swerling modellerna.

Den påverkan resultaten förväntas ha på militära operationer och system diskuteras och några överväganden som bör beaktas vid modellering av interaktionen mellan flygplan och radar ges.

Denna avhandling torde vara av intresse för såväl militära aktörer som försvarsindustri, eftersom analysen och möjligheten att upptäcka flygplan med radar är en viktig del av luftstrid och tillhörande planering.

Preface

The research presented in this thesis has been conducted at the Department of Military Studies at the Swedish Defence University in collaboration with the Flight Dynamics Division at the Royal Institute of Technology. The thesis contains an overview of the research area and a discussion of the main results found in the five papers appended.

I would like to acknowledge Vinnova, SAAB AB and the Swedish Armed Forces for their financial support, without which I would have been unable to conduct my PhD studies.

Secondly, I would like to thank my three supervisors: Professor Ulf Ringertz for taking me on as a PhD student and for his scientific guidance, Professor Martin Norsell for introducing me to the fascinating world of electromagnetics and radar and also for providing invaluable scientific feedback and guidance, and Associate Professor Peter Bull for being a vital sounding board for research ideas on many, many occasions.

Thirdly, I would like to thank all my colleagues in the Military Technology Division for the stimulating and interesting working environment you have provided. I would particularly like to mention three of you, who have contributed that little bit extra to my thesis: Dr Hans Liwång for advice on signature adoption and scientific guidance, Martin Bang for invaluable discussions on scientific methods, and Lt Col Michael Reberg for sharing his operational expertise in air defense. Furthermore, I would like to acknowledge Stephen Henly at the War Studies Division for proofreading my thesis, any remaining defects or grammatical errors are entirely mine.

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Björn Persson
Stockholm, April 2016

List of Appended Papers

This thesis is based on an introduction to the research subject and the following appended papers:

Paper A

B. Persson and M. Norsell. On Modeling RCS of Aircraft for Flight Simulation, IEEE Antennas and Propagation Magazine, 56(4), 34-43, 2014.

Paper B

B. Persson and M. Norsell. Conservative RCS Models for Tactical Simulation, IEEE Antennas & Propagation Magazine, 57(1), 217-223, 2015.

Paper C

B. Persson and P. Bull. Empirical Study of Flight-Dynamic Influences on Radar Cross-Section Models, *AIAA Journal of Aircraft,* 53(2), 463-474. 2016.

Paper D

B. Persson and M. Norsell. Reduction of RCS Samples Using the Cubed Sphere Sampling Scheme. Submitted for publication. 2016.

Paper E

B. Persson. Radar Target Modeling Using In-Flight RCS Measurements. Submitted for publication. 2016.

Division of work between authors

Paper A

Persson was responsible for the work and analysis, the research objective was suggested by Norsell. The paper was written by Persson with support from Norsell.

Paper B

Persson was responsible for the work, analysis, and formulating the research topic. The paper was written by Persson with support from Norsell.

Paper C

Persson was responsible for the work, analysis, and formulating the research topic. The paper was written by Persson with support from Bull. Experimental data was provided by Norwegian Air Shuttle ASA and Saab.

Paper D

Persson was responsible for the work and analysis, the research objective was suggested by Norsell. The paper was written by Persson with support from Norsell.

Paper E

Persson was responsible for the analysis, formulating the research topic and writing the paper. The Swedish agencies FOI and FMV conducted the experiment.

Contents

Appended papers

Introduction

"If ignorant both of your enemy and yourself, you are certain to be in peril"
— Sun Zi

At 0200 on January 17th 1991 the allied offensive, code name: Operation Desert Storm, was initiated as part of the first Gulf War. One hour later, strategic targets in Baghdad, the capital of Iraq, had been destroyed; targets which Iraqi air defenses most likely had as the highest priority to protect. This occurred in spite of the fact that Iraqi air defense forces were in possession of sophisticated Soviet and French anti-aircraft missiles and radar. It has been estimated that the density of air defenses in Baghdad was twice that of many heavily defended targets in Eastern Europe at the time [1]. The ability to strike against targets deep within defended enemy territory was in part enabled by a newly developed stealth aircraft: the F-117 Nighthawk, which was specially designed to avoid detection by the enemy. Stealth aircraft proved to be a valuable asset during the campaign [2] and the stealth technology and counter technology has continued to evolve ever since. Technologies for signature reduction and counter technologies have become important aspects, which need to be taken into consideration for military air operations, air defense, as well as for the development of fighter aircraft.

The effectiveness and use of technological advances, and their influence on military operations, are studied within the discipline of Military Technology at the Swedish Defence University. The technological systems armed forces choose to acquire can affect their ability to emerge victorious from an armed conflict [3]. In addition, technology and tactics, among other things, have to be procured, developed, and practiced through close collaboration between technological experts and users in order to maximize the military utility of the technology [4].

In order for stealth technology to bring military utility to its users, it must be possible to use the reduced probability of an enemy detecting a stealth platform to improve the chances of achieving mission objectives. This thesis aims to analyze and model various aspects related to aircraft radar cross-section (RCS), which influence the probability of detection of airborne targets using radar and, therefore, should be of interest to operators and designers of both surveillance radar systems and combat aircraft.

Knowledge of the signatures of both your own and your enemy's platforms is fundamental to the analysis and successful execution of most modern operational plans.

Radar

"The bomb may have ended the war but radar won it"
— Louise Brown

The scientific advances in electromagnetics during the late 19th Century laid the foundation for many innovations which were to be realized during the 20th Century, such as radio, television, microwave ovens, mobile phones – and radar. Radar was patented by Christian Hulsmeyer in 1904 and further developed simultaneously in several countries before World War II [5]. Radar is an acronym for RAdio Detection And Ranging and operates within the radio frequencies in the electromagnetic spectrum. Radar was used during World War II by both Allied forces and the Axis powers and was deployed on naval vessels, trucks, aircraft, and fixed sites [6]. The primary use of radar was for navigation and target detection and over the years its position as the primary sensor for detecting and tracking platforms above the sea surface has remained undisputed. All branches of modern military forces capitalize on the advantages of radar technology and the number of applications continues to grow. Some examples are: navigation radar, artillery locating radar, air and ground surveillance radar, fire control radar, radar altimeter, weather radar, proximity fuses, small arms fire radar, ground-penetrating radar and guidance radar. Figure 1 shows an example of a modern surveillance and air defense radar.

Different applications place different requirements on radar, which is why a large number of techniques and frequencies are used in various radar applications; although different in detail they all share some common principles. The basic principle for all radar systems is that at a specific instant in time the radar transmits an electromagnetic signal from an antenna; this signal moves at the speed of light and if the signal comes into contact with an object, it is scattered in all directions. If the scattered signal is strong enough to be received by the radar antenna, it is possible to calculate the range to the object that scattered the signal in relation to the radar.

Figure 1. The Giraffe AMB radar which can be used to detect and track airborne platforms, © Saab AB, Photograph: Peter Liander

By using antennas with directivity it is also possible to determine the direction to the object with respect to the position of the radar. Moreover, by considering the shift in frequency, due to the Doppler effect, it is possible to determine the approach speed of the object [7]. The maximum range at which an object can be detected by radar is governed by several factors. Some depend on the radar, such as transmitted power, antenna gain, carrier frequency, signal processing, etc. Other factors are environmentally dependent, such as atmospheric attenuation and the terrain. Finally, the maximum detection range is dependent on the RCS of the object, i.e. a measure of how much of the incident energy is scattered in various directions. The strength of the scatter primarily depends on the geometry and materials of the object, the aspect angle to the radar, and the polarization and frequency of the radio waves [8].

Radar provides armed forces with the means to detect and track the enemy at a distance, which is a prerequisite for engagement or counter other actions related to the threat. This in turn makes the platform carrying the radar a tactical entity, well worth targeting by the enemy. Technological progress in the military arena is a continuous battle between development of new technology and counter technology, and radar is no exception [9]. Techniques to interfere with an enemy's radar signal are important aspects of modern warfare. This is achieved either by passive mechanical means, such as chaff [10], or by electronic jamming [11], i.e. using another transmitter designed to interfere with the radar signal. Jamming is often called Electronic Attack. However, jamming is not the only counter technology that needs to be considered. The fact that radar emits electromagnetic signals may allow an opponent to exploit the signal and estimate the location from which the signal originated and, from a signal library, possibly determine the radar type; this is often referred to as Electronic Support Measures. In combination with Electronic Protection, Electronic Attack and Electronic Support Measures constitute what NATO calls Electronic Warfare [12]. Electronic Protection includes, but is not limited to, low observable technology, commonly known as stealth technology, which is the subject of the next section.

Stealth

"Stealth enabled us to gain surprise each and every day of the war"
—Lt. Gen. Charles A. Horner, USAF

Reduction of the RCS of a platform can decrease the distance at which the enemy can detect the platform using radar. Use of this idea on an aircraft was proposed by the British during World War II [13], but was never turned into an operational reality. Instead the work of a Russian physicist, Petr Ufimtsev, on predicting electromagnetic scattering is considered to have laid the foundation for RCS analysis [14]. Ufimtsev's work made it possible to predict the RCS of low observable aircraft without the need to build them; two examples are the F-117 Nighthawk and B-2 Spirit. Most modern military aircraft have been subjected to RCS analysis and RCS reduction, for example the F-35 Lightning II, Eurofighter Typhoon, JAS 39 Gripen, PAK FA, J-31 and the unmanned combat aerial vehicle (UCAV), Neuron, seen in Figure 2.

Figure 2. The UCAV technology demonstrator NEURON, © Saab AB, Photograph: Stefan Kalm

For aircraft the primary technique for RCS reduction is shaping, whereby the geometry of the aircraft is designed so that only a small portion of the energy from the illuminating radar is scattered in tactical sectors, and most of the energy is scattered in directions considered to be safe [15]. Shaping is often accompanied by constructing parts of the aircraft using radiation-absorbent materials (RAM), which can further decrease the RCS [16].

Aircraft designed using shaping have additional design objectives to conventional aircraft and, therefore, often look quite different. This has resulted in the common misunderstanding that stealth aircraft and aircraft with low RCS are synonymous. In fact, low RCS is just a small portion of the stealth concept and is only relevant if the enemy is in possession of radar technology. As stated in the previous section, most modern military forces are in possession of radar, which is why low RCS is an important aspect of modern stealth platforms. However, a more holistic perspective on stealth is required; all types of signatures must be considered and controlled, such as thermal infrared, visibility to the human eye, and the acoustic signature. Moreover, electromagnetic emission control is just as important as low signatures and possibly the most important aspect of all is the tactics used to benefit from the technological advantages which true stealth technology provides. All the aspects of stealth above should be in balance to achieve an effective military platform [15]. Signature reduction often means sacrifices in other areas [17], such as payload capacity or endurance, and low signature in one part of the electromagnetic spectrum is worth little if the enemy detects the platform using a sensor that operates in another part of the spectrum. Similarly, onboard radar or communication channels can easily become the weakest link in the stealth chain and could greatly reduce the benefits of hard-won low signatures. Nevertheless, radar is the primary sensor for surveillance of both airspace and sea surface, which is why low RCS values are key parameters in most modern military platforms.

It is difficult to achieve low RCS is all directions [18]; therefore, it is important that operators of stealth platforms deploy their platforms in such a way that allows them to orient their tactical sectors towards enemy receivers; this is studied in Paper C. Attempts to achieve this by using trajectory optimization algorithms have been made [19, 20]; such endeavors require conservative and smooth RCS models, which is one of the subjects of Paper B.

Studying the duel between air surveillance radar and opposing aircraft requires knowledge from several scientific domains, and this is why this thesis takes a multidisciplinary approach, which is the subject of the following section.

Research approach

“Research is formalized curiosity. It is poking and prying with a purpose”
– Zora Neale Hurston

This thesis contains five papers, each of which addresses different questions and ideas related to the role of aircraft RCS in military applications. Paper A addresses modeling issues concerning the possibility of interpolating the RCS, and analyzes how fast rigid body fluctuations occur due to changes in aspect angle. Paper B extends the work in Paper A by discussing the need for smooth conservative RCS models for flight path optimization and operational planning. In Paper C three flight experiments, with different aircraft, are presented in order to investigate how large the uncertainties in aspect angle to a distant sensor are due to flight dynamics. Paper D presents a new RCS sampling scheme to be used in electromagnetic computation, where the new scheme solves the problem of oversampling at high and low elevation angles. Finally, Paper E addresses the validity of Swerling models and explores real-world RCS fluctuations using in-flight measurements.

Regardless of whether the mission objective is to defend an area from airborne attack, or to penetrate hostile air defenses, a sound understanding of both the physics encountered and the tactics to be used is required. Several academic disciplines are required in order to describe the complexity of defending against, designing, or deploying a military aircraft with the aim of being able to approach hostile radar undetected. Figure 3 shows a conceptual Venn diagram where the small bulged yellow rectangle in the middle represents the perspective used in this thesis. Other disciplines may also be required to extend the analysis presented, but this thesis emphasizes the topics limited to the intersection between the four disciplines seen in Figure 3.

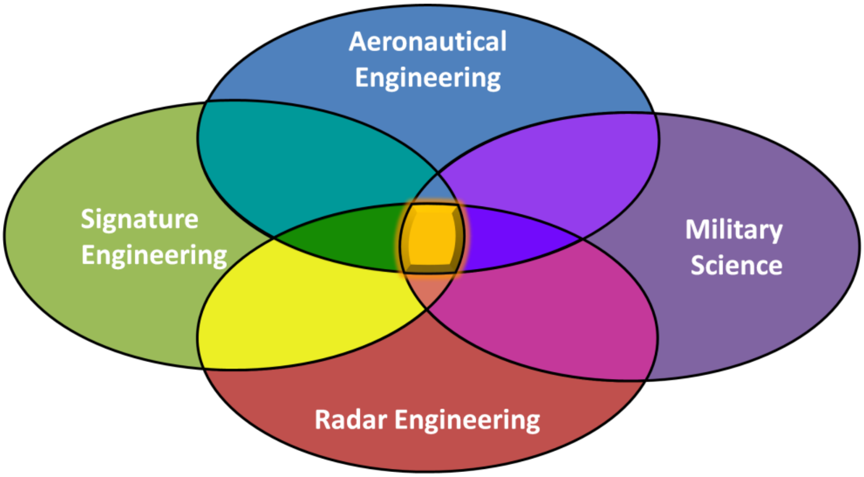

Figure 3. Conceptual Venn diagram of the four disciplines used in the multidisciplinary research contained in this thesis.

Starting from the perspective of the aircraft, some fundamentals of flight dynamics, aircraft design, and lightweight structures are required from the field of Aeronautical Engineering. This, combined with Signature Engineering, the prediction and reduction of signatures, allows the design and development of aircraft which may be hard to detect. In order to understand how a surveillance radar system will react to a platform, knowledge from Radar Engineering is important: how such sensors work, the possibilities they offer, and their limitations. Finally, in order to gain military benefits from the technology, a military perspective is required; simply avoiding detection and the detection of incoming aircraft are not military objective in themselves. Therefore, Military Science also plays a role in the multidisciplinary work presented.

Aeronautical, Signature, and Radar Engineering rely heavily on the natural sciences and they in turn are also multidisciplinary sciences, relying on disciplines such as materials science, electromagnetics, control and optimization theory, signal processing, solid mechanics, aerodynamics, etc. Traditionally, Aeronautical, Signature, and Radar Engineering are closely associated with the development of military systems and they are often necessary (but not sufficient) when designing systems which are useful to military organizations. In order to create effective systems, other aspects, which are not purely technical, must be considered. Stealth systems in particular take advantage of uncertainty, fear, and deceit, which are ever present in war. Military Science relies on both Social and Natural sciences, with the main objective of increasing the probability of victory in armed conflicts. Armed conflicts contain many complex elements which are studied within Military Science, such as strategy, operational research, tactics, psychology, international law, medicine, military history, etc.

By combining the four subjects seen in Figure 3 it possible to study the complexity of military aircraft approaching surveillance radar, which is important for planning both air defenses and the suppression of enemy air defenses.

Analysis

“Not ignorance, but ignorance of ignorance is the death of knowledge”
— Alfred North Whitehead

Military systems, particularly stealth systems, for good reasons are often classified. This makes the topic somewhat problematic to study, since the scientific process relies on openness and scrutiny. All data presented in the appended papers are either unclassified or declassified, and the main focus of this thesis is to present generic aspects and methods that should be taken into consideration when analyzing the interaction between radar and aircraft. Nevertheless, the specifics of some of the findings are of particular interest, foremost the measurement of aircraft motion and RCS fluctuations found in Papers C and E. This thesis shows that it is possible to perform experiments and research methods of analysis, which can be utilized later by military actors, even though it may not be possible to study or publish classified aspects of many military undertakings or systems.

Answering the question: *At what range can radar system A detect aircraft B?* may seem trivial from a strict energy perspective. However, the problem is quite complex. In order to give an answer, numerous things must be known. Rough estimates can be obtained using various forms of the radar range equation. However, there are a number of processes involved, which are, or appear to be, stochastic, such as internal noise in the radar receiver, clutter, and the fluctuating RCS of the target. This means that the above question should be rephrased to say: *What is the probability that radar system A can detect aircraft B at a range of C km?* Further complexity is added when considering what the pilot is trying to achieve, depending on the mission, knowledge of the threat, the own aircraft and equipment, and the tactics adopted accordingly. Examples of some variable parameters when attempting to penetrate air defenses are altitude, speed, route and time of day. Thus, more information needs to be included in the question for it to be relevant: *What is the probability that radar system A can detect aircraft B at a range of C km provided that the aircraft follows trajectory D?* Answering this question is of great interest to developers and operators of both air defense systems and aircraft attempting to penetrate such systems. In order to answer this question, any theoretical analysis must involve several models. The following would be a minimum requirement: a radar model, a RCS model, a flight dynamic model, and a model of the tactical procedure, all of which need to be verified and validated.

Experiment

“The test of all knowledge is experiment. Experiment is the sole judge of scientific ‘truth’ ”
– Richard Feynman

Experimental methods are nothing new to military organizations. However, as discussed in the previous section, sharing the results with the rest of the world is uncommon. Experimental data may contain information advantageous for an adversary and the risk that the information falls into enemy hands is reduced by classification or other means of deliberately not sharing the data. However, this procedure limits the advancement of knowledge and prevents researchers outside the organization from giving their view, thus impeding scientific progress.

This thesis describes two types of experiments, one considering the possibility of orienting the tactical sectors of an aircraft towards a known threat, which is in Paper C. The other experiment concerns measured RCS data from in-flight measurement, which can be found in Paper E. Undoubtedly, the same types of experiments have been performed by nations who develop stealth aircraft; however, as the results are not made available to the public, it is hard for researchers to come by experimental data to validate or falsify theories on the matter.

Research on radar target modeling, RCS fluctuation [21-28], and trajectory optimization [29-33] is extensive. However, for various reasons much of the work is highly theoretical. One of the objectives of this thesis is to provide analysis methods and experimental data which can be used for the development, validation, and parameterization of the models used in such research. As is often the case in experimental work, it is only possible to explore a small portion of the entire domain. For example, the number of aircraft investigated is limited, as are the frequencies of the RCS measurement system. However, the results give an indication of the order of magnitude of the relevant quantities required for subsequent analysis, even though other researchers may not be analyzing the aircraft investigated herein. Similarly the results on RCS fluctuations in Paper E both validate the use of Swerling Case 2 [34] for one of the flight cases, and reveal that the RCS fluctuates at several hundred hertz and upwards, which is much faster than what can be attributed to changes in aspect angle alone. These fluctuations may be caused by structural vibrations in the airframe [35-37] and rotation of the blades in the jet engines [38]. This is a hypothesis, which is suggested by the literature; however, there could be other explanations as well, such as electrical or filtering phenomena.

The rapid fluctuations are of the same order of magnitude as the changes in RCS due to variations in aspect angle and, therefore, deserve equal attention. Such experimental results have a generic value both scientifically, and to military and industrial organizations that work with signature reduction and Swerling models. The rapid fluctuations also provides reason to investigate the dynamic RCS of particular aircraft that such organizations may be working on, or are aiming to detect, in an operationally relevant configuration.

Modeling and simulation

"All models are wrong, but some are useful"
– George Box

Digital modeling and simulation is a method which allow for analysis of events and processes without the need to construct anything physical. Modeling and simulation is both an art and a science of its own [39] and its advantages are many. The ability to try new ideas and discover weaknesses in a design, before realization of the idea, leads to reduced development costs and improved end results [40]. In addition, modeling and simulation are often a good complement to experiments, as they enable exploration of larger portions of the problem domain. Moreover, for military applications, modeling and simulation are important tools that allow analysis of military capabilities of both one's own and an opponent's forces, without the need for actual fighting. Similarly, modeling and simulation allow analysis and training in situations which are realistic, but too dangerous or costly to perform in real life, e.g. practicing evasive maneuvers after missile lock-on in real fighter aircraft.

The downside to modeling and simulation is the simple fact that it is not real. Models rely on assumptions; time and other quantities are discretized in most simulators, and there is always the risk of missing key components in models. Therefore, to minimize this risk, it is imperative that the models used in any simulator are verified and validated against real-world experiments whenever possible [41].

Additionally, models never truly capture all aspects of reality; however, that is not the intention with a good model. A good model is developed for a purpose and what is important is that the model captures those aspects that are significant to the problem at hand, and that one has some estimate of what deviances to expect between the model and reality. Likewise, just because a model works well solving some problems does not guarantee its applicability in solving problems the model was not developed for.

The modeling and simulation of interactions between surveillance radar and an approaching aircraft are no exceptions to the above.

Aspects of creating models which allow the pilot to take advantage of RCS variations in different sectors are discussed in Paper A. Furthermore, different interpolation schemes are investigated, as well as the spatial fluctuations of the RCS of an F-117 model obtained using Physical Optics. In Paper B considerations on creating smooth, conservative, and tactical RCS models, achieved by down-sampling RCS data and keeping local maxima values, are discussed. It is shown that generalized extreme value theory captures the interpolation error in the conservative models well. Parameter values to be used for modeling aircraft rigid body dynamics are given in Paper C, along with an analysis method for the degree of uncertainty in aspect angle for the different aircraft. Paper D suggests a new sampling scheme, called the Cubes-Sphere, which reduces the number of samples required in models like those described in Papers A and B. In Paper E experimental data is compared to the classical Swerling models and it is shown that excellent agreement is obtained when the aircraft approaches a radar station head on.

Discussion

"We have to learn again that science without contact with experiments is an enterprise which is likely to go completely astray into imaginary conjecture"
– Hannes Alfven

Numerous studies of aircraft RCS exist [42-47]; however, the electromagnetic signature is often studied using computational electromagnetics or static measurements. There are two main reasons for the large number of studies. The first is because an aircraft's RCS is highly relevant for military operations and for the design of the aircraft. The second is because an aircraft's RCS is a complex quantity to study, both due to confidentiality and other difficulties related to its measurement or estimation. However, the number of unclassified reports about dynamic RCS is limited and those available generally present processed data rather than measurement data. Measurement of in-flight RCS data can be representative of the actual operational behavior of the aircraft, which is what is required to validate both computations and static measurements. An important phenomenon, which was revealed when working with Paper E, is the rapid fluctuations of the RCS which were found in the experimental data. Another study which contained measurements on a fighter aircraft revealed slower but similar fluctuations [21]. The faster fluctuations are probably due to reflections from the blades of the two jet engines. However; when illuminating the aircraft from the side, fluctuations of several hundred hertz could also be observed. These fluctuations are probably caused by vibrations and deformations of the airframe, which change the geometry enough to yield scatter of varying amplitude. The rapid change in amplitude of the RCS is of the same order of magnitude as the changes in amplitude due to changes in aspect angle. In comparison to other vehicles, aircraft are elastic structures and are deformed by aerodynamic forces when in-flight [48], and it can be misleading to consider them as rigid bodies when performing RCS analysis. More unclassified research is required to confirm the source of these rapid fluctuations and whether the levels can be predicted. Both static measurements and computations should benefit from including such dynamics in future analyses, since they risk underestimating the RCS values if this dynamic phenomenon is ignored. This would be troublesome for operators of both air defenses and combat aircraft. Air defenses which underestimate the signature of the threat will deploy more assets than necessary to establish sufficient radar coverage to detect the threat, assets which could otherwise have been used in a more tactically effective manner. Deploying aircraft where the amplitude of the RCS has been underestimated could result in trajectories which bring the aircraft too close to air defense systems, resulting in possible detection, failed mission objectives, damaged or destroyed aircraft, and casualties.

So far, the subject of jamming has only been touched upon; however, this is an important aspect to be considered when analyzing the possible penetration of air defenses. As discussed previously, development of military technologies is a continuous struggle and it is uncertain whether or not jamming will play a dominant role in future air operations. The trend is that Low Probability of Intercept (LPI) technology will become available [49], Electronic Protection in modern radar systems will evolve [50], Electronic Support Measures will improve [51], and Anti-Radiation Missiles [52] will be more common. Thus, jamming may become an increasingly difficult activity which has little effect on an opponent's systems, and only puts the platform carrying the jammer at great risk. In addition, jamming has the great tactical disadvantage of alerting the enemy to the possibility of an imminent attack. Therefore, it is also of military interest to study the interaction between attack aircraft and air defenses, without considering Electronic Attack.

Another subject which has not been considered so far is the technique of using much lower radar carrier frequencies than usual to detect stealthy platforms. By doing so the wavelength becomes larger than some critical dimension of the platform and the scattering mechanisms are then considered to be Rayleigh or resonance scattering. At lower frequencies it is much more difficult to reduce an aircraft's RCS, since the shape is of less importance at these frequencies [53]. An example of this can be seen in Paper D, where the RCS of an F-117 model is calculated at 100 MHz and 5 GHz. When the aircraft is illuminated head on the monostatic RCS is approximately 24 m^2 at 100 MHz and 0.0001 m^2 at 5 GHz. These statistics are calculated from a rather simplified model and are not entirely representative; however, they reveal the fundamental fact that, by using lower frequencies, the radar range equations predict that, in free space, the stealth platform can be detected at a distance approximately twenty times larger than what is possible at higher frequencies. However, there are good reasons why radars have been developed to work with higher carrier frequencies, until stealthy platforms arrived on the scene. Low frequencies produce large clutter returns, and the lobe width of a given size of antenna is approximately proportional to the inverse of the carrier frequency, which in turn will limit the positional accuracy that the radar can achieve. Therefore, lower frequencies can improve the probability of detecting stealthy platforms; however, once detected, it is more difficult to determine the exact direction to the platform. Modern air defenses solve this by deploying several radar systems, which operate at different frequencies and work in cooperation to detect and enable engagement of stealthy airborne targets [54]; an example of a low frequency radar which is said to be able to detect low observable targets [55] can be seen in Figure 4. However, from a military perspective, low RCS should not be interpreted as no longer of use. The fact that a potential opponent is forced to deploy multiple radar systems, using antennas that are several orders of magnitude larger than otherwise required, is a successful outcome in a wider context, even if such counter technology prevents the platform from achieving the mission objectives it was originally designed for. Furthermore, the large antennas required for low frequencies can only be deployed on large carrier platforms; thus, a low RCS at higher frequencies is still useful against radars carried by fighter aircraft and missiles. On the other hand, the development of counter stealth radar emphasizes the importance of a sound threat and signature analysis of airborne platforms, and the balance between signature and other performance parameters in such platforms.

Figure 4. An acquisition radar operating on low carrier frequencies, designated 55Zh6M Nebo-M.ⓒVitaly V. Kuzmin

Other technology that could benefit from knowledge of an aircraft's RCS are decision support systems, i.e. onboard computers which assist the pilot in making decisions [56, 57]. The RCS of an aircraft in different sectors and frequencies is simply too much information to be considered by humans when making decisions, especially under stress. Computers, on the other hand, can process the information, analyze the threats, and suggest trajectories which orient the aircraft in a favorable position with respect to the threat. In such analyses the uncertainty in the ability to follow a certain trajectory should also be considered; here the methodology and results presented in Paper C could be of use. This could result in more intelligent use of the hard-won low signature of fighter aircraft.

Several models are required for a theoretical analysis of an aircraft's ability to approach a radar system undetected. The first requirement is a radar model, which is correctly parametrized and where the detection criterion is related to the aircraft's RCS fluctuations and the flight-path chosen by the pilot. Secondly, a model is needed to capture the aircraft's dynamics, so that different trajectories can be tested, and aspect angles to the threat can be estimated. The third requirement is a RCS model of the aircraft. The RCS model should be frequency and aspect-angle dependent and, if relevant for the aircraft being investigated, it should also incorporate the fluctuation in RCS due to deformation or vibration of the airframe. Finally, a model which captures environmental factors is important, factors such as electromagnetic noise, atmospheric damping, gusts, terrain effects on line of sight, etc. Combining these models in a time-evolving simulator would allow the analysis of the interaction between one or more radar systems and aircraft. If properly developed, verified, and validated such simulators can provide knowledge of the capabilities of both one's own and opposing forces, and become an important tool for operational planning. Such simulators could also assist in the design and development of military radar and aircraft systems.

Conclusions and future work

"It is always wise to look ahead, but difficult to look further than you can see "
– Winston Churchill

Presenting a low signature to a potential opponent's sensors has and will continue to be an important aspect for military platforms. However, subsequent analysis and the possibility of predicting when detection is possible are equally important to capitalize on a low signature or to defend against attack by low observable platforms.

Simulation is one of few methods which allow the study of future armed conflicts, however many physical aspects need to be modeled for the simulators to be suitable for such analyses. This thesis has focused on understanding and modeling the physics of aircraft radar signatures in operational contexts. Similar investigations and open scrutiny of modeling the physics required in various models, such as radar, propagation effects, Electronic Attack and Electronic Support Measures, need to be performed and brought together. Once validated, it would be possible to study military procedures and tactics for both air defenses and airborne platforms. Such simulators could also be an important tool for technological forecasting [58] related to radar and Electronic Warfare.

The hypothesis in Paper E, that the rapid RCS fluctuations are caused by vibrations of the airframe, is supported by the literature. However, more research is required, particularly experiments, in order to fully understand the underlying phenomenon. Questions like: *Which parts of the aircraft vibrate? Do all aerial targets exhibit such fluctuations? How can this be captured in static measurement ranges and electromagnetic codes?* and, *Is it possible to predict and control these rapid fluctuations for a given aircraft?* need to be addressed.

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