Sensor and Signature Modeling for Aircraft Conceptual Development

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.

Daniel, vill du vara med när jag skriver det allra sista i avhandlingen?

Abstract

The aircraft design process has several phases, the first of which is conceptual design. In this phase, models describing an aircraft concept's properties are used to evaluate its function and identify designs that meet given requirements. Fighter aircraft are generally expected to be capable of communicating, delivering munitions and gathering data about their environment to gain situational awareness. The ability to avoid detection by hostile sensors can also be important, depending on the aircraft's role.

The design process of the aircraft itself has usually focused on an aircraft's flight performance and ability to carry loads, e.g. munitions and extra fuel. While acceleration, rate of turn, maximum speed, and operational range are important parameters, the success of military missions also depends on sensor capabilities and signature levels. However, sensor installation and signature reduction measures can affect the aircraft and its flight performance. Whether an aircraft concept fulfills the requirements given is evaluated using simulations in appropriate scenarios. The concept's performance is assessed using models of aircraft properties, weapon properties, sensor capabilities and signature levels. Models of the aircraft properties are usually connected dynamically, and respond to changes in such things as the size of the concept. However, sensor and signature models are often the result of a separate optimization process and are only statically connected to the aircraft model. The complete aircraft model can be improved by introducing sensor and signature models that dynamically describe both their functions, and their impact on the aircraft. Concurrent design of all the aircraft properties may improve the quality of results from scenario simulations. When models used in simulations contain parameters coupled to each other, analysis of the resulting data is particularly important because that is what supports a decision maker's design choice.

Sensor and signature models, in some cases combined with flight performance models, have been used to test methodologies intended for use in conceptual aircraft design. The results show that even seemingly simple models can produce results that can make a significant contribution to the aircraft design process.

Populärvetenskaplig sammanfattning

Det första steget vid flygplansutveckling är konceptfasen, där alternativa förslag på flygplan representeras av modeller som beskriver det tänkta flygplanets egenskaper. Modellerna används i simuleringar som genomförs i olika scenarion, för att utvärdera och rangordna de olika flygplanskonceptens förmågor. För stridsflygplan är det viktigt att kunna manövrera och leverera vapen såväl som att skaffa och upprätthålla en situationsuppfattning. Beroende på flygplanens roll i uppdraget kan det också vara en prioritet att undgå upptäckt från fiendens sensorer.

Konceptsfasen är vanligtvis inriktad mot flygplanets prestanda och kapacitet att bära last, exempelvis extra bränsle och vapen. Förmågan att framgångsrikt genomföra ett militärt uppdrag beror på egenskaper som har att göra med svängprestanda, acceleration, topphastighet och räckvidd såväl som sensorernas egenskaper och flygplanets signaturnivå. Simuleringar av scenarion med modeller av flygplanets egenskaper, vapenprestanda, sensoregenskaper och signaturnivåer, möjliggör värdering av ett flygplanskoncepts förmåga att genomföra sitt uppdrag på ett tillfredsställande sätt. De modeller som beskriver flygegenskaperna är vanligtvis sammankopplade och ändringar i exempelvis flygplanets storlek påverkar alla modeller. Sensor- och signaturmodeller, är däremot ofta ett resultat av en separat konstruktionsprocess och inte kopplade till exempelvis flygegenskaper. Genom att införa modeller av sensorprestanda och signaturnivåer som är dynamiskt kopplade till flygplanets modeller finns det möjligheter att förbättra konceptanalysen. Resultatet ger möjligheter att få mer fullständigt resultat från simuleringarna i scenarion, vilket i sin tur ger beslutsfattare ett bättre underlag.

I den här avhandlingen presenteras modeller av sensorer och signaturnivåer, avsedda att användas vid konceptkonstruktion av flygplan. Vissa av modellerna är kopplade till modeller för flygprestanda. Resultaten visar att även till synes enkla modeller ger resultat som kan utgöra ett användbart bidrag till konstruktionsprocessen.

Preface

Five papers are included in the thesis. All papers are published or presented at conferences.

I Military utility: A proposed concept to support decision-making

Published in Technology in Society, Elsevier
`doi.org/10.1016/j.techsoc.2015.07.001`

II Balancing the Radar and Long Wavelength Infrared Signature Properties in Concept Analysis of Combat Aircraft - a Proof of Concept

Published in Aerospace Science and Technology, Elsevier
`doi.org/10.1016/j.ast.2017.10.022`

III Balancing Antenna Performance vs. Radar Cross Section for a Passive Radar-Detecting Sensor on an Aircraft

Presented at AIAA SciTech '19, San Diego
`doi.org/10.2514/6.2019-2047`

IV Detection Chain Model Designed for Aircraft Concept Development

Published in Journal of Aircraft, AIAA
`doi.org/10.2514/1.C034930`

V Aspects of the Design, Evaluation and Accuracy of Airborne Sensor Clusters Using Time-Difference of Arrival

Published in Aerospace Science and Technology, Elsevier
`doi.org/10.1016/j.ast.2019.07.025`

Acronyms

AESA	Active Electronically Scanned Array
CONOPS	Concept of Operations
DSE	Design Space Exploration
EMCON	Emission Control
ECM	Electronic Counter Measures
EoI	Element of Interest
ESM	Electronic Support Measures
EW	Electronic Warfare
FDTD	Finite-Difference Time Domain
FEM	Finite Element Method
GO	Geometrical Optics
GTD	Geometrical Theory of Diffraction
IR	Infra Red
IRS	Infra Red Signature
IRST	Infra Red Search and Track
MDO	Multi-disciplinary Design Optimization
MoE	Measures of Effectiveness
MoM	Method of Moments
MoP	Measures of Performance
OR	Operations Research
PO	Physical Optics
PTD	Physical Theory of Diffraction
RF	Radio Frequent
RCS	Radar Cross Section
TSE	Trade Space Exploration
MoE	Measures of Effectiveness
MoP	Measures of Performance
OR	Operations Research

PO	Physical Optics
PTD	Physical Theory of Diffraction
RADAR	Radio Detection and Ranging
RF	Radio Frequent
RCS	Radar Cross Section
TSE	Trade Space Exploration

Terminology

An **aircraft concept** is an idea of an aircraft design, represented by basic models.

A **model** is a description of something. It is never correct, but can still be useful in simulations.

A **simulation** is when models are used together to get an answer to a question.

A **sensor** is a device that is capable of detecting energy.

A **radar** is a sensor that transmits electromagnetic energy and uses signal that has been reflected against something to detect objects.

An **active** sensor transmits energy, a **passive** sensor does not.

How much an object stands out compared to the background is called the **signature**.

An **active signature** is associated with a transmission of energy, e.g. when using a radar, communication through radio or radiation of heat energy.

A **passive signature** describes how incoming energy is reflected, but does not spontaneously radiate itself.

When energy travels from one position to another it **propagates**.

Red forces are hostile, **blue** forces are friendly.

Acknowledgments

The importance of acknowledgments in dissertations is analyzed in [1]: "Here the writer can present a self disentangled from the complex conventions of powerful academic discourse types and reveal a real individual coping with the perplexing demands of research and overcoming a myriad of contingent issues which conspire to overwhelm the project."

OK, now disentangling. Many people have been involved in supporting me through my PhD studies. Without all of you, no papers, no dissertation, no graduation. Period. Ett fyrfaldigt leve [1] för:

Main supervisor: Peter M; co-supervisors: Torleif, Peter B, Christopher and Kristian; adjunct co-supervisors: Tina, Björn, Kent, Ronny (officially, there is of course no such thing as an adjunct co-supervisor). We made it all the way here!

Co-authors: Kent, Christina and Martin R, we got published without being established, well-known authors!

Project startup support: Knut and Stefan, you recognized that I was about to do something a bit strange, but probably useful, and helped me over the initial obstacles.

Professional environment at Saab: All my colleagues have provided so much encouragement and answered all kinds of odd questions.

Professional environment at the Swedish Defence University: I have been given a massive knowledge expansion module about all things related to military operations.

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Effective, yet gentle language proofing: Steve, the ideas come across so much better without unnecessary mistakes. Thank you.

Friendship close support: Vibeke, Lovisa, Anna and Katarina, who have always been there for me.

Parental close support: Siw and Lennart, you never asked about the date.

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[1]Hip, hip, horray with quadruple cheers, instead of the Anglo-Saxon three.

Very significant other: Daniel, no words will suffice.

At times when things seem overwhelming and out of proportion, the words of MIT professor Samuel Mason [2], can be a comforting: "However, if you press me for honest advice, dear reader, I must say that if I were you, I would perhaps glance at the pictures, (which all look the same, anyhow), and then go on to better things. John Truxal has his filler, I have a publication, and, after all, in a hundred years we will all be as bald as billiard balls and the earth will be covered with paper to a depth of forty-two feet"

Carina

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CHAPTER 1

Introduction

Fighter aircraft designs are the result of compromise between several requirements, some of which can be contradictory. Some examples of desired properties are good maneuverability, long operational range and time, the ability to carry heavy payloads, powerful sensing capabilities and a low signature in order to avoid detection. The first step towards a new aircraft is the conceptual design phase, where the requirements of the aircraft are met with possible solutions, aircraft concept designs, which are then tested in order to identify viable solutions. Testing can be performed in tactical simulations, where models representing the properties of the aircraft concepts are used in relevant scenarios to determine the ability to perform a task or a mission. This dissertation addresses the modeling of the sensor functions, which describe the aircraft's ability to detect objects, and signatures, which influence the aircraft's vulnerability to detection by other sensors.

Data from the sensors on board an aircraft is a key component in establishing and maintaining situational awareness [3–5]. This is particularly important for fighter aircraft because it affects their survivability [6]. Maintaining situational awareness, allows the aircraft's actions to be adapted to the current situation. However, sensors increase an aircraft's signature [7], which can be exploited by potential enemies, to improve their situational awareness. Several means can be used to adapt the aircraft's signature in order to reduce the risk of detection. The shape of the aircraft can be adjusted and special materials can be used. Furthermore, signature contributions from the sensors can be minimized, using special techniques. The installation of sensors also influences the aircraft due to their volume, mass and their power and cooling requirements.

The aircraft's flight performance, for instance its ability to turn and accelerate, and its maximum velocity, can influence the outcome of a tactical situation. If the sensor installations and signature reduction measures affect such things as the size, shape and mass of the aircraft, they will influence its flight performance.

Consequently, there is a need to achieve a balance between, on one hand, the benefits of the sensors and signature adaptions and, on the other, the costs in terms of the effect on flight performance, and vice versa.

Literature on fundamental aircraft design focuses, not unexpectedly, on aircraft design and performance. The susceptibility to threats is considered in [8, 9] and guidelines are given on how to design and reduce signatures, focusing particularly on those that relate to radar and infra-red sensor systems. The sensors are regarded as a part of the avionics system in [8] and, in the initial design stages, the avionics are allocated a certain mass and volume in the aircraft. The sizing and trade studies focus on aircraft performance, but the possibility of multi-disciplinary optimization is discussed.

There are potential benefits in designing an aircraft and its sensor systems concurrently. If the aircraft's flight performance, its signatures and capabilities, in terms of sensor systems and weapons, can be balanced, it may be possible to increase the utility of the aircraft in tactical situations. To design aircraft this way requires design methodologies that are capable of handling multidisciplinary design properties. By designing sensor and signature models that work together with models of the aircraft, and using Design Space Exploration, DSE, [10–12] the resulting aircraft concepts will have sensor and signature properties that are connected to the properties of the aircraft. These properties are valuable from an evaluation perspective, where tactical simulations [13] are used to determine which aircraft concepts are capable of performing certain tasks in a given scenario. The models could be used in a Multidisciplinary Design Optimization, MDO, [14] context and when performing Trade Space Exploration, TSE, [15, 16] to enable interactive presentation of the results to support the decision making process.

There are several aspects to consider when designing sensor and signature models intended for use in the context of aircraft concept design. First, as described above, the models should fit the design process and be properly connected to adjacent models. They also need to be capable of delivering results that are relevant to the tactical simulations and subsequent evaluation. Different phases in the aircraft design process can require models with different levels of detail, i.e. models that are suitable for their purpose. For example, the use of elaborate models designed for sensor development purposes may not be suitable for the evaluation of the sensor function in a scenario, c.f. [17] "All models are wrong some are useful."

In this dissertation, models of sensors and signatures are proposed, investigated and discussed with the aim of providing a means to include them in aircraft conceptual design. The ability of the models to support the evaluation of aircraft concept designs and to balance utility against the risks posed by sensor installations, is of particular interest.

1.1   Research Idea and Aims

Paper I, which concerns the evaluation of technology in a military context, became the starting point for the development of ideas on how to improve the aircraft conceptual design process. Because the installation of a sensor can affect both the

signature and flight performance of an aircraft, it seems logical that a sensor model, which encompasses all these properties, will be valuable in evaluations using tactical simulations. Ideally, groups of engineers, capable of carrying out the modeling, should interact and design the models together, from the perspective of their respective fields of expertise. For example, if a larger sensor system provides an improved sensor function, but also affects flight performance, this effect should be reflected in the models used in the tactical simulation, in order to obtain consistent results.

Limited relevant research has been found on the subject, which is expected because of the confidential nature of military sensors and signatures. Nevertheless, there are examples such as [18, 19], where sensors and signatures are included in the analysis. It is possible to publish if the focus is on methodologies and general results. The research presented in this dissertation exists in the space between aircraft design, operations research, and sensors and signatures, see Fig. 1.1. It primarily links the aircraft's sensor functions and signature levels with the simulations, and the subsequent evaluation, which belongs in the operations research domain.
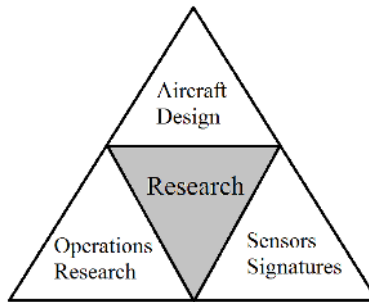
Figure 1.1: Research area surrounded by adjacent domains.

It is important to clarify that the value of the research lies in the connection it provides between the three fields. It is intended to improve aspects of the conceptual design process in several ways:

1. Improve the ability to balance several combinations of properties related to the function of the aircraft, e.g. signature levels, sensor performance and flight performance.
2. Provide a connection between the effects of sensor installations and an aircraft's signature levels, with the intention of improving the quality of results from tactical simulations.
3. Consider the level of detail required in the model to suit the simulation to be performed.
4. Include the ability to present and interpret the results as part of the methodology.

The methodologies developed and reported in Papers II through V concern different aspects of conceptual design and can be adapted to other situations with

similar design issues. The models and methodologies are intended for use in aircraft conceptual development to support trade-offs between different properties of the aircraft and when performing tactical simulations. Table 1.1 shows the different types of sensors and signatures considered in the appended papers. For terminology, see the list of abbreviations or Chapter 4.

Table 1.1: Types of sensors and signatures in the appended papers

	Sensor		Signature	
Paper	Active	Passive	Active	Passive
Paper II	Radar	IRST	IRS	RCS
Paper III	Radar	RF receiver	RF signal	RCS
Paper IV	Radar			RCS
Paper V		RF receiver	RF signal	

1.2 Delimitations

The research focuses on, but is not limited to radio-frequency sensors and signatures.

The methodologies developed can be adapted and applied to other sensor technologies, where the questions are analogous and the data is in a similar form.

Signature management is primarily of interest in a military context, while the sensor function is also of interest in a civilian context.

The evaluation of results is also a consideration, but the results presented in the papers are only intended as examples to show what kind of results the methodology can produce. No tactical simulations have been carried out in a complete DSE context, but some initial testing has been performed. To determine how different designs should actually be ranked, requires tactical simulations.

Electronic Warfare will only be considered in passing, due to the security classification of the subject.

1.3 Outline

The contents are organized as follows: As background and theory, basic aircraft concept design from a sensor and signature perspective is described in Chapter 2, and the evaluation is considered in Chapter 3. The sensors and signatures, and aspects of their electromagnetic modeling, are introduced in Chapter 4. Results relating to the interaction between the sensors and the conceptual design are presented in Chapter 5. The link to the utility of the aircraft and the evaluation are in Chapter 6 and the sensor system perspective is considered in Chapter 7. The discussion and conclusions can be found in Chapter 8 and an outlook in Chapter 9. A list and a brief summary of the five appended papers can be found in Chapter 10.

Background

A Sensor and Signature Perspective on Aircraft Conceptual Design

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The first step towards the modeling of sensors and signatures is taken by briefly considering the aircraft conceptual design phase, which is where the models are intended for use. The design phase is discussed here from a sensor and signature perspective. In literature, e.g. [8, 9], this development phase is described from an aircraft perspective where the sensors and signature reductions are considered as fixed objects with certain properties. If the sensor and signature models were dynamically connected to the aircraft models new possibilities may emerge. The concept could then be evaluated with a link between a sensor and the aircraft's performance. This would enable trade-offs to be made between such things as the sensor function and the signatures it adds. Basic parameter sets that connect sensor and signature models to the aircraft are suggested at the end of the chapter; the sensor and signature models' interaction with the simulation environment are dealt with in Chapter 3.

2.1 A Description of the Design Process

Three phases of aircraft design are commonly identified e.g. in [8, 9]; they are Conceptual Design, Preliminary Design and Detail Design.

The conceptual design can be seen as a phase where the set of initial requirements are transformed into concepts through design iterations. These concepts encompass the general geometry of the aircraft, the technologies to be used, what trade-offs will be made, and how they relate to the missions driving the design. The aircraft configuration is chosen and the physical properties of the aircraft, e.g. mass, volume, length, thrust, are defined.

Because the methodologies proposed in the appended papers concern the conceptual design, the preliminary and detail design phases will not be discussed here. If new methods are used in the conceptual design, the effects will be carried forward into the subsequent design phases.

2.2   Conceptual Design Incorporating Sensors and Signatures

Descriptions of the conceptual design process, as in for example [8, 9], are based on a set of design requirements having been established. Before discussing sensor and signature modeling from a conceptual design perspective, consideration is given to the role of the models in the requirements extraction process, see Fig. 2.1.

Determining the needs, operational requirements and functional requirements is usually considered to be part of the Operations Research, OR, domain, see Chapter 3. The operational and functional requirements are the basis for extracting the performance and technical requirements, which in turn influence the conceptual designs.
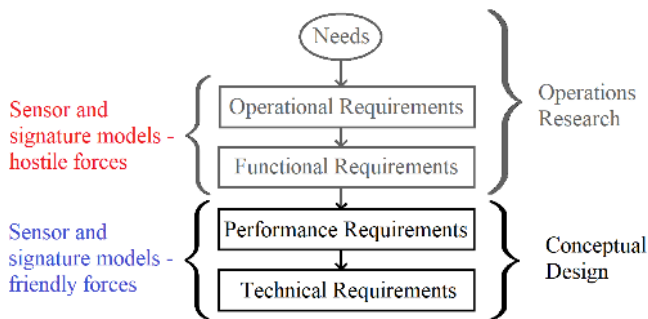

Figure 2.1: Requirements extraction.

The needs an aircraft must meet are usually identified from a description of a mission and point performance. In an ideal design process, the next step is to determine the operational requirements based on scenarios and information about the needs. At this stage, sensor and signature models representing hostile systems are useful. Different tactical situations can be used to derive operational requirements, such as a target should be destroyed with a certain probability, and within a particular time frame. The functional requirements can then be determined. These include factors such as adequate operating range and the ability to carry munitions sufficiently close to a target.

This is where the conceptual design phase begins. It is a process, usually iterative, which encompasses activities where the functional requirements are used to obtain performance requirements and technical requirements. The latter are the basis for the design specifications for the finished aircraft.

The performance requirements describe the function of the aircraft and its systems. Typically, they include maneuverability, maximum range, maximum

payload, signature levels and sensor capabilities. In terms of weapons delivery, they can include having a signature that prevents or delays detection in order to enable the weapons delivery. The sensor function must be able to detect and identify the target, and weapon systems may also need sensor support after release. In all these activities, sensor and signature models representing both the red and blue sides are useful. Finally, the technical requirements related to the design of the aircraft concept can be obtained from the performance requirements. When models of the aircraft and its subsystems have been generated, they can be used in simulations to determine whether the operational requirements are fulfilled.

Figure 2.2 shows one way of describing the conceptual design process. The focus is primarily on the aircraft's performance, while the sensors and signatures are considered as part of the subsystems, which come towards the end of the process; see the "Analysis" block bottom center in Fig. 2.2.
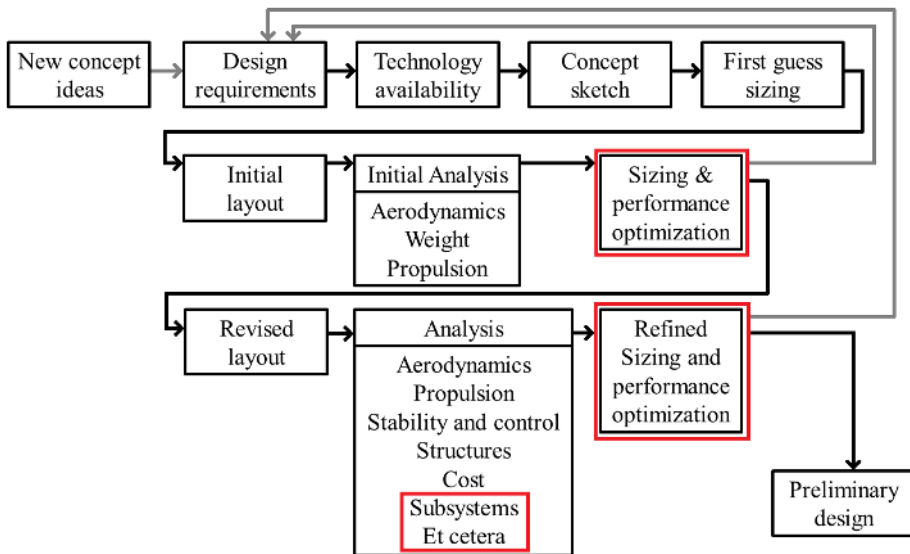
Figure 2.2: The traditional design process, as described in [8]. The red rectangles represent steps where sensor and signature considerations can be incorporated.

A more complete aircraft model is obtained by introducing models that dynamically connect the sensors and signatures to the aircraft in terms of both their function and their impact on the aircraft, and the aircraft's flight performance. The sensor and signature models can be incorporated in the conceptual design stages that involve sizing and performance optimization; see the two red rectangles to the right in Fig. 2.2. During the conceptual design, evaluations in tactical situations, c.f. Fig. 3.1, are used to determine whether the design fulfills the functional requirements,s or whether it has to be adjusted for another iteration. An aircraft model that incorporates the effects of sensor functions and signature levels, thus providing a more complete description of the aircraft can contribute to a more balanced design through more accurate results from tactical evaluations.

2.3   Exploring Different Aircraft Concepts

The traditional design process shown in Fig. 2.2 is realized in a point-based fashion, i.e. one or more aircraft concepts are taken through the iterative process and refined. Incorporating sensor and signature models into the trade studies described in [8, 9], is simply an expansion of an existing process. Instead of regarding the equipment as a fixed mass that occupies a certain volume, it is a flexible part of the aircraft design. By adopting such an approach to the aircraft, the installation of a sensor or application of signature reduction measures could be incorporated into trade studies. The iterations in the point-based context, see Fig. 2.3a, will cause the design point to shift from its original position, creating a small design space. Three dimensions are used in the example, but in practice, the number of dimensions are too many to illustrate.

(a) Point-based design, one design point and its environment

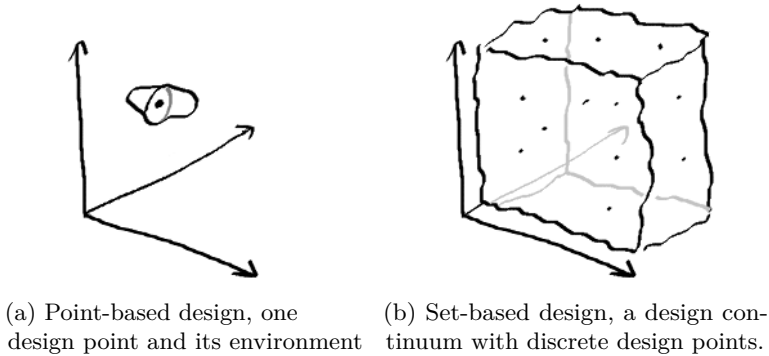(b) Set-based design, a design continuum with discrete design points.

Figure 2.3: Design paradigms illustrated in three dimensions.

Set-based design is another approach to the conceptual design process, in which the concepts are generated and tested in parallel processes. As illustrated in Fig. 2.3b, the design space is a considerably larger continuum with variations in the numerous design dimensions. It contains many points where the designs are realized. Set-based approaches have been proposed for use in the procurement [20] and design of aircraft [21], and the design of aircraft taking RCS into consideration [22]. The sensor and signature models to be discussed can be used in either design scheme. The models' parameters are the same, but their implementation is adjusted to suit the needs. To be useful in DSE, implementation should support variations in all the necessary parameter values and include dependencies, where relevant. To maintain organized procedures, this part can be considered as a Design of Experiments, DOE, [23, 24]. The models must interact properly and contain the information needed to carry out the design work. If there is a goal function for the design, performing an MDO is an option. In the work related to this dissertation, the models have not been applied in DSE/MDO contexts.

2.4   Sensor and Signature Models that Support Conceptual Design

The modeling of sensors and signatures can be divided into two parts. First, the connection to the aircraft, and second, a description of the sensing function and signature reduction useful in a tactical evaluation environment. Here, the focus is on the parameters that connect to the aircraft. The following basic parameters are proposed for a sensor model:

– Mass [kg]
– Volume [m^3]
– Power consumption(time) [W]
– Cooling needs(time) [W]
– Signature(θ, ϕ, f) [m^2] (Shared with the tactical simulation models, Section 3.2)
– Maintenance/availability
– Cost

The mass and volume parameters represent the sensor system hardware. The sensor systems' power and cooling needs represent only a fraction of the systems' mass and volume in the aircraft and that mass is not accounted for in this model. Similar bookkeeping for the signature requires more attention. The sensors can increase the signature, and this is accounted for in the corresponding models described in Chapter 3. The installation of sensors can also affect other features of the aircraft in such a way that the signature increases. This effect is also included in the signature parameter. Returning to the avionics perspective given in [8, 9], the sensor model can be seen as an expansion of the process, and not a disruptive change. The sensor may affect the maintenance needs, and thus the availability of the aircraft, which is important from an operational point of view. Finally, the equipment will have a cost, which is important when considering the cost estimate for the entire aircraft.

For signature reduction measures, the following basic parameters are proposed:

– Mass [kg]
– Volume [m^3]
– Signature(θ, ϕ, f) [m^2] (Shared with the models for tactical simulation, Section 3.2)
– Maintenance/availability
– Cost

The mass and volume represent the signature reduction materials. The signature parameter is a function of angles θ, ϕ and frequency, f, which represent the levels after the application of signature reduction measures. Here, these measures are considered to be passive with no requirements for power or cooling. The signature is of particular interest because it depends largely on the shape of the aircraft, which also influences the flight performance. In a tactical situation, this implies a trade-off between the ability to remain undetected and the maneuverability. Adding sensors will also influence the signature and most likely the shape of the aircraft, suggesting

a similar, preferably simultaneous, trade-off. The maintenance/availability and cost parameters have an analogous connection with the sensor model.

The proposed parameter set is limited, but could meet the needs in a conceptual design phase. It connects sensors and signature reduction measures to the aircraft, thus enabling study of subsequent changes in flight performance.

The values, or estimates, of the parameters that describe sensors and signatures are ideally based on knowledge of current technologies and estimated performance of technologies under development. Depending on suitability, the parameters can be expressed in different forms, as functions of different inputs. In Paper IV, for instance, the area of the antenna was used as input for the sensor and signature models.

A key point is adapting the complexity of the model to the simulation to be performed. The model must describe the properties accurately without using an unnecessarily high degree of detail, which may result in a model requiring too many resources in terms of computational effort and time. Therefore, the models must be tested to ensure that they behave as expected, and deliver accurate results that work with other models in the simulation. The models must also work within any time and computational constraints.

In this chapter, the sensor and signature reduction models were considered as black boxes, connected to the aircraft through a few parameters. In the next chapter, the black box approach is also applied, but there, parameters related to the sensor performance and signature levels used in the scenario evaluations will be discussed.

Operations Research and Tactical Simulations

It was assumed that the needs, operational and functional requirements that initiated the iterative aircraft concept design process in the previous chapter were generated by OR. Here, the OR activities will be discussed in more detail and the use of tactical simulations will be introduced. First, OR contributes to the conceptual design process by providing the initial requirements. Second, OR is a part of the process as the concepts are evaluated in tactical simulations. Now, the sensor and signature models also contain parameters that are useful in a tactical simulation context. This aspect of the models will be introduced in this chapter. The simulation results are intended to support decision making in the design process, which makes the ability to present and interpret the results important.

3.1   Operations Research

Operations Research (OR) supports decision making by using analytical methods to investigate a situation. As a field, OR gained momentum during the Second World War, [25, 26], where it was used to optimize the use of resources and reduce losses. Today, in addition to military applications [13], it is used in a wide range of areas e.g. urban planning, organization of manufacturing, logistics and company management. The OR process involves a number of activities. The situation at hand is considered and a problem is formulated. A scenario is identified, the necessary properties of its entities are determined, and a Concept of Operations, CONOPS, is established. The CONOPS states, among other things, how the entities are allowed to act. Scenario simulations are then conducted, the results of which can be evaluated enabling a solution to be presented.

The evaluation process of one iteration in a point-based conceptual design process is shown in Fig. 3.1. Sensor and signature models related to the hostile

forces are part of the scenario; the corresponding models for own forces are part of the aircraft concept. The CONOPS is designed to match the properties of Concept n so that it can perform at its best in the tactical simulation. The results are then evaluated, yielding either a viable solution, or the requirement for another iteration.
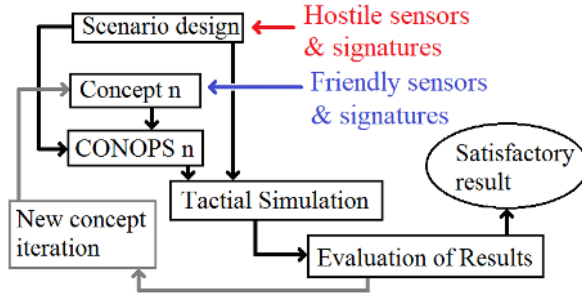

Figure 3.1: Evaluation of an aircraft concept in a scenario

To extract design requirements, it is necessary to have sufficient knowledge of the properties of the environment and situations in which an aircraft operates. Here, the military application of OR is considered. Consequently, the environment is hostile and most likely more unknown than in civilian applications.

3.1.1   Scenarios

The scenario can be seen as the game board, or a model of the reality, where the simulation will take place. It can include information about geography, the time of day and year, weather conditions, and hostile forces and their capabilities, behavior and initial positions. The components in a scenario are models of the surroundings and enemy forces, and they have inherent limitations that influence how the results from the simulations can be interpreted and used. In a sense, the scenarios are also a design space, since their properties, e.g. capabilities and positions of hostile systems, weather conditions and time, are parameters that can be varied. Consequently, scenario design influences the result of the simulation.

Scenarios can also be designed and used to test hypotheses about future developments to obtain relevant estimated requirements. In [27], the automatic generation of scenarios for the future is discussed. This could support testing how changes in technical capabilities and assumptions about doctrine, strategy and tactics, influence the result of the analysis. The process of assessing future technological needs is described in [28]; the acquisition of relevant data and assessment of future concepts needs are also discussed.

Scenarios also are frequently used for training purposes. These scenarios are designed to support learning and, consequently, are not interchangeable with scenarios designed to evaluate technology. There is a need to generate new scenarios as training progresses and this makes automating scenario design of interest, [29–31].

These techniques could be useful in a tactical simulation context, if there is a requirement to generate a large number of scenarios to complete the simulations.

3.1.2 Concept of Operations

With the scenario in place, the next step is to consider how to use the available resources and personnel. Here, the Concept of Operations, CONOPS, is considered to be a description of how to reach the goal in the scenario, what resources are available and how they should be used, and what they should do. The enemy CONOPS is considered as a part of the scenario. There are several definitions of CONOPS, and the one used depends on the organization and the task; [32] describes the NATO version. In a military context, the CONOPS will indirectly contain, elements of doctrine, strategy and rules of engagement that are relevant to the mission.

3.1.3 Tactical Simulations

The OR process relies on simulations, in which models of all entities, their behavior and the environment are used to obtain results, which are then evaluated. Tactical simulations are often carried out in a computer environment. There are many options, from frameworks that support the implementation of simulation environments to software dedicated to a particular type of simulation.

Simulations can be deterministic, with no random variables. This type of simulation is valuable when testing the behavior of a scenario to ensure that it works as expected. The other option is with stochastic variables, which can be useful when an element of uncertainty is desired. Circumstances will dictate which type of simulation, or combination [33] of types, is most suitable. Another dimension of the simulation is whether it is continuous or discrete in terms of time. This is merely a question of what drives the actions in the scenario although, in a sense, all simulations are discrete, since the actions are realized at discrete points in time. Continuous simulations are carried out by advancing a relatively small step in time of a chosen length. In a Discrete-Event Simulation (DES), the events of interest are considered, [34]. It is also possible to perform simulations that are a combination of both types, see [35, 36].

In the scenario, the entities, e.g. aircraft concepts, can operate as agents with rules that control their behavior, i.e. agent-based modeling. The behavior models can be a result of the CONOPS design, or designed purely based on the technology of the entity. Because the behavior of an aircraft influences the signature that is shown to a sensor, this could make a difference between being detected or undetected.

3.1.4   Comments on Evaluating Results from Tactical Simulations

Criteria that define whether an outcome is successful or not are useful when evaluating results from tactical simulations. Two criteria often used are Measures of Effectiveness (MoE) and Measures of Performance (MoP); see [6]. The MoE relates to the results for an entire mission as in Paper II, where the number of aircraft needed was considered, or to the performance of specific equipment. The MoP relates to the performance of equipment, which can be signature levels and sensor capabilities. Examples of formulations of MoE in a naval context can be found in [37] and examples of performance of an Electronic Support Measures system are in [38].

Using criteria to evaluate simulation results makes it possible to discard concept designs that do not perform as desired. To support decision makers, the data relating to the remaining concepts should be presented in such a way that makes it possible to interpret the results and make a design choice. For results pertaining to set-based approaches, suitable methods are needed to handle the vast amounts of data that will be generated.

3.2   Sensor and Signature Models

Connecting sensor functions, sensor signatures and signature levels to the aircraft, as in Chapter 2 addresses only some of the prerequisites for performing simulations. The sensors generate data that can be turned into information, which then contributes to situational awareness. Signature reduction measures are aimed at denying, or at least delaying, the ability of hostile forces to update their situational awareness. and consequently their ability to perform an effective engagement.

The models should describe the parameters that concern the sensors' capabilities the consequences of the signatures that they add, and the benefits of signature reduction. These properties are useful in the tactical simulation. On the other hand, the models should, not contain any unnecessary parameters that make the models difficult to use or make the results difficult to interpret.

The sensor and signature properties generally depend on frequency (f) and the geometry between a sensor and the observed object as an angle (θ, ϕ). It is assumed that the simulation software will handle both the local coordinate systems, in which the sensor and signatures properties are expressed, and the global coordinate system of the scenario.

A basic model of an energy emitting, **active sensor**, e.g. radar, could contain the following parameters:

– $\Omega(\theta, \phi)$ Search sector [sr]
– t_s Search time [s]
– $R_{det}(\sigma_{tgt})$ Detection range of a target with signature σ_{tgt} [m]
– $\sigma(\theta, \phi, f)$ Signature [m^2]
– Active signature, see below

The first four parameters are linked to the radar equation; see Chapter 4, Eq. 4.1. The search sector and search time can be defined by tactical needs, which then affect the detection range. When a radar is used with no external disturbances, such as EW or land and sea clutter, the signature of the target, σ_{tgt}, and the attenuation of the transmitted energy due to the atmosphere, are the external factors that influence the detection range. When occurring, the transmissions constitute an **active signature**:

– $P_d(\theta, \phi, f, R)$ Power density [W/m^2]

where R is the distance from the source. Both active and passive sensors have a **passive signature**:

– $\sigma(\theta, \phi, f)$ [m^2] Signature

A **passive sensor** detects energy/signal emissions:

– $\Omega(\theta, \phi, f)$ In a search sector [sr]
– $R_{det}(P_d)$ Detection range for a given power density P_d at the sensor [m]
– $\sigma(\theta, \phi, f)$ Signature [m^2]

The implementation of the models is not discussed here, because that depends on the question that the model will be designed to answer. Even which ones of the parameters that are considered output or input is not self-evident. The signature of an antenna system, can be the result of antenna size requirements on the antenna size, but it could also be a result of requirements that specify how the antenna installation should be performed. The search sector and search time influence the detection range, or they can be a the result of a specific detection range requirement. If the models are implemented using a programming technique that avoids having to choose which parameters are in- and output, there is no need to restructure the mathematical expressions.

3.3   Sensor and Signature Models from a Conceptual Design Perspective

To be suitable in aircraft conceptual design, from a conceptual design perspective, the models must perform fast enough to allow the simulations to be completed within the timeframe stipulated by the design process. They should be well-documented and adaptable to the needs of different simulations.

The introduction of parameters that describe the sensor and signature functions connects the models, i.e. the black boxes to the tactical simulations in two ways. First, through the aircraft and consequently its flight performance and second, through the sensor function and signature levels. The parameters are few and simple, but they cover the basic properties of the sensors, their signatures, and general signature reduction measures. The next chapter describes the detection process, which is the link between the sensors and the signatures.

Sensors and Signatures from an Electromagnetic Perspective

In the two previous chapters, the sensor and signature models were considered as black boxes. This chapter describes the background to the sensing and communications functions from an electromagnetic perspective, i.e. the inside of the box. In this dissertation, the sensors, signatures and wave propagation are considered parts of a detection, or communications, chain. Models of sensors, signatures and wave propagation can be combined into a model that describes the ability to detect objects, and communicate or detect signals. In this chapter, the parts of the detection and communications chains will be discussed with the aim of supporting the design of meta-models to make evaluation with scenarios more efficient. A meta-model, [39], or surrogate model, is a model that describes a phenomenon in a such way allows use of the model in a simulation, without having to deal with an abundance of details.

A meta-model can be created by first selecting an existing intricate model or existing data, then determining which parameters are most influential. The input- and output parameters of the model are then selected to match the needs of the design process and to properly describe the phenomenon. Finally, the meta-model can be defined and implemented.

Meta-models' abilities to capture the essential behavior of a system, make them suitable for conceptual design, where minute equipment details are not desired because either, a) they are not within the scope of current activities or b) the equipment does not exist and the ongoing activity is testing of higher level functions.

Because sensors, signatures and wave propagation are variously related to RF systems, their electromagnetic properties must be determined in order to conduct modeling. A number of computational methods are available, but not all are suitable for use in a conceptual design phase. The reasons for this will be discussed, and examples of suitable methods will be given.

4.1   The Function of a Sensor System

In a military context, the capability to acquire situational awareness (SA) and deny it to the enemy, is crucial to the successful completion of a mission. Whether a mission is performed by one or more aircraft, the ability to sense the surroundings is required even if there is prior knowledge of the situation. This capability ties in with the OODA-loop (Observe, Orient, Decide, Act), which is attributed to John Boyd, [40]. The OODA-loop can be described as a model for decision making. In the "Observe" phase, the situation is considered on the basis of available information and interaction with the environment. Then, the situation is analyzed in the "Orient" phase, that is followed by a hypothesis on how to act in the "Decide" phase. Finally, the "Act" phase is the test of the formulated hypothesis. The sensor system provides SA, which is part of the observation necessary for the subsequent steps in the loop. The ability to stay undetected, which can be achieved through signature reductions, can disrupt the enemy's OODA-loop. The sensors and signatures are thus part of the balance between friendly and hostile OODA-loops. For sensing remote objects, a number of technologies are available, which make use of energy that radiates from, or reflects off, those objects. The discussion here will address the electromagnetic spectrum, focusing primarily on radio- and microwaves, RF, and some aspects of infrared radiation, IR.

The trend today is moving towards system architectures where the sensor systems and their apertures, regardless of the technology used, can be considered as one unit that performs various functions. Such systems are considered to be "cognitive" and have the ability to reconfigure themselves and adapt to the current situation, [38, 41]. This implies that one antenna can be used as an active radar, for Electronic Warfare (EW), passive sensing of signals, and for communications. EW includes the use of RF transmissions to reduce the quality of the enemy's SA by disturbing its sensors, degrading sensor performance and/or capacity and introducing false data into the systems. The subject of EW and the effects it has on enemy sensors is not discussed here due to the security classiftcation of the subject, but [42–45] is recommended as introductory literature.

Active, energy-transmitting systems, represented by RF communications equipment and radar, transmit RF energy and interpret the returning signal to detect objects. The transmissions of active systems can be detected by passive, corresponding sensors. An Infrared Search and Track (IRST) sensor is a passive sensor, which detects radiation that objects emit due to their temperature.

The models of the sensors, signatures, and their associated wave propagation, must be designed so that they may be suitably combined. This includes having matching input- and output parameters that also cover the proper frequency intervals.

4.1.1   Sensor Models

Before discussing the sensors, their output is briefly considered. There are many definitions of data and information, but here data will be equal to one or a few sensor observations. The data could be the sensor's view of the location of, velocity of, or direction to an object or signal source. Here, information is generated from sensor data that has been refined, or fused into information. Both data and information can trigger events in scenarios.

Models used in sensor development generally contain many parameters that are not of interest in aircraft concept development. The level of detail in the models could also mean that they require too much computational power to be useful in a tactical simulation. Nevertheless, they are an excellent foundation for creating meta-models of the sensing functions.

The sensor model can be divided into several parts: First, the internal parameters e.g. internal losses and required Signal-to-Noise Ratio (SNR) which represent the signal processing. Second, parameters that concern antenna aperture selection, which have an impact on such things as antenna pattern, gain, output power and the signature. The parameters connecting the sensor to the aircraft are described in Chapter 2.4.
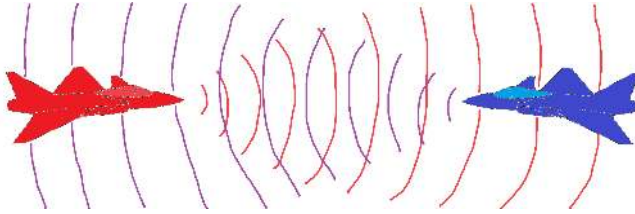

Figure 4.1: The red aircraft's sensor illuminates the blue aircraft, which returns part of the signal due to its radar signature, i.e. its the Radar Cross Section(RCS). The red aircraft's sensor then detects the return signal from the blue aircraft is.

For an active radar, for example, see Fig. 4.1, the range and direction to the object, as well as its velocity are examples of basic measurement parameters. The velocity and direction data is a result of system choices and signal processing. Here, the detection range is the first concern, and the ability to determine the direction and velocity are assumed to be the system parameters given for a particular radar system.

Assuming that the radar searches through an angular sector, in terms of detection range, the radar equation [46] can be expressed as:

$$R_{det,RR} = \sqrt[4]{\frac{P_{avg}\tau_d G_{tx} G_{rx}\sigma\lambda^2}{(4\pi)^3\,\mathrm{SNR}\,L_{sys}\,\mathrm{NF}\,k_b\,T_0}}\,, \tag{4.1}$$

where $R_{det,RR}$ is the detection range of the radar, P_{avg} is the average transmitted power, τ_d the dwell time, G_{tx} the gain in transmit mode, G_{rx} the gain in receive mode, σ is the RCS of the observed object, λ is the wavelength, SNR is the Signal-to-Noise Ratio, L_{sys} are the system losses, NF the noise figure, $k_b = 1.38 \cdot 10^{-23}$

J/K (Boltzmann's constant) and T_0 is the system temperature. Note that, from a radar perspective, the object's RCS is the only unknown factor.

The radar equation, Eq. 4.1, can be re-written in a form where the radar's properties are combined into one factor, $K_{det,RR}$, separate from the observed object's RCS, σ:

$$R_{det,RR} = K_{det,RR} \sqrt[4]{\sigma} \,. \tag{4.2}$$

A description of the sensing function as per Eq. 4.2, can be used to investigate the general effects of variations in sensor capability and signature levels in a general sense. By assuming realistic intervals for the factors $K_{det,RR}$ and σ, and performing a tactical simulation, information about the effects on sensor performance and signature levels can be obtained.
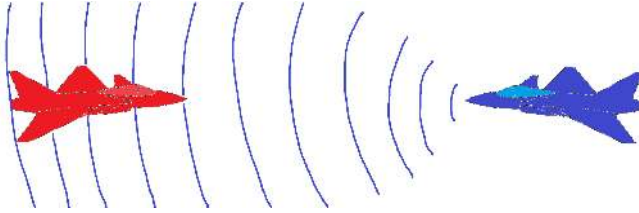

Figure 4.2: The blue aircraft emits RF energy which is detected by the red aircraft.

For a passive signal detection system, for example, see Fig. 4.2 the maximum detection range can be described as [46]:

$$R_{det,signal} = \sqrt{\frac{P_{tx}G_{tx}G_{rx}\lambda^2}{(4\pi)^2 \, \text{SNR} \, \text{NF} \, k_b \, T_0 \, B}} \,. \tag{4.3}$$

where $R_{det,signal}$ is the detection range, P_{tx} the transmitted power, G_{tx} the gain of the transmitting system, G_{rx} the gain of the receiving system, λ is the wavelength, SNR is the Signal-to-Noise Ratio, NF the noise figure, $k_b = 1.38 \cdot 10^{-23}$ J/K (Boltzmann's constant) and T_0 is the system temperature, and B is the bandwidth. The transmitted power, P_{tx}, and the gain, G_{tx}, are the two factors that are not controlled by the receiving sensor system.

The simplified model for 4.3 can be written as:

$$R_{det,signal} = K_{det,signal} \sqrt{P_{tx}G_{tx}} \,. \tag{4.4}$$

where $K_{det,signal}$ represents the receiving system parameters. Here, there are two unknowns P_{tx} and G_{tx}, which can be treated as one factor.

The energy of the radar propagates to the observed object, is reflected off it and returns back to the radar; see Figure 4.1. The reduction of the amplitude is thus proportional to $1/R^4$. In communications, or the detection of active transmissions, the signal only travels one way (see Figure 4.2) and the reduction of the amplitude is proportional to $1/R^2$, i.e. significantly lower for $R \gg 1$.

Having established basic detection ranges for RF systems, the radar signature is discussed in the next section.

4.1.2   Signature Models

The signature represents how an object contrasts with its surroundings. An object's signature allows sensors (both friendly and hostile) to detect it. Signatures can be passive, when the object reflects incoming energy, or they can be active, when the object itself radiates energy. The radar signature, RCS, [7], is an example of a passive signature. Two examples of active signatures are RF transmissions and IR radiation. Signature adaption entails aiming to mimick the background as much as possible. For an aircraft at high altitude this means that the RF signature, the RCS, [7] should generally be reduced becasue there is no background present in that situation. Reducing the IR signature is more complex, because the position of the sensor in relation to the aircraft and its environment is important and the radiation is difficult to suppress.

In the appended papers the focus is on RF signatures. The RCS is defined [7] as:

$$\sigma = \lim_{R \to \infty} 4\pi R^2 \frac{|\vec{E}_s|^2}{|\vec{E}_i|^2} \,. \tag{4.5}$$

where $\vec{E}_s$ is the scattered electical field and $\vec{E}_i$ is the incident electrical field, both in the far field. The signature is presented equivalent square meters, $[m^2]$ as a function of elevation and azimuth angles, frequency and polarization.

The fuselage and wings, engine exhausts and, of interest here, the sensor apertures all contribute to the RCS. The signature of a sensor aperture is determined by the size of the aperture, how it is integrated into the aircraft and by its internal structure. The design of the antenna elements will influence the RCS of an antenna, as will the optics of an IRST. When a radar or a communications system is being used, it emits RF energy, which can be detected, i.e. it has an active signature. One way to mitigate the risk of active transmissions is to apply Emission Control (EMCON) schemes, where transmissions are allowed depending on the phase of a mission, and the acceptable risk at that point. This means that aircraft may use an active sensor to transmit the data/information to another aircraft which can, for the time being, remain hidden.

When making a signature model, by either direct calculation or meta-modeling using existing data, there are a number of things to consider. The frequency bands, range of azimuth and elevation angles, and resolution should be sufficient for the simulation. The models can be created either using levels of known generic objects, or by performing electromagnetic calculations, perhaps with limited angular resolution or in a limited angular sector.

At the early stages of conceptual design, the model may mostly be concern with signature levels as a function of frequency, and more details can be added at later stages. Extremely simplified models that represent different signature levels in various angular sectors may be sufficient, see Fig. 4.3. These signature models that do not correspond to an actual aircraft design.

When installing sensors that increase the signature of an aircraft, signature models can be used to determine whether the data or information provided by the sensor justifies the added risk of the increased signature. Signature models are necessary when determining whether the data or information a sensor pro-
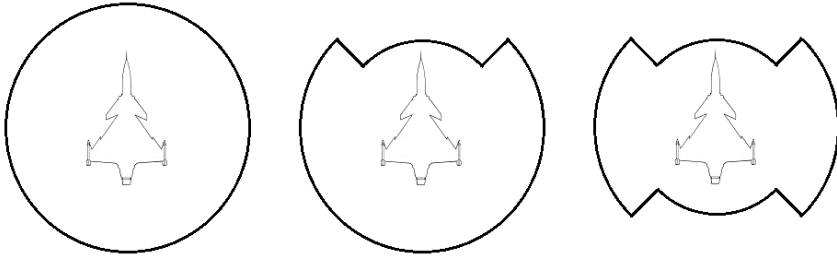
Figure 4.3: Left: a single-value model; middle: Pac-man; right: bow tie.

vides is sufficient to make the added signature acceptable. Another aspect is the evaluation of signature adaption measures. Reducing the signature decreases the risk of detection. The cost can be expressed in increased mass and maintenance requirements and consequently, reduced availability of the aircraft, as discussed in Chapter 2.4. Signature reduction can be useful from perspectives other than reducing the detection range. A reduced signature can increase the effectiveness of EW activities.

4.1.3   Propagation Models

Wave propagation can have a considerable impact on sensors' detection ranges and it must be taken into account. Because the associate calculations are not straightforward, the phenomenon is sometimes omitted, which can reduce the usefulness of the results. In radar applications, the radar horizon due to the curvature of the earth must be considered; this was done in Paper II. Radar range is usually limited by the radar horizon; however, there are over the horizon radars [47] that exploit physical phenomena to allow the waves to propagate beyond it.

The attenuation of RF propagation by particles and gases in the atmosphere is described by mathematical expressions in [48]. For practical purposes, the expressions should be used to create meta-models,rather than being used directly. The attenuation of transmitted signals also depends on frequency and aircraft altitudes. Other environmental parameters are also of importance, such as time of day, time of year, and climate zone.

Propagation models for IR [49] are complicated by the fact that each infinitesimal part of the atmosphere itself radiates IR. While detection ranges for IR sensors can be in the order of 100 km at high altitudes where the atmosphere's influence is very limited, the environment closer to the ground is significantly more challenging.

Propagation functions are very suitable for turning into meta-models, because the data is independent of the concept design choices. A practical sensor model of the wave propagation would use data related to the sensor and the target and indicate whether the sensor can detect the target. In an RF context, a simple model is that there is a specified attenuation per unit of distance, X dB/km; this model was used in Paper III through V.

If the detection range is long, the attenuation, if it is taken into consideration, can be significant enough to change the status of the detected object from "detected" to "undetected". This type of model generally assumes that the two aircraft are at the same altitude. If this is not the case, a more advanced model must be used to take into account changes in the atmosphere's composition at different altitudes.

4.2   Electromagnetic Computations

In order to make models describing the electromagnetic properties of sensors and signatures, methods that provide a solution to Maxwell's equations are useful. There are many different kinds of computational methods available, but not all of them are suitable in the conceptual design stage. The option are constrained by the level of detail required, available computational time and resources. In the following sections, computational methods will be discussed, and two options suitable for conceptual design will be described. The results of the calculations can be antenna patterns used to describe the sensor function, and the aircraft's RCS to describe the signature.

4.2.1   Electromagnetic Computational Methods

When considering different electromagnetic computational methods, factors such as accuracy of the result, time to perform the computation and computer resources are relevant. Solving Maxwell's equations, which is the core of the task, cannot be done analytically for the absolute majority of real electromagnetic problems. Instead, numerical techniques are applied. These can be divided into full-wave methods, and asymptotic, or high-frequency methods. The full-wave methods provide solutions for general structures by using the geometry to create a calculation mesh, which is used to solve the equations. Examples of these methods are the Finite Difference Time Domain (FDTD) [50], Finite Element Method (FEM), [51], and the Methods of Moments (MoM) [52].

For these methods to deliver accurate results the mesh needs to have a sufficiently high resolution, in terms of divisions per wavelength, and be able to resolve the geometry features properly. This means that it may be impossible to analyze a big (in terms of wavelength) object accurately, if the computer resources, in terms of both memory and execution time, are inadequate for the problem. Even an object that is sufficiently small in terms of wavelength may not work, if there are features that require a very high resolution of the mesh. An inadequate mesh can lead to an erroneous result, which is sometimes not obvious and takes experience to recognize. The generation of the mesh, unless expertly automated, is also a time-consuming activity. Mesh generation difficulties are shared with other branches of computation, including fluid dynamics and stress analysis, which are relevant for aircraft design. As computing power has become both more available and cheaper, full-wave methods have become more accessible, but still have limitations due to computational capacity.

Despite being excellent for analyzing electromagnetic problems, full-wave methods are not inherently a good fit in the conceptual design process, because of the demands they place on computational resources. Here, high-frequency approximation methods offer an interesting option. These methods provide approximate solutions to Maxwell's equations, and work on principles of the geometries of the analyzed objects being large, in terms of wavelength, which allows an alternate description of the scattering mechanisms. Furthermore, the requirements of the mesh are often less strict than for full-wave methods, which means that the generation of the mesh is less demanding compared to full-wave methods. Examples of these methods are the combination of Geometrical Optics (GO) with Geometrical Theory of Diffraction (GTD) [53] or Uniform Theory of Diffraction (UTD) [54]. The combination of GO and UTD was used in Paper III. For details on UTD and its history, an excellent overviewcan be found in [55] and many examples of basic applications can be found in [56]. Another approach is Physical Optics (PO), which was used in Paper IV. The PO results can be enhanced using Physical Theory of Diffraction (PTD) [57].

4.2.2   Geometrical Optics and Physical Optics with Diffraction Extensions

While GO and PO and their respective diffraction extensions are oth high-frequency methods, their characteristics differ. In GO and UTD, expressions that describe the fields are evaluated whereas in PO and PTD integration of expressions is performed.

GO is based on the use of rays to approximate the electromagnetic fields, and treating the mechanism that generates the outgoing field as a local phenomenon at reflection points according to the law of reflection, [56].

In PO, the impinging field induces a PO surface current, $\vec{J}_{PO}$ on a surface element:

$$\vec{J}_{PO} = 2(\hat{n} \times \vec{H}),\qquad(4.6)$$

where $\hat{n}$ is the normal vector on the surface and $\vec{H}$ is the total magnetic field. The PO surface current is then integrated to obtain the reflected fields. The currents are not the actual surface currents, but rather those of an infinitely large plane. This means that there are no effects on the current distribution from the edges, which is normally the situation.

A schematic description of the results from GO and PO are shown in Figure 4.4. The GO result exhibits an abruptly changing field, which does not naturally occur. Furthermore, this result is not sensitive to the frequency of the incoming field. The PO result is more nuanced because it is influenced by the finite size of the surface element in a way the GO result is not.

To improve the GO result, the contribution of diffracted rays can be added. The UTD coefficients are suitable and give a good result, particularly when the point at which the ray hits the edge, the diffraction point, is located in the middle region of the edge, and not near its endpoints. The treatment of endpoints is a problem that can be dealt with by integrating incremental diffraction coefficients.
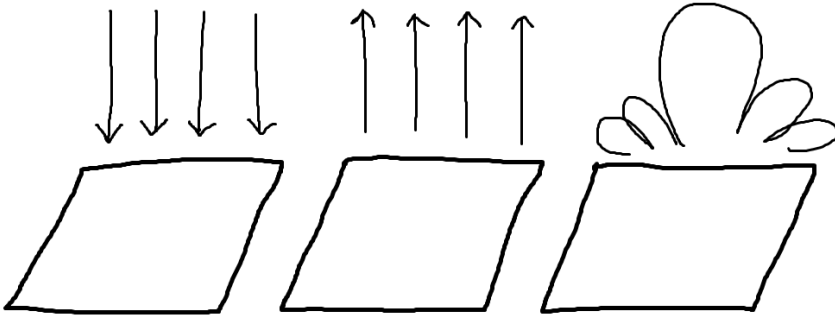
Figure 4.4: From left to right: Plane wave impinging in the normal direction onto a square surface element, resulting GO reflection and corresponding PO response.

The PO is supplemented with the integration of the PTD terms, which are found by integrating representations of the edge currents which are found via diffraction coefficients.

4.2.3 High-Frequency Methods in a Conceptual Design Perspective

From a conceptual design perspective, high-frequency methods can be very useful because they can be streamlined to meet the needs of the design process and limit the computational time. Streamlining choices must be made with clear knowledge of the computational method and the type of object that the calculation concerns. Using a surface geometry described by triangular facets, the size of the facets can be adjusted; this relates to the computational time. When employing PO, there is a choice of whether to incorporate PTD results. If they are not needed, time can be saved. For the GO+UTD calculation, the number of diffractions that each ray undergoes can be adjusted, but should ideally be kept to a minimum to minimize the computational time.

When calculating the RCS, the PO result may be sufficient, as in Paper IV. There PO was used to calculate the antenna's contribution to the RCS, with the antenna placed in the nose of the aircraft. The PTD contribution was not deemed necessary at that stage. The antenna structures in Paper III were modeled with GO and UTD to represent the antenna pattern when installed on the faceted surface. Rays that were diffracted over more than one edge were present in the calculations, but due to their low amplitude their contribution to the result was indiscernible.

The model that describe the sensing functions and the signature levels should be adapted to suit the needs of the conceptual design. The models types described in this chapter contain a great deal of information, some of which is internal and some external. However, but the connections between the model and the tactical simulation are limited to those parameters required to give an adequate description of the sensor function and signature levels.

Contributions

Aircraft Perspective

The methodologies in the appended papers support conceptual design in different ways and at different levels. All but one of the papers concern sensor and signature models and their use in a design process. The paper that differs provides a context for the aircraft concepts and their evaluation by introducing a user perspective. Results from the papers that are relevant to conceptual design will be presented in this chapter. The results range from sub-system design to a consideration of an entire sensor system.

5.1 Design Support from the Perspective of Military Utility

The concept of Military Utility presented in Paper I is linked to, but does not describe, the design process. The application of a Military Utility analysis enables the evaluation of equipment, referred to as the Element of Interest (EoI), in a military context to support decision-making about such things as the use of technology, and funding of research and development. From an aircraft conceptual design perspective, the result of the analysis can be used to determine how design alternatives influence the utility of the EoI for the military actor.

Military utility encompasses three dimensions: Military Effectiveness, Military Suitability and Affordability. Military Effectiveness concerns the degree to which the equipment can perform satisfactorily in order to accomplish a mission. Military Suitability concerns the degree to which equipment fits with other components in the military capability system. Can the equipment be used by suitably trained personnel, within the desired doctrine and tactics? Is it interoperable with other equipment? Finally, Affordability concerns whether the acquisition and operation of the equipment lies within the financial means of the organization.

In the context of aircraft conceptual design, with a focus on sensors and signatures, Military Utility can be applied in different ways. If the choice of sensors and signature levels only affects the survivability and lethality of the aircraft, then it could be sufficient to evaluate the design in the Military Effectiveness dimension at the aircraft level. If the choice also affects the availability of the aircraft, because of maintenance requirements, then it will be necessary to evaluate the Military Effectiveness at the campaign level. Furthermore, if the design decisions have an impact on procedures, tactics, organization or operational cost, Military Suitability and Affordability must be considered as well.

The Military Utility concept provides a perspective on design for military purposes that is not usually considered by industry. The potential benefits of such a perspective are improved, balanced designs, not only from a technical perspective, but also in terms of circumstances that are particular to military operations.

5.2   A Passive, Distributed Sensor System

In Paper V a passive, signal-detecting sensor system concept is presented. The use of a passive systems makes it possible to improve situational awareness without transmitting energy. However, the technique does depend on the transmissions of signal from the unknown sources, which limits the amount of data that can be obtained.

The system considered is a cluster of flying sensors that detects signals and determines the direction of and distance to the signal source by using Time-Difference of Arrival, TDOA, [58]. TDOA uses data gathered by several spatially separated sensors in the form of the arrival time of a signal from a source at the sensors, and the position of the sensors. The timing and positioning accuracy, the number of sensors and their geometrical configuration influence the accuracy of the estimated position of the source. The accuracy of the estimate was investigated using the Cramér-Rao Lower Bound, CRLB, [59, 60] for five geometrical sensor cluster configurations and two levels of accuracy in timing and positioning. The CRLB provides the best possible result that can be achieved with a maximum likelihood estimator. The results do not guarantee *actual* system accuracy, but provides a means to compare system configurations.

The general result is that the accuracy of the position estimate improves with more accurate timing and positioning, an increased number of sensors and greater distances between sensors. The methodology can not only be used to support the choice of these equipment parameters, but also in the geometrical configuration of the sensors, and to determine the system's robustness in the event of one or more sensors being removed from the cluster.

5.3   Effects on Aircraft Performance Due to Sensor Installations

The situational awareness benefits that the sensor system provides can be counteracted by negative effects of its installation on the aircraft. If the signature increases, which could be one consequence, so does the risk of detection. If flight performance is affected, and the maneuverability required in some situations is reduced, the survivability and lethality of the aircraft could be reduced. This interaction between conflicting properties, the benefit of sensors and the drawback of reduced flight performance and/or increased signature, is exemplified in Paper IV. There, a radar system with an Active Electronically Scanned Array (AESA) radar is placed in the nose of a fighter aircraft. The radar model supports conceptual design by providing a link between the sensor function and the aircraft in terms of mass, volume, required power and cooling. Four aircraft of different sizes, see (Fig. 5.1) with associated radar antenna versions were investigated.
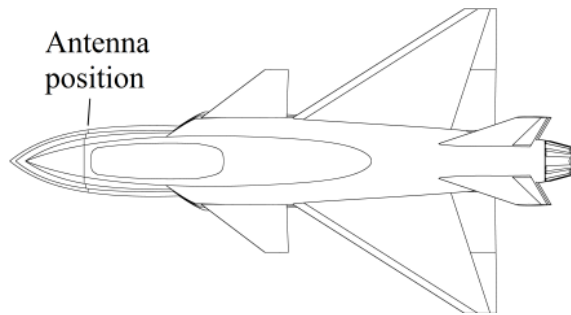

Figure 5.1: Contours of the four different aircraft. The changes in the aircraft mainly concern the front section where the radar antenna is installed. Adapted from Paper IV.

The sensor performance is presented in terms of detection range and search volume using a target with a fixed RCS. The shape of the aircraft changes due to the antenna installation, mostly in the front section. This in turn affects both the RCS of the aircraft and its flight performance which is presented in terms of drag, acceleration, sustained and instantaneous turn. The drag is presented in Fig. 5.2 where the fourth aircraft concept clearly exhibits greater drag than the other three.

To properly assess the effect of the sensor installation, its benefits should be weighed against the risk of detection due to the RCS and the effects on flight performance.

The results of the model testing show that the methodology can be used to describe both the sensor function and the effect of the installation on the aircraft. When there is strong dependence between the sensor system and its influence on the airframe, and consequently the flight performance, it is imperative that the models used in scenario evaluations contain a proper connection between these properties. With such models, the results of the scenario evaluations will reflect both the positive and negative effects of the sensor installation.
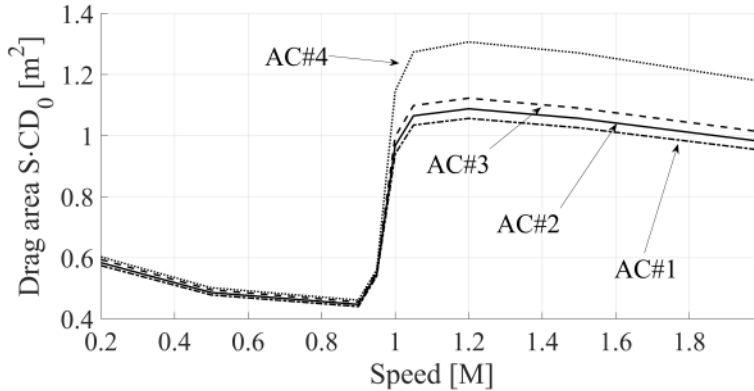
Figure 5.2: Drag for the four different aircraft concepts. Adapted from Paper III.

5.4   Balancing the Sensor Performance against Signature

The passive RF sensor system in Paper III consists of groups of antenna elements, called antenna assemblies, placed at the wing tips of a fighter aircraft to provide minimal obstructions for the sensor. The antenna assemblies are used to find the direction to a signal source, assumed to be an aircraft's scanning radar. In this paper, the focus is on the interaction between the two sensor systems. The aircraft itself is not considered beyond being able to fly straight and having a radar signature adapted to match the sensor system. More specifically, the signature of the sensor system is assumed to constitute a specific fraction of the aircraft's entire RCS. This makes it possible to investigate features of the sensor system independently of the aircraft. From an aircraft perspective, the flight performance is likely to be affected by the masses at the wing tips and modeling of that effect is necessary. An adaption of the methodology used in Paper IV could be used to investigate this design dimension.

The models connect the sensor function with the signature of the antenna assemblies, which can be used to balance the properties of the sensors. This ability can be used in a tactical simulation to assess the influence on the sensor design.

Being able to investigate the tactical effects of different sensor systems can provide an understanding of what drives their design, and make it possible to determine what range of sensor designs provides useful functionality with acceptable negative effects.

5.5   Balancing Two Types of Signatures

Differences in signatures of aircraft become important when there are sensors in the environment that exploit signatures. The RF and IR signatures of a fighter aircraft and a cruise missile are investigated simultaneously in Paper II. The distance at which detection occurs is crucial, because detection triggers weapons launch, which in turn can cause kill of the aircraft or cruise missile.

The size of the aircraft and the missile, and choices of material influence both types of signatures. Whether these signatures are balanced is not only determined by the signature levels; the capabilities of the hostile sensors is also a factor that needs to be considered. Thus, the balance is dependent on factors outside the control of the aircraft designers. In a conceptual design phase, the methodology presented in Paper II is useful because it supports the testing of signatures, tactics and sensor properties.

By assuming reasonable sensor properties based on physics and/or knowledge of sensor technologies, a general balance can still be achieved. This brings valuable additional knowledge to the aircraft design and reduces the risk of designing an aircraft that is unsuitable for its intended operational environment.

Evaluation Methodologies

A primary goal of sensor and signature models is to provide means to evaluate a range of system choices in order to find balanced design points or ranges with suitable distributions between utility and risk. The goal of evaluation is to acquire data that can be used in at least two ways: to provide a route to better understanding of the design space and to support decision-makers at a highly conceptual level. The concept of military utility relates to the needs of the user in a military context, which provides an additional factor to the business driven goals of the defense industry. The evaluations in the appended papers range from one performed in a relatively elaborate scenario with different tactics, to more basic approaches intended to test the functions of the models at a more technical level. For a system not explicitly threatened by hostile forces, or where the threat matters less because the equipment is less valuable, the evaluation can be performed from a solely technical perspective.

6.1   Supporting the Evaluation of Military Utility

The three dimensions of Military Utility presented in Paper I, Military Effectiveness, Military Suitability and Affordability, provide a framework that allows evaluation of designs at system levels. Each dimension is associated with indicator levels connected to the system's performance. None of the appended papers in this dissertation present results concerning Affordability or Military Suitability, but results related to Military Effectiveness are included. The proposed indicators in the operationalization of Military Effectiveness are: compliance with desired outcome, schedule, cost objectives and risk objectives. In order to be militarily effective the contributions from the sensor and signature designs must increase the likelihood of the military actor completing the mission effectively, in the desired

time frame, with acceptable operational cost and within acceptable risks to the
crew and other military objectives.

Concerning the evaluation of the indicators presented above, it is not uncommon
to present them as a compounded Military Effectiveness value, i.e. a weighted
sum, after having applied coefficients to the individual indicators. This makes
ranking of the alternative concept designs easy, but information is lost in the
process. One way of dealing with this issue is to apply a more transparent process
where the non-compounded values of suitably chosen indicators are shown to allow
decision-makers to see what lies behind the numbers.

6.2   Evaluation in a Realistic Scenario

Paper II describes the most developed scenario evaluation of all the appended
papers. In this scenario, illustrated in Fig. 6.1, air defense systems equipped
with both RF and IR sensors are approached by an aircraft, at either medium or
low altitude, or by a cruise missile at low altitude. The aircraft and missile are
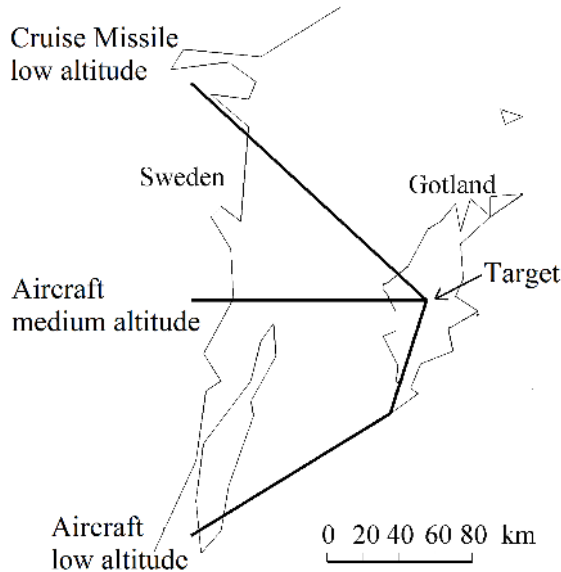

Figure 6.1: The scenario with three missile/aircraft flight paths and the target
located on the island of Gotland. Adapted from Paper II.

each given four levels of signature, a combination of IRS and RCS. The aircraft's
objective is to get close enough to the target to drop bombs while the missile needs
to reach the target. When the air defense system's RF and IR sensors detects the
incoming aircraft/missile, surface to air missiles are launched. The goal in the
scenario in Paper II is to fulfill the two MoE, see [6], where the first was that the
target should be neutralized with a certain range of probability and the second was
the number of aircraft/missiles needed to complete the mission. Calculating the kill

probabilities for the surface to air missiles, given the detection range range between the launch site and aircraft/missile, yielded a measure of how many aircraft/missiles are needed to engage the target before the MoE requirement was fulfilled.

The detection results were presented in diagrams indicating the distance at which the different signatures were detected, given specified weather conditions. Such a presentation displays the difference between the effects of having different signatures in an accessible manner. Figure. 6.2 shows four different RF signatures, between 4 and 0.01 m^2, and four IR signatures, represented by a large (L) and small (S) aircraft that have computational equivalent IRS front areas of 6 and 12 m^2, respectively, combined with two emissivities of 0.5 and 0.9.
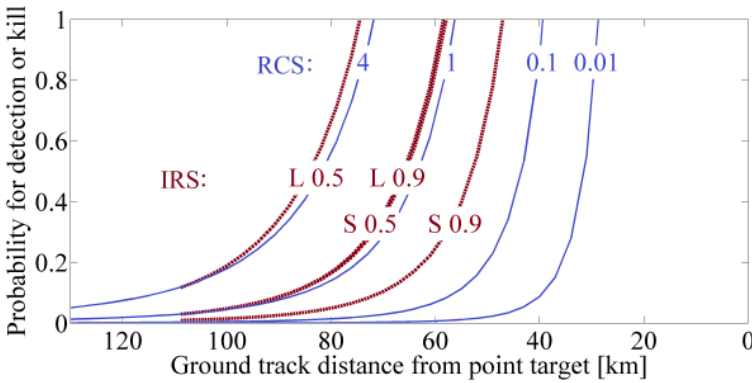

Figure 6.2: Detection diagram for aircraft with different IR and RF signatures. Adapted from Paper II.

The results showed that if the mission was performed in conditions of low visibility, the IR sensors would not pose a risk, and that the RCS was the limiting factor for detection. On the other hand, on a clear day, IRS adaptions were important in reducing the risk of detection. This methodology can be used to assess how different levels of signatures influence the detection of aircraft. The types and number of signatures can be changed, and the flight paths and mission objectives altered. The results can be compounded and considered as a design dimension terms of aircraft detection, which through the subsequent risk of being killed is connected to the survivability.

The signature of an aircraft can be reduced through choice of shape and/or materials. This holds true for both RF and IR signatures, and it is possible that measures taken to adapt one signature affect others. The methodology in Paper II supports simultaneous evaluation of several signatures. The results can be used to formulate requirements for such things as the design of advanced materials that provide simultaneous RF and IR signature reductions.

6.3   Evaluation in Limited Tactical Situations

6.3.1   Passive system

A simple tactical situation can be very useful in the initial functional testing of a sensor system model. In Paper III, five version of a passive sensor system with antenna assemblies at the aircraft wing tips are presented in five different versions. The five antenna assemblies have varying antenna and signature performance which manifests itself in good antenna performance being accompanied by a large signature. In the tactical situation, two aircraft fly towards each other, at the same altitude and constant velocity, and detect each other by means of an active radar or passive sensor system. The aircraft with the passive sensor system does not emit signals, while the other uses its radar. By stipulating that the passive system should be able to detect the radar at a certain level of the sidelobes, detection ranges for each of the antenna assemblies can be calculated. Given that the aircraft's RCS is known and includes that of the antenna assemblies, the detection range of the hostile radar can be determined.
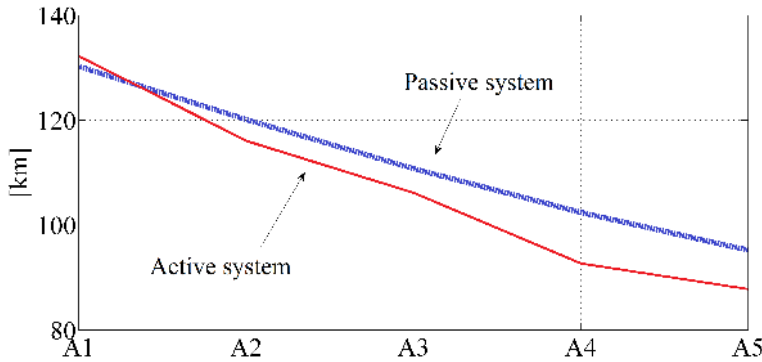

Figure 6.3: Detection distances for passive and active systems, five different antenna assemblies. Adapted from Paper III.

The evaluation can now be completed, based on the two detection ranges, see Fig. 6.3. Ideally, the passive system should detect the active system first. All but one of the antenna assemblies fulfill this condition. The one that does not exhibits the best antenna performance but, unfortunately, also has the largest signature. Consequently, this design is unsuitable for its purpose. The remaining four assemblies perform within the stipulated condition for detection. There are two interesting parameters, first the difference in blue, passive, and red, active, detection range and second the actual blue detection range, i.e. at which distance the blue aircraft detects the red. As can be seen in Fig. 6.3, A4 exhibits the largest distance between blue and red detection ranges, but it is likely that the blue detection range is also an important factor, and A2 and A3 are better than A4 in that respect. Because this choice has do be made with tactical considerations in mind, the results presented inconclusive because they only describe the situation from a sensor perspective in terms of detection ranges.

The results do show that the methodology works as expected from an electro-magnetic perspective. It is thus possible to integrate it into a tactical simulation where the balance between sensor performance and sensor signature is of interest.

6.3.2 Active System

In Paper IV, the properties of a radar and the flight performance are considered. Once again, the tactical situation involves two aircraft flying towards each other, at the same altitude and with constant velocity and detect each other by means of an active radar. The hostile aircraft is assumed to have a fixed RCS, which is used in all calculations regarding the properties of the friendly radar. The methodology connects parameters related to the flight performance of the four different aircraft introduced in Section 5.3, Fig. 5.1, and the sensor performance of their nose radar systems. The detection range results are given for a reference target signature; the effects on search volume as a function of antenna size are as expected. The signature of the aircraft itself was assessed in terms of relative increase in detection range by a hostile radar system. The flight performance was presented in terms of drag, acceleration, sustained and instantaneous turn. The biggest aircraft exhibits a noticeable change in drag as can be seen in Section 5.3, Fig. 5.2, and a consequent change in acceleration time see Fig. 6.4.
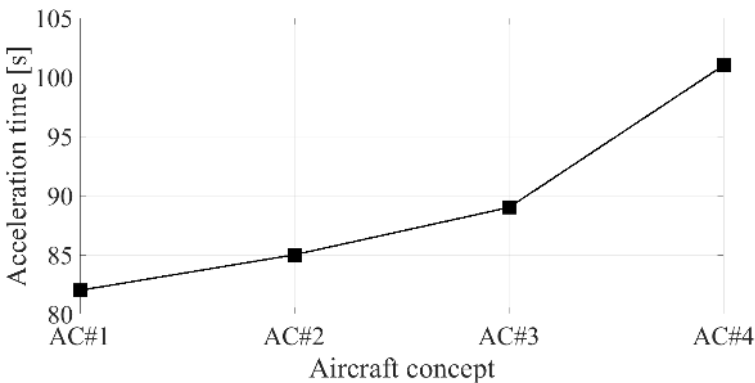

Figure 6.4: Acceleration time for the four different aircraft concepts. Adapted from Paper IV.

There was a moderate linear decrease in sustained and instantaneous turn between the smallest and largest aircraft.

The models in Paper IV connects the sensor and the sensing function to the aircraft and its flight performance. No tests in scenarios with a tactical situation were carried out. However, the results of the model tests indicate that there could be a breaking point where the sensing advantages of a larger sensor, and consequent improved sensor function, are negated by a reduction in the flight performance due to the sensor installation. The acceleration time see Fig. 6.4, and the radar's detection range shown in Fig. 6.5 can be considered as two dimensions in a design space and used as input to a tactical simulation.
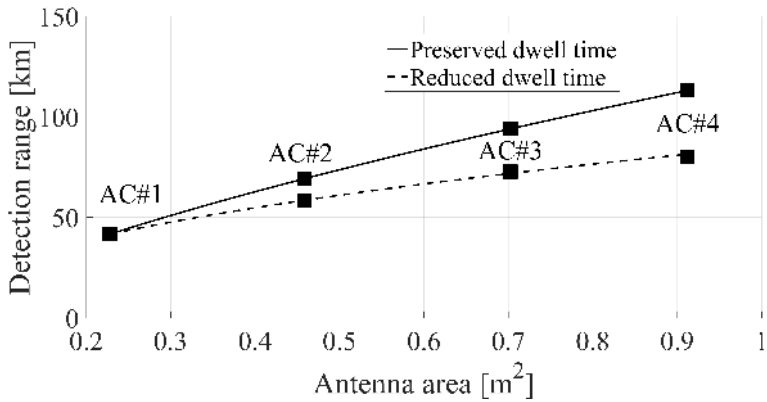
Figure 6.5: Detection ranges for the four radars. Adapted from Paper IV.

The methodology could be used to obtain data that can subsequently be used to find a relationship between sensor performance and flight performance of the aircraft concepts. This is valuable when performing tactical simulations, because both the survivability and the lethality of the aircraft are influenced by the balance of the design.

6.4 Evaluation of Data Associated with a Surface Element

Finally, in Paper V, visualization of the data and the formulation of requirements is a methodology in itself. Data concerning for example RCS, IRS and sensor performance, is often calculated in an angular sector and then presented as a colored sphere, as in Fig. 6.6. The evaluation of this data and the formulation of requirements are complicated due to the nature of the data.
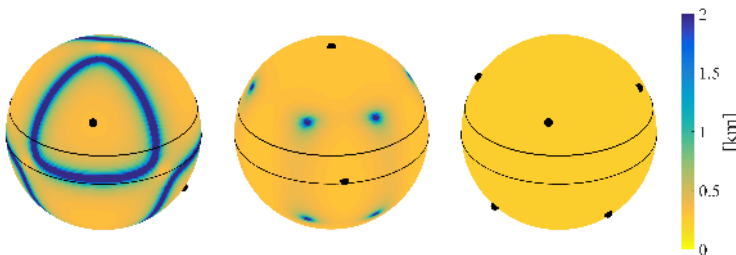

Figure 6.6: Examples of inaccuracies in estimated source direction. Adapted from Paper V.

This is so because the data is calculated for discrete directions where each data point represents a value of, for example an amplitude and is associated with a surface element; see Fig. 6.7. The sizes of the surface elements can differ between

data points, and this needs to be considered when calculating such things as an average value, because the surface elements act as a weighting function.
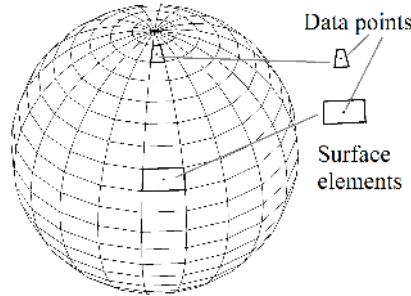

Figure 6.7: Data points with surface elements on a sphere. Equal distribution of surface elements in azimuth and elevation.

Another way of considering the results is by displaying them in such a way that retains some of the characteristics of the visual presentation on the spheres. Part of the data from Paper V will be used to illustrate such a representation.

When formulating requirements for data of the kind shown in Fig. 6.6, some possible options are using measures in terms of maximum values, number of peaks, distance between peeks, and mean or median values. The drawback is that requirements formulated in these terms are not exact, which makes it difficult to asses compliance with them difficult. However, this can be improved by using the form of the proposed form of data representation.

The data used as an example is calculated with TDOA (see Section 5.2) on a sphere with a diameter 20 times larger than the sphere on which the sensors are placed, see Fig. 6.8. The black dots in Fig. 6.6 represent the directions of the sensors, not the actual sensor positions.
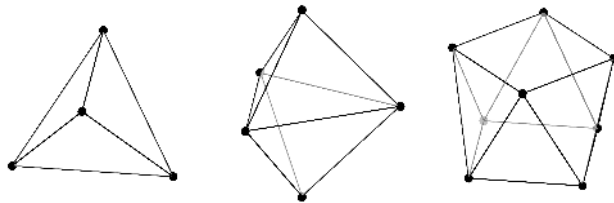
Figure 6.8: Geometries of the sensor clusters, from left to right: tetrahedron, hexahedron and square antiprism. Adapted from Paper V.

A proposed representation is shown in Fig. 6.9. The lines illustrates the percentage of the surface between the two black lines of the spheres in Fig. 6.6 that is associated with a certain value, or larger. The thick top line representing the results from the tetrahedron is used as an example to explain how to interpret

the graph. The data value at x=100 represents the smallest error, approximately 0.75 km. Following the line, it is possible to determine that, for example 90% of the surface contains errors that are 1 km and larger, and that 40% of the surface contains with errors that are 2 km or larger. The lowest thin line is horizontal and represents a constant value over the entire angular sector where the data is found.
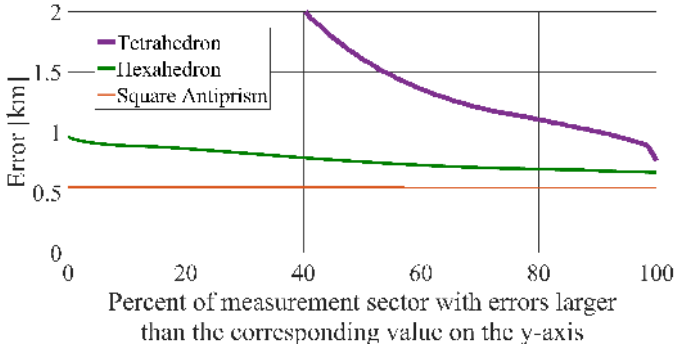
Figure 6.9: Representations of inaccuracies. Adapted from Paper V.

With this form of data representation, it is possible to analyze the data, and define requirements, in terms of how much of the surface is allowed to have data points and associated surface elements with values at or above a certain level. This is useful because this type of data occurs frequently in aircraft conceptual design (c.f. signature levels and sensor performance), and more of the data characteristics is retained compared to for example presenting an average value.

Sensor and Signature Aspects

In this chapter, several properties of models of RF sensors and signatures will be considered. At this level, the results of modeling are intended to verify that the models behave as expected, in order to provide realistic results within the tactical simulation. The models can be either meta-models related to an actual or realistic system, or assumptions about the properties of sensors and signatures to investigate how a change in parameter values influences the results of the tactical simulation.

7.1   An Active Radar System

In Paper IV an active radar system with an AESA is evaluated in terms of its detection range and search volume. The key point is the connection between the sensor performance and how integration of the sensor influences the aircraft's flight performance and signature. The positive effect of the larger antenna may be negated to some degree by a reduction in aircraft flight performance and an increased signature. All sensor performance parameters are presented as a function of the antenna area, with the intention of tying it into the geometry of the aircraft. A larger antenna will increase the detection range because of its higher output power combined with the increase in antenna gain; see Eq. 4.1. Another effect of a larger antenna is, however, a reduction in the lobe print of the antenna. Assuming a fixed search sector, a reduction in lobe print means that it will take longer to cover the sector. Alternatively, the dwell time in each direction can be reduced, but that will decrease the detection range; see Fig. 7.1. The result is that, in terms of the search volume, it is more beneficial to increase the search time instead of reducing the search sector. It is, of course, possible to apply a reduction in search sector and an increase in search time to achieve a suitable balance between the
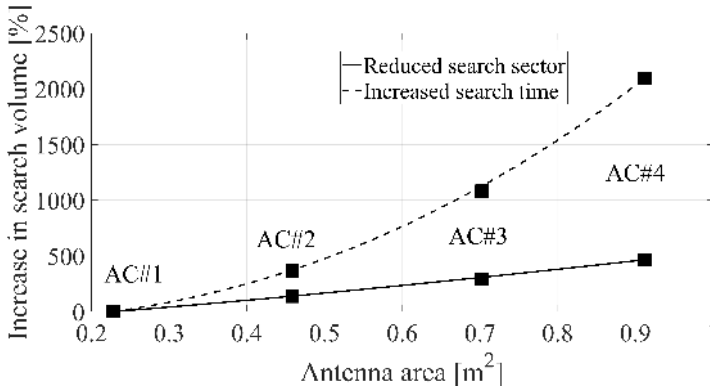
two.

Figure 7.1: Increase in search volume with reduced search sector or increased search time. Adapted from Paper IV.

The changes in RCS are a consequence of the changes to the front sector of the aircraft. The total signature is created by adding a constant signature contribution from the wings and fuselage. The RCS of the antenna and radome increases by 50% from the smallest option to the largest and is predominant in comparison to the RCS of the wings and the fuselage. Because no hostile system is modeled in detail, the detection ranges due to changes in the RCS are presented in terms relative to the shortest detection range.

The methodology presented in this paper can be used in a tactical simulation to determine the influence on the results are affected by the size of the chosen sensors, and the effects on its installation on flight performance. This type of analysis can be used to optimize the combination of aircraft performance, signature and sensor performance.

7.2 A Passive Sensor System

Both the sensors in the distributed passive system and the signal source in Paper V were modeled conservatively, with isotropically radiating antennas and a transmission power that is realistic for a communications system. Using this information and the expression for one-way RF transmission (Eq. 4.3), the greatest distance at which the sensor system would be able to receive the signal was established and used in the calculations. This is a conservative approach because performing the calculations at long distances from the signal source yields larger errors than at smaller distances.

In Paper V the focus was on investigating the system design from the perspective of sensor distribution, timing and positioning capabilities. It is also possible to integrate more advanced RF system models by introducing antennas that have directional properties, and expand analysis of the estimation accuracy to incorporate effects of the received signal's SNR.

7.3   A Passive-Active Mix

In Paper III, two RF sensors are modeled, one passive and one active. The passive sensor detects the active radar transmission, but the installation of the sensor has a cost in terms of increased RCS, which the hostile radar can exploit. The RCS of the antenna assemblies varies seven by a factor seven between the first and last antenna options. The antenna assemblies are assumed to have been allotted a fixed part of the total RCS, i.e. the antennas determine the total RCS. Signature reduction is achieved by changing the shape of the antenna assemblies, which has a marked impact on the performance of the antennas, and consequently entire sensor system. Installing a reduced-signature antenna, with limited performance, on an aircraft that is already close to or exceeds the required signature levels, only results in a sensor system with reduced capability, and no signature reduction benefits. Consequently, the allocation of signature to each sensor system must be controlled when balancing the entire design.

These results concern the simultaneous management of an aircraft's signature and sensor performance. In the design space, these two dimensions are not necessarily connected or investigated together. By using a methodology that provides a means to do so, the balance of the aircraft concept can be improved.

Closing

CHAPTER **8**

Discussion and Conclusions

8.1 Discussion

Traditional aircraft design methods do not include sensor and signature models that can interact dynamically with the aircraft's flight performance models. The capabilities of a sensor system, its signature and the aircraft's signature can be balanced separately, but the results will likely be less nuanced than those of a design process where all model types are integrated. The models and methodologies described in the appended papers are the result of a practical need, but they have not yet been incorporated into an actual design process.

Models of the sensor function and signatures can be incorporated into an aircraft flight performance model. The necessary links are provided by the sensors' mass, volume, power consumption, and their cooling needs where applicable, the signature reduction measures. When considering future systems, it may be useful to develop different branches of models, corresponding to different implementations of technology, where certain sensor capabilities or signature levels represent significantly different volumes, masses etc. The development process for sensors and signature reduction measures generally requires different models than the tactical evaluation process. By focusing on the effect provided by the equipment, e.g. sensing capability and signature levels, rather than its detailed design, a seemingly simple model can be very useful. By employing models that encompass more properties in the aircraft design process, the range of results may increase. How the equipment is used, c.f. Paper I, greatly influences the outcome. The CONOPS is consequently important in a tactical simulation. By assigning a behavior to each aircraft concept that allows its systems to operate at maximum efficiency, a fair comparison of performance can be made.

The uncertainty of simulation results is significantly increased because the military factor implies the presence of hostile forces, whose technical capabilities and tactics may be unknown to some extent. However, the simulation results can provide a relative ranking of different aircraft concept designs, which will allow decision makers to choose from the best options.

8.2 Conclusions

Were the research aims in Section 1.1 achieved? In this section, the appended papers that describe methodologies are linked to the research aims.

Aim 1. Improve the ability to balance several combinations of properties related to the function of the aircraft, e.g. signature levels, sensor performance and flight performance.

In Paper II, two types of signatures, IRS and RCS, were included, but there was no connection to the aircraft's flight performance. In Paper IV the methodology included the flight performance in the model, but only one signature, the RCS. In Paper V, the accuracy of estimating the position of a signal source was investigated in terms of sensor system properties, which in turn can be transformed into a meta model and used in a tactical simulation.

Aim 2. Provide a connection between the effects of sensor installations and an aircraft's signature levels, with the intention of improving the quality of results from tactical simulations.

This aspect was investigated in both Paper III and Paper IV. Simple tactical situations were used to demonstrate how different sensor capabilities and their associated signature levels influence the detection ranges of both friendly and hostile systems.

Aim 3. Consider the level of detail required in the model to suit the simulation to be performed.

There has been no explicit testing of models of the same sensor or signature with different levels of detail. However, the results from Paper II and Paper III show that using relatively simple models can yield useful results.

Aim 4. Include the ability to present and interpret the results as part of the methodology.

The evaluation process in Paper V can be used on any type of data, where the data points are associated with differently sized surface elements. This applies to sensor function, the ability to transmit and receive signals, and to signatures. In Paper III, the distances were translated into times, i.e. the time available to evaluate a situation and react to it. The results in Paper II are presented using a diagram that merges properties of sensors and weapons.

The results from the use of the methodologies in the appended papers show that these methodologies can be useful in an aircraft conceptual design process. They can be combined as necessary to investigate various phenomena relevant to aircraft conceptual design. Although the tests have been carried out in a predominantly point-based design process, the models can also be used in a set-based.

Outlook

The introduction of sensor and signature models, which are dynamically connected to the aircraft, is just one element in the bigger picture of to generally improving the design process. Much can be gained by moving from a point-based, iterative approach for conceptual design towards a set-based, parallel approach. However, significant efforts are required develop the necessary environment and tools.

9.1   Potential Advantages of a Set-Based Approach

Share knowledge, improve understanding, and support decision makers

A set-based approach to the design process will yield vast amounts of data that can help to increase understanding of how design choices influence the usefulness of the finished product. For engineers, this could mean greater understanding of the interaction between different systems on the aircraft, and how properties of designs should be changed to improve overall performance. Decision makers would be provided with information in real-time about the effects of different design changes, within the defined parameter range and, consequently, have a more complete basis for the choice of design.

A more efficient design process

the ability to connect models from different engineering disciplines automatically has the potential to reduce the time spent on transferring data between different computer environments. Automated checks of the compatibility of models, and their completeness, can prevent the introduction of errors. A more consistent and efficient presentation of results and design options can make the communication from, and within the design group more effective.

A more objective design

One valuable feature is a more objective view of what designs could be possible. This can be achieved by working in such a way that allows a range of designs to emerge, all of which are within the specified parameter limits. Two benefits of this are that unexpected solutions could be identified, and that personal preferences become less prominent in the choice of design.

9.2 Some Aspects of Establishing a Set-Based Design Process

To establish and maintain the ability to adopt a set-based conceptual design approach, there is a need to combine the efforts of engineers and researchers.

Development environment and collaboration

Because the conceptual design is performed in a computer environment, adopting practices from software engineering is close at hand. The models are realized through computer code, which involves version handling and automated testing. Furthermore, the organization of models in an overall framework can benefit from knowledge of software architecture in order to maintain a coherent structure. Additionally, engineers specializing in different areas, such as aerodynamics or sensor technologies, could define their models as software specifications which are then implemented by professional programmers adhering to coding guidelines. Collaboration between engineering disciplines must be supported, and this is an issue that concerns resources in terms of computer hardware and software, and organizational structures.

Model design

The use of models to describe equipment's technical properties, such as sensor capability or signature levels, may not be sufficient. The utility of equipment is influenced by both its technical properties, and how it is to be used. A CONOPS can be seen as a model of the behavior of, for example, an aircraft, and how it uses its equipment. The scenario is a model of the environment in which the models are used; consequently, scenario design will also have an impact on the simulation results. Research into the design of scenarios tends towards social sciences rather than engineering, and there is very little research into the design of CONOPS in the open literature. The design of both scenarios and CONOPS influences the design process itself; therefore, research is needed to improve the set-based design process. The effective generation of meta models that encompass several engineering fields, and suit the needs of a specific simulation, is also an area in need of further development

Evaluation and presentation of results

The evaluation of results in a set-based context differs from that in the point based. The large amount of data, compared to single points, makes it possible to detect features of the data that indicate trends, and local and global maxima and minima, by applying mathematical methods. The tactical simulation that

generates the data will also work differently, when compared to point-based design. The generation of the CONOPS is itself an optimization process, incorporating the tactical simulation in the scenario, where the goal functions could be a set of MoPs and MoEs. This makes the choice of values for these parameters important and worthy of investigation alongside with research into CONOPS design. The presentation of results is important because this is where the message generated by the work is communicated to co-workers and decision makers. For data that has more dimensions than can be easily visualized, presentation techniques that draw in and guide the audience are of great value. Sometimes simple graphs will be effective, on other occasions 3D virtual, putting the audience "inside" the scenario will be more effective.

The methodologies used for analysis and design have always evolved, and they will continue to do so. However, any predictions about the direction of the road ahead are almost certainly guesswork, albeit educated guesswork. The contributions presented in this dissertation are unlikely to decide any future direction, but they do offer an opportunity to widen that road once it is opened.

Brief summary of papers

Five papers are included, all of them published.

I Military utility: A proposed concept to support decision-making

Published in Technology in Society, Elsevier
`doi.org/10.1016/j.techsoc.2015.07.001`
My contribution was limited to the discussions during meetings a small amount of text. It is nevertheless appended because it was the starting point for the research and makes the dissertation more complete.

This paper proposes the concept of military utility as a way to evaluate military equipment, or Element of Interest, EoI in a balanced way by including the user of the equipment and the context in which it is used. The framework consists of thee dimensions, Military Effectiveness, Military Suitability and Affordability which are compounded from underlying information of the EoI. If either of the three dimensions is not satisfactorily fulfilled, no military utility is achieved.

II Balancing the Radar and Long Wavelength Infrared Signature Properties in Concept Analysis of Combat Aircraft - a Proof of Concept

Published in Aerospace Science and Technology, Elsevier
`doi.org/10.1016/j.ast.2017.10.022`
I did half of the research design and analysis, all of the electromagnetic modeling, and half of the writing.

In this paper, a methodology to simultaneously evaluate two different types of aircraft signatures is proposed and tested in a scenario. It is common practice to evaluate signatures one at a time, but since simultaneous use of different types of sensors is becoming frequent, the evaluation methodologies must follow. If one

of two sensors can detect an aircraft, it is not hidden anymore. By visualizing the consequences of the two signatures, related to given sensor performance, the trade-off is made more accessible.

III Balancing Antenna Performance vs. Radar Cross Section for a Passive Radar-Detecting Sensor on an Aircraft

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I am the sole author of the paper.

To silently intercept signals from a hostile radar and determine from which direction the signal comes before it detects you is an advantage in a tactical situation. The antennas that provide the coverage of the surroundings also provide an increased radar signature which will make the enemy able to detect the aircraft at a longer distance, i.e. reduce the time it is hidden. Planar antennas that are directed towards the enemy provides good antenna function but unfortunately also high signature. Is there a point of balance when the signature is low enough but the antenna function is still good enough? The methodology that is presented provides a way to balance both detection distances and measurement accuracy for a sensor system.

IV Detection Chain Model Designed for Aircraft Concept Development

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With the exception of the aircraft sizing and flight performance estimations, I did all the research design, modeling and writing.

Sensor models are often limited to describing the sensing function, and do not take into account the impact the installation of the sensor has on the aircraft's infrastructure. The size of the sensor influences the radar signature, but perhaps even more important, the flight performance. In this paper, two engineering disciplines meet to develop a methodology that can be used to evaluate whether an improved sensor function is worth its cost.

V Aspects of the Design, Evaluation and Accuracy of Airborne Sensor Clusters Using Time-Difference of Arrival

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I am the sole author of the paper.

By combining information on when a signal is received at different, known, locations, it is possible to determine where the signal came from. This paper provides a methodology to evaluate how clusters of aircraft equipped with sensors that have a given accuracy in their positioning and timing capabilities influences the accuracy of the estimate regarding the position of the signal source. The number of aircraft and the geometrical configuration of the clusters are investigated and an evaluation methodology for the data is proposed.

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