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# Signature Adaptation of Radar Antennas

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Gothenburg, Sweden 2016

PRODUCT DEVELOPMENT PROJECT REPORT 2016:06

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Cover: Saab AB's ground based radar systems that this thesis focus on. From left: ARTHUR, GIRAFFE AMB, GIRAFFE 4A and GIRAFFE 1X.

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## Abstract

This master thesis has been conducted during spring 2016 with the aim to explore if it is possible to camouflage the transmitting and emitting front plate of a Saab ground based radar antenna without cause negative impact on the radar system's performance. The front plates are today not camouflaged and are major contributors to reveal the location of the systems due to visual rotation and reflection.

This thesis proves that it is possible to camouflage the antenna front plate with assistance of camouflage nets without affecting the radar performance. Methods being used during this development project have been both qualitative methods and quantitative methods, with much focus on the testing phase of the development process. Technical knowledge and support during the project have been gained from employees at Saab AB and a reference group was also provided by Saab AB.

This thesis has resulted in several conceptual ideas of how to design camouflage solutions for the GIRAFFE AMB, GIRAFFE 4A and ARTHUR radar systems' antennas. Observations and evaluations along the project have proved that by making the camouflage solution equal in all directions the visual rotation of the antenna decreases. Camouflage nets with much structure decrease the reflection from the front plate as it helps to change the surface signature of the antenna.

Finally, for further development, it is recommended to continue with the full scale testing and observe how the camouflage nets affect the radar performance of radar systems when they are exposed to different environmental conditions. Possibilities with both rotating and stationary camouflage solution are recommended to investigate further.

Keywords: Saab, Barracuda, Sweden, radar, antenna, camouflage, Chalmers, Product Development

# Acknowledgements

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- Thorbjörn Andersson, System Verifier, Saab AB, Business Area Surveillance
- Karl Johan Lauren, System Engineer at Saab AB, Business Area Surveillance
- Reference Group provided from Saab AB, Business Area Surveillance
- Erik Hulthén, Examiner and supervisor from Chalmers University of Technology

We are convinced that Saab Surveillance finds this project useful and that it can provide a foundation for further work and discussion regarding camouflage solutions for radar system's antennas.

Anna Arbman, Patrik Jacobson, Gothenburg, June 2016

# Contents

## Abbreviation List

**2D** - 2 Dimension

**3D** - 3 Dimension

**AESA** - Active Electronic Scanned Array

**AMB** - Agile Multi Beam (version of GIRAFFE radar, acronym used by Saab)

**ARTHUR** - ARTillery HUnting Radar

**C-band** - Is part of the microwave band of the electromagnetic spectrum with a wavelength of approximately 6 cm

**CW** - Continuous Wave

**GIRAFFE 1X** - New compact Saab radar for ground and naval applications

**GIRAFFE 4A** - New Saab AESA radar for ground and naval applications

**IR** - Infrared

**IFF** - Identification system that determine friend or foe.

**ITU** - International Telecommunications Union

**mrad** - Milli radians

**rpm** - Revolutions Per Minute

**RAM** - Radiation Absorbent Material

**RTM** - Radiation Transparent Material

**S-band** - Is part of the microwave band of the electromagnetic spectrum with a wavelength of approximately 12 cm

**TWS** - Track While Scan

**X-band** - Is part of the microwave band of the electromagnetic spectrum with a wavelength of approximately 3 cm

# 1
# Introduction

*The introduction chapter of this master thesis report aim to present what this project comprises: i.e. its background, problem definition, purpose, scope and limitations.*

## 1.1 Background

Radars represent a valuable asset for military forces around the world as they keep track of enemies and works as vital tools to protect own land/air/sea areas. It is important to camouflage these systems as good as possible, both in visual range and IR range, in order to minimise the risk of hostile detection. The antennas are traditionally not camouflaged on the front side where the radar is transmitting and receiving signals in order to maximise radar performance. This makes the systems easy to detect especially in combination with reflections that occur during rotation of the antennas. Therefore an interest in investigating if it is possible to camouflage the front side of an antenna emerged at Saab AB.

Saab AB is a Swedish aerospace and defence company, founded in 1937. Saab is active in aerospace-, land- and naval defence, civil security and commercial aviation technology. Today Saab has 14 700 employees and operates on all continents. Technically Saab is a leader in many areas, and one-fifth of the revenue goes to research and development. [31]

This master thesis is conducted at the business area Surveillance within Saab AB. This business area is responsible for all sensor development at Saab and the main products are radars, electronic warfare systems and laser rangefinders. Saab Barracuda AB, further referred as Barracuda, is also involved in the master thesis with their expertise concerning camouflage solutions. Barracuda is a subsidiary of Saab AB and a producer of military camouflage products.

Because of the broad interest in this project Saab provided the authors of this master thesis with a reference group consisting of product leaders of the systems, people with military background and customer perspective, and people with system and mechanical knowledge. Meetings were held every other month and functioned as information meetings and sounding board where every attendant had the opportunity to bring forward their opinions about the project.

## 1.2 Problem Definition

The main focus of this master thesis is to answer the question:

”*How can the transmitting and receiving side of ground based radar systems antenna be camouflaged with a camouflage net without influence on radar performance?*”

Research has also been conducted regarding the following two supplementary research questions:

- What specifications and requirements need to be developed for a camouflage solution that uses camouflage nets as concealment?
- How can camouflage solutions be designed for Saab AB’s ground based radar systems’ antennas?

## 1.3 Purpose

The purpose of this master thesis is to investigate the impact on radar performance when radar antennas’ front side are camouflaged and propose practical solutions for how fixed and rotating antennas can be camouflaged in a visual and IR perspective.

## 1.4 Scope

Saab AB has three main types of radar systems; ground based, naval and airborne. The scope of this master thesis is focused on the ground based vehicles and their radar systems. The antennas are of different sizes and mounted on different cabins. The following radar systems and frequency bands are of interest: ARTHUR (C-band), GIRAFFE AMB (C-band), GIRAFFE 4A (S-band) and GIRAFFE 1X (X-band). All of the antennas operate in the frequency span of 2-12 GHz.

## 1.5 Limitations

The master thesis shall consider following delimitations:

- The project will only convey an easier understanding in how a radar system is working. For further information and deeper understanding the reader is referred to the book *Analysis of Radome Enclosed Antennas* written by Dennis J. Kozakoff [14] and the book *Lärobok i telekrigföring för luftvärnet: radar och radartaktik* written by Försvarsmakten [12]
- The project shall not consider naval and aircraft radar systems
- The project shall not consider seasonal camouflage
- The project is not required or allowed to camouflage the radar signal
- Only a limited amount of camouflage solutions produced by Saab Barracuda will be tested during the project because of limited time
- The final solution shall not be a complete product; 3D-pictures for visualisation or conceptual drawings for demonstration of performance is accepted

# 2

# Theoretical Framework

*This chapter is divided into three parts, the first part is describing radar history, the second part is about radar applications and its physical grounds and the third part describes which products this thesis focuses on.*

## 2.1 Radar History

In 1888 Heinrich Hertz formulated the basic principles for radar systems: Transmitted radio waves that get reflected against an object and then bounce back. Although, it was not until the end of the 1920s that the interest for radar technology awoke as countries wanted to protect themselves from the fighter aircrafts that started to appear. The first radar apparatus was the Continuous Wave (CW)-radar which was introduced in the 1930s. The radar worked by using a transmitter- and a receiver antenna that were situated far apart from each other. The radar can register when an airplane passed through the so called “radio cord” between the transmitter and receiver. As the CW-radar can not determine neither the distance nor the airplane’s course or speed, the CW-technology was soon replaced by pulsing signals and duplex antennas. [34]

In 1935 engineer Watson-Watt presented a foresight idea about measuring in three coordinates (distance, bearing and elevation angle), using short wavelengths (high frequency) and high transmission power to be able to get a long reach. The electron tubes from that time can only reach frequencies around 75-200 MHz corresponding to wavelengths just above one meter. In 1939 Great Britain managed to develop a new magnetron that had a high output and can achieve wavelengths at around 10 cm (S-band). New areas of use were discovered during the World War II for the radar systems such as fire control radar to anti-aircraft guns. [8]

It was during the 1950s as the calculation of the Doppler Effect got refined and well developed. The Doppler Effect is based on transmitted signals that are shifted in frequency when they encounter something that moves. This small change enabled the image on the radar screen to become “cleaner” and easier to interpret, as unchanged signals (resulting from stationary objects) can be sorted out. [3]

When the electron tubes can be replaced, in 1960s, by transistors, it revolutionised the radar industry. The transistors enabled the signals to keep their phase from pulse to pulse during transmission which refined the use of the Doppler Effect to a great extent. At the end of the 1960s the analogue signal processing started to be substituted with digital signal processing and the engineers needed computers to manage the signal processing and control of radar. [8]

In the 1970s a lot of focus was put on refinement of the antenna. In the military area the radar was at this time used for surveillance, tracking, and fire control, as guiding system for missiles, navigation and measurement of the projectile initial velocity of the cannon. Today’s radar systems work similar to those that were developed during the 1980s and are described in the following chapter.

## 2.2 Radar Applications

Radar is an acronym for "Radio Detection and Ranging". "Radio Detection" means that it is possible to, with the help of radio waves, detect targets/objects and "Ranging" stands for that the distance to these targets/objects can be measured [4]. Radar is today used within a wide range of different application areas. These applications can be ground based, sea based, in aircrafts and in space. It has been found that the use of radar within these main areas is more or less innumerable [34]. The following list describes what functions radars have in the most applications [4]:

1. Detect and locate objects in darkness, rain, fog etc.
2. Position measurements of target range, angular coordinates, etc.
3. Tracking, processing successive measurements to estimate target path
4. Imaging, generating a two (or three) dimensional image of target or area
5. Classification, discernment and identification, determining the characteristics, type, and identity of a target/object.

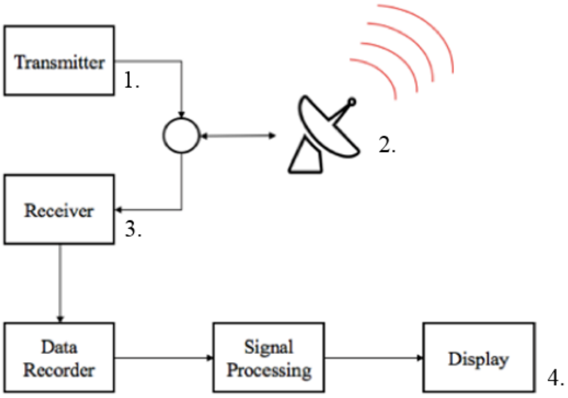
This thesis covers the application of ground based radars for military use. Different radars have been significant for the defence industry and the demands on military radar equipment are considerably greater than on civil ones. The demands differ depending on what kind of radar it is. For a long range searching radar it can be longer range, robustness and interference immunity against electronic or other disturbances that are requested. For local searching radar, it can be rapid target detection and to be able to scan the area fast enough that have the highest priority. [8]

## 2.3 Physical Grounds

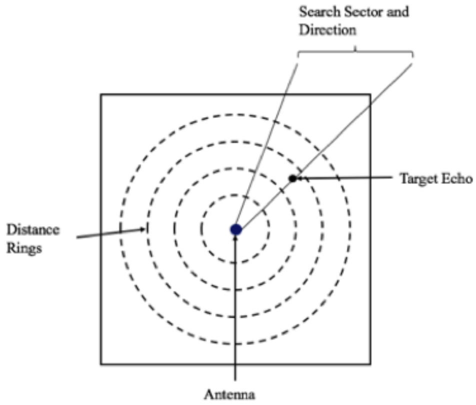
Radio waves are built basically on the same electromagnetic radiation as visual light. The distinction between them is the wavelength, which is completely different. Different wavelengths produce different characteristics. A situation showing the various characteristics is that radio waves are not attenuated in the same way during rain and fog as visual light is. That is why radar can detect targets/object through difficult weather conditions, though with a shorter reach. [19][18]

The easiest way of describing radar and its main components is by Figure 2.1a. It consists mainly of four parts [35]:

1. Transmitter. The transmitter generates radar signals in the shape of pulses.
2. Antenna. The antenna has mainly two tasks; the first is to send out the generated radar signal and the second is to receive the echoes/radar reflectors from eventual targets/objects nearby. The antenna allows the operator(s) to detect from where the received signal is coming and by that confirm the direction to the target/object.
3. Receiver. The reflected pulses that are captured by the antenna are often weak and need some kind of processing. Amplification is in most cases needed and sometimes other processing is needed as well in order to detect targets/objects.
4. Indicator/display. The information from the radar is presented on a display and is often visualised in accordance to Figure 2.1b.




(a) The basic principles of radar is visualised through a block diagram.




(b) Operators view on a display.

**Figure 2.1:** Basic function of radar and operators view.

Since this thesis is focused on the antenna, and the transmitted signals and how the radar performance is affected by a camouflage in front of the antenna, following paragraph discusses the antenna more in detail and how it works. The generated radar signals are by the radar antenna transformed to radiation which in most cases is emitted in a small angular sector, a so-called main lobe. As visualised in Figure 2.2, side lobes are also created beside the main lobe. In order for the radar to detect whether there is a target/object within the signal range, it must appear in the main lobe. According to Lindälv[1] the radar technology used today spreads the power over a larger area over which then many receiver lobes are added (GIRAFFE AMB, GIRAFFE 4A and GIRAFFE 1X) and by that a larger area can be searched at the same time. In order for this to work it is a prerequisite for the antenna to be able to handle the received signal separate as well. If the received signal is not handled separately, it is impossible for the receiver to detect from which main lobe the signal was received. The operator(s) cannot then determine if the target/object was detected near ground or far up in the air for example.

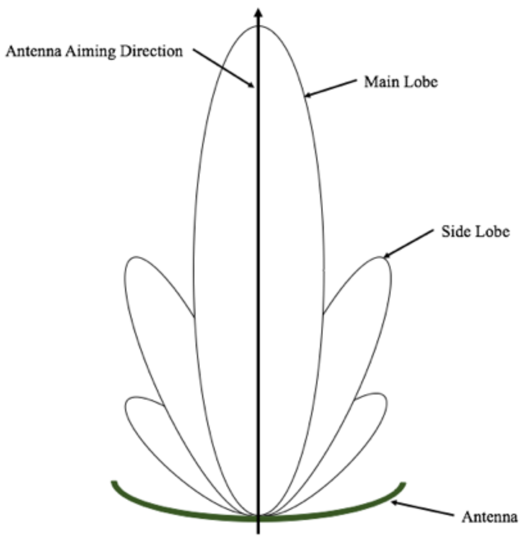



**Figure 2.2:** Generated radar signals emitted in a main lobe together with side lobes.

[1]Erik Lindälv (System Engineer | Saab Surveillance), interviewed by authors January $21^{st}$ 2016.

## 2.4 Electromagnetic Fields

A propagating electromagnetic field consists of two fields perpendicular to each other, electric (E) and magnetic (H) fields. The fields are both then perpendicular to the propagation direction and the wavelength is the distance between two maximums or minimums, visualised in Figure 2.3. [32]

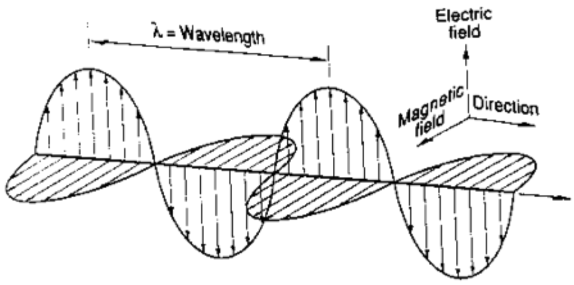



**Figure 2.3:** Schematic picture of electromagnetic field.

The electromagnetic field is propagated with a velocity of c (velocity of light), which in vacuum is equals to $c_0 = 3 * 10^8$ m/s. In real materials, the following relationship applies: $c \leq c_0$. The number of wavelengths ($\lambda$) is determined by the propagation velocity (c) in current material and the frequency (f). The frequency is constant and independent of the material the electromagnetic field is propagated in. Following relationship holds between these units: [26]

$$c = f * \lambda \tag{2.1}$$

### 2.4.1 Radio Frequencies

The region of microwaves, electromagnetic waves, is often specified over the spectrum of 3 MHz to 300 GHz. Frequencies as low as a few MHz is often operated by operational HF over-the-horizon radars and the other end of the frequency spectrum, up to 300 GHz, is operated by experimental millimetre wave radar. Other applications using microwaves are for example wireless internet traffic, mobile phones and microwave ovens. Table 2.1 describes the standard radar frequency letter band nomenclature. As described in Section 1.4, main focus for this master thesis is within the frequency range of 2-12 GHz. [20][34][2]

**Table 2.1:** Standard radar frequency letter band nomenclature, IEEE Std. $521^{TM}$-2002.

**International Table**

| Band Designation | Nominal Frequency Range | Specific Frequency Ranges for Radar Based on ITU Assignments in Region 2 |
|---|---|---|
| HF | 3-30 MHz | |
| VHF | 30-300 MHz | 138 - 144 MHz<br>216 - 225 MHz |
| UHF | 300-1000MHz | 420 - 450 MHz<br>890 - 942 MHz |
| L | 1-2 GHz | 1.215 - 1.4 GHz |
| S | 2-4 GHz | 2.3 - 2.5 GHz<br>2.7 - 3.7 GHz |
| C | 4-8 GHz | 5.25 - 5.925 GHz |
| X | 8-12 GHz | 8.5 - 10.68 GHz |
| Ku | 12-18 GHz | 13.4 - 14 GHz<br>15.7 - 17.7 GHz |
| K | 18-27 GHz | 24.05 - 24.25 GHz |
| Ka | 27-40 GHz | 33.4 - 36 GHz |
| V | 40-75 GHz | 59 - 64 GHz |
| W | 75-110 GHz | 76 - 81 GHz<br>92 - 100 GHz |
| mm | 110-300 GHz | 126 - 142 GHz<br>144 - 149 GHz<br>231 - 235 GHz<br>238 - 248 GHz |

### 2.4.2 Factors Affecting Radar Range

There are several factors affecting the range of the radar. The range of the radar can vary widely at different times because the signal attenuation is dependent on the weather. Microwaves have almost the same spread as light in the atmosphere but are not affected by the weather as much as light. Increased humidity increases the signal attenuation. Heavy rain can affect the radar range up to 50 % of original range for some of the systems[2]. The signal attenuation is also dependent on the wavelength, the larger the wavelength the less attenuation. In order to calculate the range of the radar the radar equation is used. It expresses how much different parameters, such as power and wavelength, impact the diffusion of the signal. It is only valid for cases where the conditions are ideal. An example of when this equation can be applied is when the pulse length is changed and what that results in the case of range. The simple form of the radar equation is presented in Equation 2.2. [12]

[2] Erik Lindälv (System Engineer | Saab Surveillance), interviewed by authors January $21^{st}$ 2016.

$$R = \sqrt[4]{\frac{P_S G^2 \lambda^2 \sigma}{P_E (4\pi)^3}} \tag{2.2}$$

Where:
R = Maximal radar range (m)
$P_S$ = Transmitted power (W)
G = Antenna gain (times)
$\lambda$ = Wavelength (m)
$\sigma$ = Radar target area ($m^2$)
$P_E$ = Minimum received power (W)

### 2.4.3 Factors Affecting Pointing Direction

As mentioned the radar range is of importance for a radar system but also the ability to give the operators correct and reliable information about the location of objects. For a reliable system the so called pointing error needs to be as insignificant as possible.

There are several factors that can affect the pointing direction of the antenna and generate pointing errors. Snow and ice on the antenna front plate have some impact if the thickness of it is large enough[3]. It is difficult to quantify exactly how thick the snow needs to be due to its properties. The snow properties are strongly dependent on its content of liquid water. Dry snow is more transparent than water to the radar, while snow saturated with water is significantly less transparent than water. Another factor that can cause pointing errors is camouflage painting of the antenna. This results in several transitions between colours and colour thicknesses and this has been shown to have an impact, if not significantly. As a third example of a factor causing pointing errors are radio antennas. If one or several radio antennas are in the radar search area they can reflect and scatter the transmitted power. This can lead to higher side lobes, wider main lobe and pointing errors.

## 2.5 Focus Products

Within Saab's portfolio of ground based products, there are mainly four different models this thesis focuses on. The products are ARTHUR, GIRAFFE AMB, GIRAFFE 4A and GIRAFFE 1X. The following paragraphs describe the products on a basic level and a technical specification is presented for each of the system. [29]

*ARTHUR*
ARTHUR is specialised for artillery location and is operating within the C-band at a frequency at approximately 5.5 GHz corresponding to a wavelength of 6 cm. The radar is following the horizon during the search in order to discover artillery rounds as soon as they appear. If an artillery round is detected the radar has the possibility to track it for a while, within its elevation range, and perform calculations. The calculations are based on the typical ballistic properties of an artillery round and the different location points it measured at. These points give information and by that it is possible to estimate the parabola of the artillery. A simplified visualisation is presented in Figure 2.4 and a technical specification of the system is presented in Table 2.2.

[3] Karl Johan Laurén (System Engineer | Saab Surveillance), mail conversation regarding pointing errors April $26^{th}$ 2016.

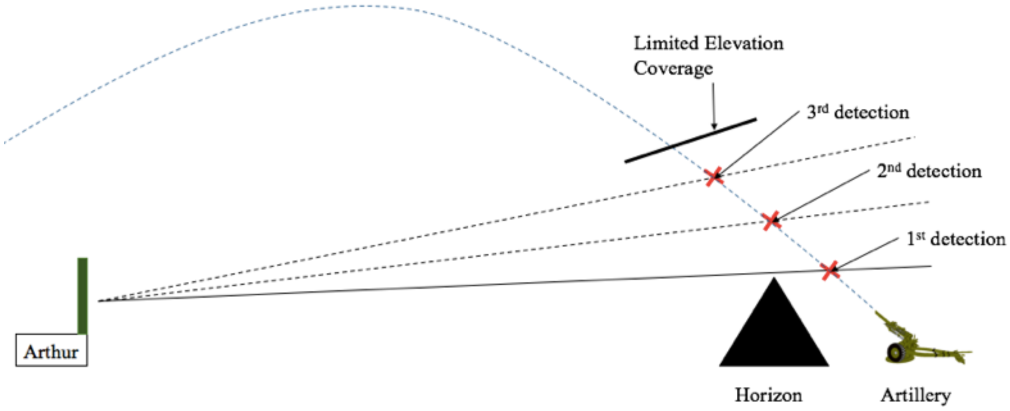



**Figure 2.4:** Visualisation of how the ARTHUR radar system works.

**Table 2.2:** Technical presentation of ARTHUR.


ARTHUR

- Superior mobility
- Single vehicle configuration
- Deploys in less than 2 minutes
- Operation in all climate zones; in-land, coastal, desert and arctic

*Technical data*

| | |
|---|---|
| Radar type | Azimuth (horizontally) and Elevation (vertically) Electrically Scanned |
| Antenna type | 2D passive phased array |
| Frequency | C-band |
| Rotation rate | No rotation |
| Search volume | 120 degrees, only sector |
| Antenna size | 1.3 x 3.0 m |
| Instrumented range | 60 km |

*GIRAFFE AMB*
The GIRAFFE AMB is specified for air surveillance and air surveillance of for example fighters. The main focus for this radar is within the upper hemisphere, air mode. It operates within the C-band at a frequency at approximately 5.5 GHz corresponding to a wavelength of 6 cm. GIRAFFE AMB can detect artillery at shorter range with less accuracy than ARTHUR, but at the same time it can detect artillery in 360° during rotation instead of a sector of 120°. GIRAFFE AMB has superior range for air surveillance. The transmitted power for a GIRAFFE AMB is not as focused as for an ARTHUR. Table 2.3 presents a technical specification of GIRAFFE AMB.

**Table 2.3:** Technical presentation of GIRAFFE AMB.

© Saab AB

GIRAFFE AMB

- Covers the entire search volume every second
- Simultaneous Air Surveillance and Sense and Warn
- Is combat proven during more than 150 000 hours
- Operation in all climate zones; in-land, coastal, desert and arctic

*Technical data*

| | |
|---|---|
| Radar type | Stacked beam 3D radar |
| Antenna type | 1D passive phased array, digital beam forming |
| Frequency | C-band |
| Elevation coverage | > 70 degrees |
| Rotation rate | 60 rpm |
| Search volume | 360 degrees |
| Antenna size | 2 x 0.5 m |
| Instrumented range | 120 km |

*GIRAFFE 4A*
GIRAFFE 4A is a considerably more powerful radar than both ARTHUR and GIRAFFE AMB. It combines the functionality of ARTHUR and GIRAFFE AMB. It is a completely new product on the market and is in the last phase of development. Another feature is that GIRAFFE 4A is able to search either for 360° during rotation or in a sector when stationary. A sector search concentrates the transmitted power which enables a longer detection range. GIRAFFE 4A operates within the S-band at a frequency at approximately 3 GHz corresponding to a wavelength of 12 cm. All these properties results in a large and heavy product. Table 2.4 presents a technical specification of GIRAFFE 4A.

**Table 2.4:** Technical presentation of GIRAFFE 4A.

© Saab AB

GIRAFFE 4A

- Delivers a comprehensive and accurate air picture in real-time
- Delivers weapon locating performance against ballistic and non-ballistic artillery
- Autonomous single vehicle for high mobility and short deployment time
- Operation in all climate zones; in-land, coastal, desert and arctic

*Technical data*

| | |
|---|---|
| Radar type | Stacked beam 3D radar |
| Antenna type | 2D AESA, digital beam forming |
| Frequency | S-band |
| Elevation coverage | > 70 degrees |
| Rotation rate | 30 or 60 rpm |
| Search volume | 360 degrees or in a sector |
| Antenna size | 2 x 2 m |
| Instrumented range | |
| - Air surveillance | 280 km |
| - Weapon locating | 100 km |

*GIRAFFE 1X*

This is a new product, based on the same radar concept as GIRAFFE AMB, which is not yet tested as a complete system. GIRAFFE 1X has the same functionality as GIRAFFE AMB but the detection range is roughly half of GIRAFFE AMB and its size and weight is much lower. GIRAFFE 1X operates within the X-band at a frequency at approximately 9 GHz corresponding to a wavelength of 3 cm. Table 2.5 presents a technical specification of GIRAFFE 1X.

**Table 2.5:** Technical presentation of GIRAFFE 1X.


GIRAFFE 1X

- A small lightweight yet high performing 3D-radar
- Enables unique flexibility and redundancy in GBAD solutions
- Covers the entire search volume every second
- Operation in all climate zones; in-land, coastal, desert and arctic

*Technical data*

| | |
|---|---|
| Radar type | Stacked beam 3D radar |
| Antenna type | 1D AESA, digital beam forming |
| Frequency | X-band |
| Elevation coverage | > 70 degrees |
| Rotation rate | 60 rpm |
| Search volume | 360 degrees or in a sector |
| Antenna size | 1 x 0.5 m |
| Instrumented range | 75 km |

## 2.6 Sensor Threats

There is constantly an ongoing technical development. Sensors, weapons and different types of surveillance equipment become increasingly smarter. As mentioned in Chapter 1, the focus of this master thesis is on camouflaging the visual and IR spectra of the radar antenna. The sensor threats are visualised in Figure 2.5. The areas of interest are VIS = visual, NIR = near infrared, MWIR = mid-wavelength infrared and SWIR = short-wavelength infrared.

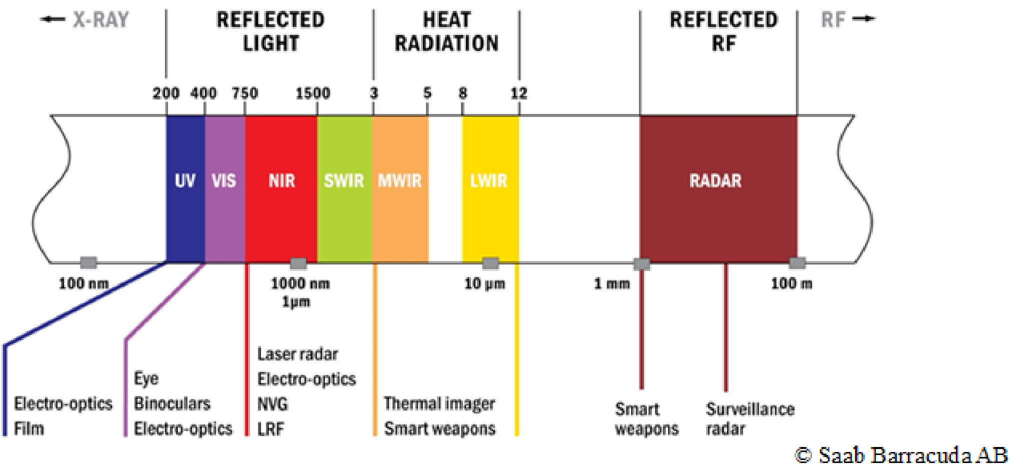



**Figure 2.5:** Visualisation of sensor threats and their respective wavelength (100 nm – 100 m). The figure was provided by Saab Barracuda AB with their permission.

### 2.6.1 VIS - Visual

Radiation visual to the human eye is said, by definition, to be the visible part of the electromagnetic spectrum. Areas and products which can be included in this spectrum are electro-optics and binoculars for example. The visual spectrum corresponds to a wavelength range of approximately 400-700 nm. The colour range extends from violet through red. White light is a mixture of all colours in the visible spectrum and black is total absence of light. Figure 7.7 visualises the scale of how the visual light is divided into different colours depending on wavelength. [38][21]

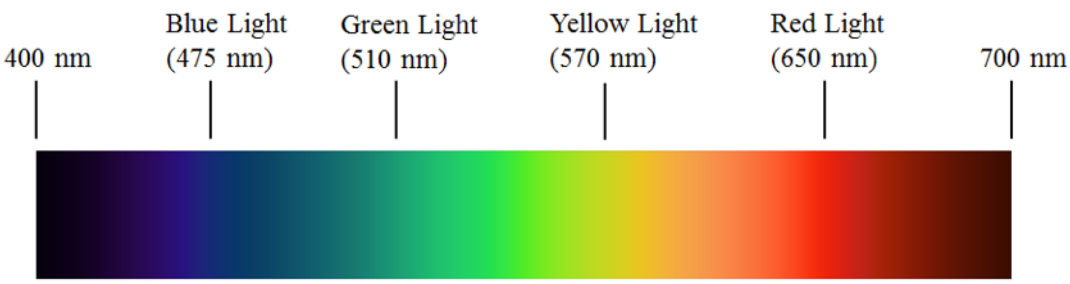



**Figure 2.6:** Linear visible spectrum. Except the marked base colours, visible violet light appears at 400 nm, indigo appears at 445 nm and orange appears at 590 nm.

### 2.6.2 IR - Infrared

Outside the range of visible light, infrared radiation appears. The infrared (IR) radiation is also a type of electromagnetic radiation but it is not visible for the human eye. The human body can feel the infrared radiation though, as heat. Heat can be transferred from one place to another in three different ways; infrared radiation, convection and conduction. IR radiation is emitted by everything with a temperature above approximately minus 268° Celsius. The IR radiation is divided into four different types of IR over a wavelength range of approximately 700 - 15 000 nm. The four types are *Near IR (NIR)*, *Shortwave IR (SWIR)*, *Midwave IR (MIR)* and *Thermal* or *longwave IR (TIR or LWIR)*. [16][22]

There are different techniques to reduce the IR signature. Barracuda works towards the idea to get good airflow through their products and by that also get a good convection cooling. A good camouflage net is represented through good ability to not allow thermal radiation to pass. According to Jersblad[4] green surrounding vegetation often adapts to air temperature. The camouflage net should not deviate more than a few degrees Celsius from surrounding air temperature even though that the object it conceal can be considerably warmer or cooler. Another technique can be to use a low emissivity in order to reflect the surrounding thermal radiation and enable a low apparent temperature looking in a thermal camera. The uncertainty using this technique is higher since the camouflage net can be too cold compared to the surrounding and the result of this is a high contrast.

## 2.7 Camouflage

Camouflage is described as the technique that helps people, animals or objects to hide or disguise in their surroundings. This is often performed by combination of materials, colours, concealment or motion dazzle. The latter method works by confusing the observer with a distinct pattern that reveals the object but makes it harder to locate. [11]

In the nature camouflage is used by preys to avoid predators, but it is sometimes also used by predators to stalk their prey. Simple camouflage is e.g. that the species has a colour or a pattern that is frequent in its surroundings or that it is using objects in the surrounding to hide. There are also animals that use a so called “active camouflage” that enables them to change colour or shape if they need. [37]

In military the main objective to use camouflage is to deceive the enemy as to the existence, location and intensions of the military arrangement. Military camouflage started to show in the 18th century when the musket got replaced by the rifle. The camouflage at that time was the use of forest green or field grey uniforms. During the First World War the motion dazzle effect was being developed on ships, and soon this technique was transferred onto humans. At the beginning of the Second World War the kidney-like camouflage pattern had been materialised and at the end of the war optical patterns had been developed. Today’s digital pattern was developed during the 1990s and has shown to be really effective for its purpose of camouflage. A digital camouflage is a pattern that is pixelated in a range of scales and helps to create a confusing effect and complicates observation from a range of distances. [23][13]

The main focus when camouflaging something lies in fooling the eye of the observer, the visual spectra, as it is the largest sense of the human, but there also exist camouflage on other areas. One example is the more and more commonly used “stealth technology” which enables to disguise, in first hand, aircraft and ships from radar and sonar technology. Another area to camouflage is the thermal emission that occurs from equipment and soldiers, e.g. the engine is a major heat source. The thermal emission can be reduced by different materials to not be visible from the outside via IR-cameras for example[5]. [28]

[4] Johan Jersblad (Senior Development Engineer, R&D | Saab Barracuda AB), mail conversation May $3^{rd}$ 2016.
[5] Johan Jersblad (Senior Development Engineer, R&D | Saab Barracuda AB), interviewed by authors January $28^{th}$ 2016.

There are mainly four areas where camouflage is used within the military sector; uniforms, land vehicles, ships and aircrafts. Focus for this master thesis, as mentioned in Chapter 1, is on ground based products and there are several products on the market for this application. Barracuda is offering camouflage products for ground based products and their products are divided into the following three product areas[6]:

1. *Static Camouflage*
   Static camouflage is used to camouflage both personal and vehicles. This type of camouflage is used to avoid visual, IR and radar detection. It is a lightweight camouflage that is easy to handle for the operators. It is also multispectral (hides the object in the visual, infrared, radar and millimetre-wave radar imaging) and non-snagging (does not stick to small protruding items such as nuts etc.). A static camouflage solution meets the toughest signature management requirements in any environment and climate. It also offers a protection against relevant types of reconnaissance sensors and target acquisition as well as reduction of incoming sun radiation (up to 70 %).

2. *Mobile Camouflage Systems*
   Mobile camouflage systems are used at different types of vehicles for camouflaging, internal heat reduction and operational energy savings. This system is based on a modular platform uniform application which can be used for most platform environments at any threat levels. It is possible to customise the modules depending on what kind of vehicle one wants to camouflage. By this, it is possible to build unique sets of camouflage using modules that fits the actual vehicle.

3. *Personal Camouflage*
   This personal camouflage is often used by Special Forces in order to blend into the environment and is used to avoid visual and IR detection. This kind of camouflage obstructs the human silhouette and blocks up to 80 % of emitted energy from the person who wear it. The camouflage also has randomised colour patterns depending on operating environment and a configuration that eliminates gloss.

Jersblad[6] states that the main task of camouflage for ground based vehicles is to avoid detection by aircrafts. Matt paint is often the basis used for camouflage. Camouflaging nets have been proven to be effective to escape visual observation. Traditional nets use a textile garnish that gives an elusive texture with shadows. According to Jersblad[6] this can further be improved with pieces of vegetation. Modern nets consist of a continuous woven material instead, which make the nets easier to arrange over vehicles. Some nets can remain fitted when the vehicles are moving.

It is proven that a stationary object is easier to camouflage than a rotating or moving object as the human eye react on movement. It has also shown that patterns provide a better camouflage when the object to be disguised is stationary, since patterns break up the object's edges, form and silhouette. If the object is rotating or moving a more homogeneous camouflage net with less or without pattern has proven to be better for camouflage use. Patterns are designed to make it more difficult to perceive shadows and shapes. One way of making a rotating/moving object, looking stationary is to build a radome around it. A radome, an acronym made from radar dome, is a structural enclosure that protects the radar system or antenna from its physical environment. Ideally a radome is constructed of material that makes it radio frequency transparent in order to minimally attenuate the transmitted or received signal. A radome by itself has not the characteristics of making the structure blend in to the surrounding environment. This can easily be solved by putting a camouflage net with some sort of structure over it. [14]

[6] Johan Jersblad (Senior Development Engineer, R&D | Saab Barracuda AB), interviewed by authors January $28^{th}$ 2016.

It does not exist any camouflage pattern that is effective in all terrains, which is a drawback for the military sector as they often move between several terrains during a day. Seasons can affect the look of a camouflage tremendously in some areas of the world. Many countries have several different camouflage uniforms as a result of this. The major types are winter land (snow), dessert, tropical (rain forest) and woodland (typical Swedish forest). This thesis is only covering woodland camouflage.

### 2.7.1 Camouflage Net

Camouflage nets are used mainly in order to gain time against enemies. A few extra seconds before being detected by the enemy can be vital in combat situations. One of the focus areas of this thesis is to investigate the possibility for transmitted power to be unaffected and absorbed by a camouflaging net. Camouflage nets can be either radiation transparent (RTM) or radiation absorbent (RAM)[7]. The more effective a RAM is the more it attenuates non-ionizing radiation from any direction meanwhile the more effective a RTM is the more invisible it is to radar radiation.

Development of radar absorbing camouflage nets started shortly after the introduction of radar in 1930's. Radar absorbing materials are designed with different loss mechanisms and often come with different shapes and structures; it can be anything from pyramidal structures, to multilayers and single coating. In order to optimise the absorption over wide bandwidths physical optics are used. Camouflage nets used for radar absorption in the military sector become often bulky, heavier, thicker, harder to handle for operators etc. The camouflage net (from a visual aspect) is only attached outside the RAM material and is not radar absorbent in itself. Applications for radar absorbing materials include anechoic chambers and for reducing the reflected signals from building around radar installations. [33]

As mentioned this master thesis is more focused on RTM. Several companies producing camouflage nets like Saab Barracuda[7] and Miranda [17] use polyester with different kind of coatings. Polyester is used because of its characteristics, among this low price, weather ability and ease of use. In order for camouflage nets to be as good as possible over the whole waveband a trade-off between functionalities and properties needs to be considered.

According to Jersblad[7] it is important to not attach the camouflage net to close to the side of the antenna where the antenna emits radiation. The reason is because of the emitted thermal emissions that can heat the net and by that make it more visible even though it has good IR properties. Another aspect of why a camouflage net should not be attached to close is because of the effectiveness of the cooling system. A well-functioning cooling system is equally important for a military vehicle as a radar antenna.

[7] Johan Jersblad (Senior Development Engineer, R&D | Saab Barracuda AB), interviewed by authors January $28^{th}$ 2016.

# 3 Methods

*This chapter describes the methods that were used during this development project and also how they were carried out. Both qualitative and quantitative methods have been used. Qualitative studies answer the questions "what", "how" and "why" and can for example be interviews, observations and focus group meetings. The results from the qualitative studies are presented in this chapter. Quantitative studies include results from conducted tests and experiments and answer the questions "how much", "how many", "how often" and "to what extent". The results from the quantitative studies are presented in Chapter 4.* [24]

## 3.1 Qualitative Methods

The aim with the qualitative study was to get familiar with Saab's ground based radar systems, the problem the project was going to solve and what camouflage solutions that exists on the market today.

In order to be able to carry out the project a research about the fundamentals of Saab Surveillance ground based radar systems and different camouflage solutions were conducted and presented in Chapter 2. Chapter 2 is based on literature studies, technical reports and article research on the internet and discussions with the supervisors of the project. Keywords used for gathering of information were **radar**, **antenna**, **camouflage**, **material**, **military**, **radio wave** and **frequency**. The reference group, presented in Section 3.1.1, supported the project with creative ideas to take into consideration during the project. The group also brought up discussions about achieved results presented along the project and gave feedback. Barracuda supported the authors with information and thoughts concerning camouflage nets, presented in Section 3.1.3. In order to gain knowledge about different areas included in the project, interviews and dialogues with employees at Saab AB and observations of radar systems were conducted. The qualitative studies ended with a brief market research where different camouflage nets were mapped.

### 3.1.1 Reference Group Meetings

The reference group meetings that were held reminded a lot of so called focus group meetings. The aim was to gather all stakeholders of the project, discuss the setup and gather requirements and customer needs. It is important that all stakeholders are heard to be able to reach satisfaction in the group. Those meetings are also excellent opportunities for stakeholders to discuss ways in solving each other's challenges. [7]

The reference group was put together for this thesis project because of a broad interest throughout the organisation of Saab. The ability to camouflage the front of the antennas (transmitting/receiving side) has never been investigated by Saab but it has been of interest for a long time. The reference group consisted of product leaders for different ground based products within Saab's product portfolio, people with military background and customer perspective as well as people with system and mechanical knowledge.

### 3.1.2 Interviews

There exist three types of interviews; structured, semi-structured and unstructured. It is mostly unstructured interviews that have been used during this master thesis, which means that the interviews have been spontaneously when thoughts and ideas have emerged. Some structured interviews have taken place via email where the interviewee has answered predefined questions. [7]

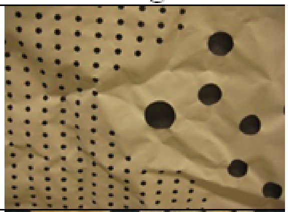
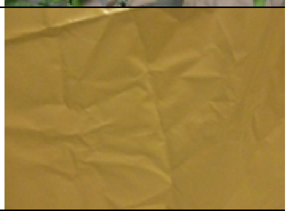
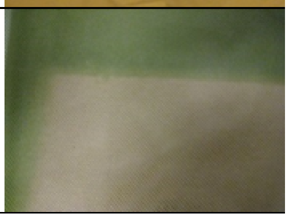
### 3.1.3 Field Trip to Saab Barracuda AB

A field trip to Saab Barracuda AB was made early in the project. The aim with the field trip was to learn more about camouflaging of military equipment such as vehicles, radars and weapons but also humans. The trip was also about receiving camouflage nets from Saab Barracuda to use during the test of radar performance.

Saab Barracuda started the field trip with a presentation of their organization and their view of the camouflage area. A short tour was made through their factory where the camouflage-colouring and the shaping of their textiles were observed. Barracuda also showed several test-areas where camouflage nets get tested for robustness as they endure different environmental conditions and a test lab where the nets are tested for their radar invisibility and transparency.

The camouflage nets that were provided from Barracuda consisted of seven radar transparent textiles presented in Table 3.1:

**Table 3.1:** Camouflage nets provided from Saab Barracuda AB.

| Art.nr | Description | Picture of Camouflage Net |
|---|---|---|
| 104408 | Colour coated polyester fabric |  |
| 101593 | *ULCAS* - Camouflage consisting of a leaf punched garnish attached to a backing. The garnish is dyed knitted fabric. The backing is colour coated polyester knit fabric. |  |
| 108832 | *ARCAS* - Colour coated polyester knit fabric |  |
| 828107 | Dyed knitted polyester fabric |  |
| 820904 | *C-90* - Leaf punched PVC attached to a net frame |  |
| 726071 | PVC coated polyester fabric |  |
| 101362 | Dyed leaf punched polyester fabric |  |

### 3.1.4 Market Research

As Saab Barracuda AB is not the only actor on the market of camouflage solutions a brief research was performed where the largest competitors were defined. Israeli Fibrotex, Swiss SSZ and Polish Miranda are all eminent in the area. Due to regulations and secrecy within the military sector, limited amount of information was available.

**Saab Barracuda AB**
The following information about Barracuda was provided from Johan Jersblad[1] during the field trip.
*Company size (number of employees)*: 170
*Number of countries served*: 58 (USA and India largest export clients)
*Products*: Saab Barracuda AB is world leading in camouflage and advanced signature adaptation. Barracuda has many years of experience of development in the front end of technology with innovations such as the world's first fully multispectral camouflage, the first true 3D camouflage and the first mobile multispectral camouflage solution. The engineers at Barracuda are specialists on all sensors threats and has in-house signature, material test equipment, field testing experience participation in internal research groups and environmental characterisation.
*Camouflage nets*: The nets are both in 2D, 3D and both sided. The nets provide protection in the whole sensor threats spectra.

**FibroTex**
*Company size (number of employees)*: –
*Number of countries served*: –
*Products*: FibroTex develops stealth solutions in the shape of mobile platforms, camouflage nets, observation posts and modular camouflage systems. Personal camouflage systems and post protection are also developed.
*Camouflage nets*: FibroTex's camouflage nets provide full protection against sensors in the UV, visual, near-IR, thermal and radar spectra. The camouflage nets are offered with two sides printing for changing environment use and 2D lightweight systems. The nets have visibility inside-out, low-storage and are easily deployed. [10]

**SSZ**
*Company size (number of employees)*: –
*Number of countries served*: –
*Products*: SSZ develops a thermal infrared suit IRDB that is based on low emissivity surface and reduces the thermal signature of a soldier with 7-10 °C (SSZ-Camouflage, 2016). Sniper suits, 2D and 3D static camouflage nets and mobile camouflage systems are also developed.
*Camouflage nets*: SSZ focuses in optimising the balance between weight and strength on their nets. Extra importance is put to durability and usability of the systems. Fabrics that not get stiff in lower temperatures are used. The nets are effective to use from cm-waves to UV radiation. [36]

**Miranda**
*Company size (number of employees)*: $> 500$
*Number of countries served*: –
*Products*: Miranda offers camouflage nets, individual camouflage, mobile camouflage and military camouflage accessories.
*Camouflage nets*: Their camouflage nets are both in 2D, 3D and both sided. The nets provide protection in VIS, NIR, TIR, RADAR and UV spectra. They focus in providing nets with low water absorption (under 20 %), high tensile strength, resistance to tearing and light weight. [17]

[1] Johan Jersblad (Senior Development Engineer, R&D | Saab Barracuda AB), interviewed by authors January $28^{th}$ 2016.

However, as Barracuda belongs to Saab Group AB and the other companies provide similar products, decisions were made that camouflage nets for tests provided by Saab Barracuda AB were sufficient for this master thesis research.

Research was also conducted on several competitors to Saab's ground based radar systems in order to investigate if there are any radar antenna camouflage solutions that are present on the market today. Competitors such as Raytheon, Thales, Selex and ELTA were investigated. Since there is limited information online within the defence area no solutions or products were found during this research.

## 3.2 Quantitative Methods - Small Scale Testing

The quantitative study of this master thesis can be divided into two halves. The first half describes the small scale testing that was conducted with help of a microwave network analyser and two small sized radar horns. The second half, see Section 3.3, describes similar conducted test but on full scale radar systems.

The quantitative study's aim was to find out how much a camouflage net affects the radar performance of a radar system if placed in front of the antenna considering radar range and pointing error. IR characteristics for the different camouflage nets and the visual characteristics for different constellations of nets in front of an antenna were also observed.

### 3.2.1 Radar Performance

The following subsections describe the test environment that was used during the small scale testing of radar performance. Methods and formulas for converting measured attenuation into loss in radar range and measured phase deviation into pointing error are also presented here.

#### 3.2.1.1 Test Environment

The small scale tests were performed in a temporarily unoccupied office section at Saab Surveillance. The test equipment consisted of a microwave network analyser *HP8720es* that was linked to two radar horns; a transmitter and a receiver. The two radar horns were placed opposite each other on individual desks with a distance of approximately 1.5 meter from each other. Between the two antennas the ends of the camouflage nets were attached in the ceiling enabling them to hang down between the antennas. Figure 3.1 visualises the camouflage net test setup.

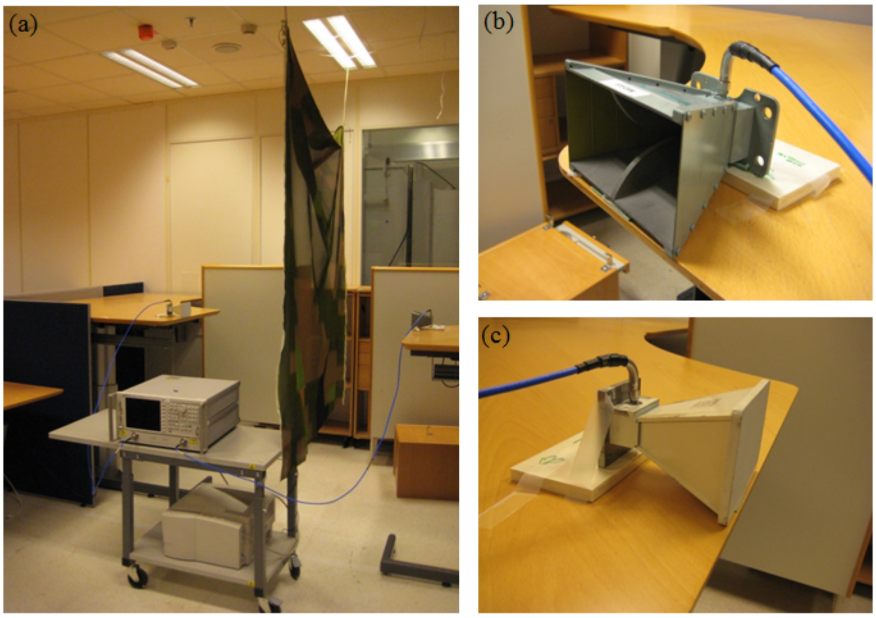



**Figure 3.1:** (a) Visualises the overall setup for the small scale tests. (b) Visualises the transmitting horn and (c) visualises the receiver horn.

The working procedure for the tests was performed according to the following list:

1. First the test equipment was calibrated by performing a measurement of the attenuation and the phase without any camouflage net between the antennas.

2. Then a camouflage net was hanged in between the radar horns and the shifting in the attenuation and the phase was registered and saved on a floppy for further analyses.

The network analyser was put on a frequency span of 2-12 GHz and sweep time of 1 second. The displayed scale was set to 0.1 dB for attenuation analysis and 1° for phase analysis. The integrated averaging tool was used for a more stable signal.

To be able to show intuitive results all measured values was imported to MATLAB and plotted with the MATLAB plot function. To be able to give a clearer overview of the measured attenuation and phase deviation a Savitzky-Golay filter was added to all plots. The Savitzky-Golay filter is a smoothing filter that is usually used to "smooth out" noisy signals with large frequency span. [25]

#### 3.2.1.2 Radar Range

To be able to measure how much the attenuation from the tests are affecting the range of the radar system the radar equation, described in Section 2.4.2, was multiplied with a attenuation constant in MATLAB. The formula was multiplied by two as the transmitter and the receiver in the test environment only measured in one direction. By taking the fourth root of the relations between the signal powers the relation between the radar ranges can be received.

The following example illustrates a case where the attenuation is 3 dB (two ways), which means that the power output has dropped by half.

$$R = \sqrt[4]{\frac{P_S G^2 \lambda^2 \sigma}{P_E (4\pi)^3}} \tag{3.1}$$

$\mathrm{R}_1 = \text{known} = \sqrt[4]{K}$
$R_2 = \text{unknown} = \sqrt[4]{0.5 * K}$
$R_2 = \sqrt[4]{0.5 * K} = \sqrt[4]{0.5} * R_1 = 0.84 * \mathrm{R}_1$

#### 3.2.1.3 Pointing Error

As mentioned in Section 2.4.3, the pointing error is of importance in order to get a reliable radar system that can locate the target correctly. The pointing error is dependent on the phase deviation which is dependent on the characteristics and suspension of the material the wavelengths are traveling through. Figure 3.2 visualises how the thickness and incidence angles can vary over the camouflage net depending on how the net is suspended over the antenna. As long as the thickness of the net is the same over the antenna the signal is delayed equally over it and will not result in a pointing error.

The figure also describes that the size of the antenna is of importance if the camouflage net hangs in the shape of an arc in front of the antenna as the incidence angle becomes different across the antenna which leads to different phase gradients over it. The deviation in phase gradients in relation to the size of the antenna gives an indication of the pointing error. In the case of a constant phase gradient across the antenna the size of the antenna is of no importance.

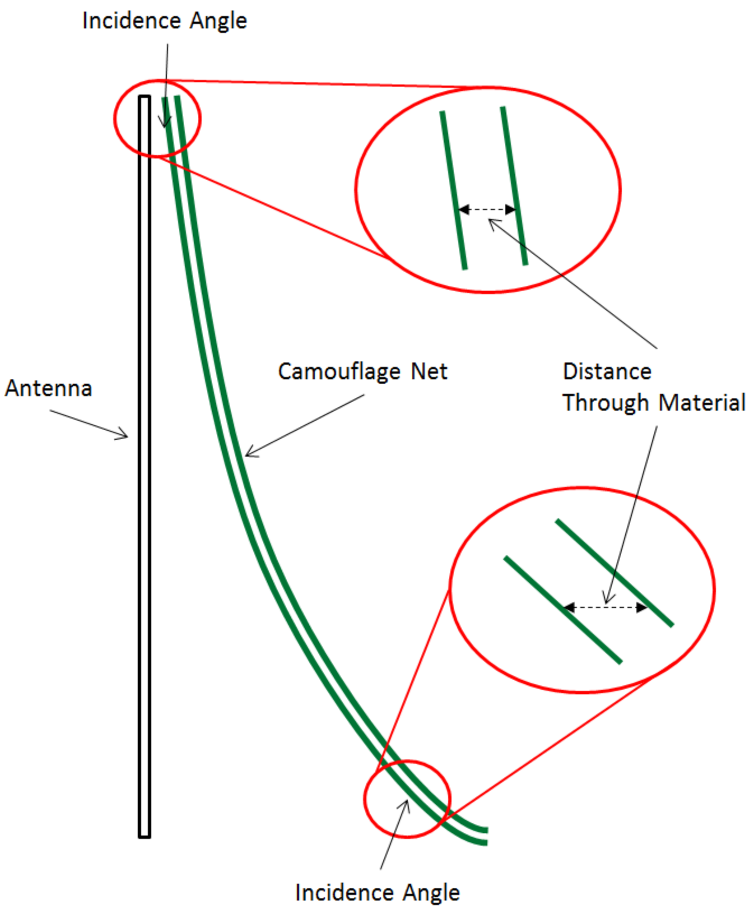



**Figure 3.2:** Visualisation of possible thickness variation of camouflage net over the antenna.

To be able to calculate the pointing error the path deviation has to be calculated first. The path deviation is the phase deviation converted to distance. The calculation is based on the wavelength, the phase deviation and a scaling factor representing the thickness variation in the net depending on the angle, see equation 3.3.

The phase deviation over the interesting frequency spectra, measured during the small scale testing, was used to calculate approximated pointing errors during this master thesis. In order to calculate the pointing error a simplified calculation model, see Figure 3.3, was created together with the provided supervisor from Saab, Erik Lindälv[2]. The calculation model was converted into a MATLAB script where the pointing error can be calculated and analysed, see Appendix A.

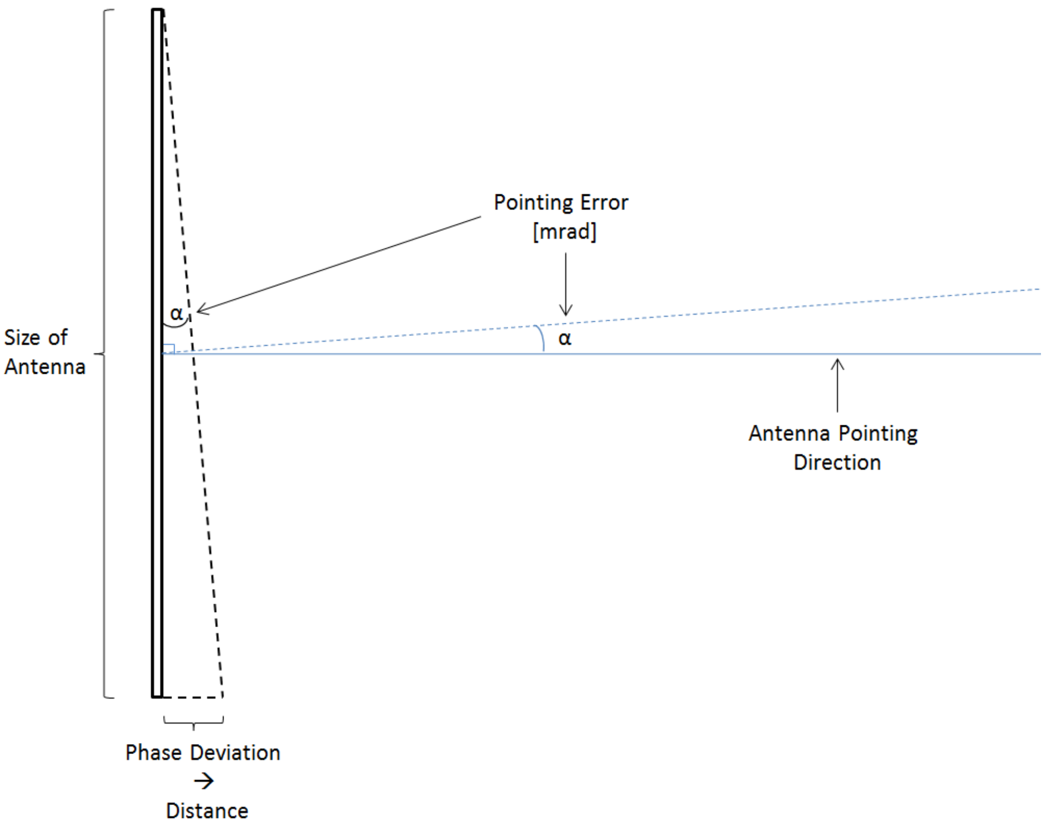



**Figure 3.3:** Simplified calculation model for pointing error.

$$\text{Scale} = \frac{1}{cos(\text{angle of camouflage net})} - 1 \tag{3.2}$$

$$\text{Path Deviation [mm]} = \frac{c}{f} * \frac{phase}{360} * Scale * 1000 \tag{3.3}$$

$$\text{Pointing Error [mrad]} = 1000 * atan(\frac{\text{Path Deviation}}{\text{Size of Antenna}}) \tag{3.4}$$

Where:
c = speed of light
f = frequency (2 GHz - 12 GHz)
scale = scaling factor (measure of variation in camouflage net thickness depending on angle of camouflage net)
phase = phase deviation measured from tests for each frequency

[2]Erik Lindälv (System Engineer | Saab Surveillance), interviewed by authors February $16^{st}$ 2016.

### 3.2.2 IR Test Environment

The camouflage net's IR characteristics were measured by a thermal camera. As there was no proper antenna available one of the authors of this thesis was acting antenna and hiding behind the camouflage nets. The surrounding temperature was 18° Celsius and the author's surface temperature was approximately 30° Celsius. By camouflaging only the lower half of the author the "not camouflaged" part can act as a reference when conducting how much the camouflage nets were filtering out in the IR spectra.

### 3.2.3 Visual Perspective Test Environment

The visual spectra was observed by letting a small scale model (scale 1:12) of the GIRAFFE 4A antenna rotate while the camouflage nets were deployed in front of them. To make the surroundings more lifelike a camouflage net was suspended as background, visualised in Figure 3.4, and a spotlight pointing to the front of the camouflage net was acting sun. The main object with these tests was to find out which type of net, or combination of nets, that camouflage a stationary antenna, a rotating antenna and the reflection of the antenna the best.

**Figure 3.4:** Arrangement for small scale visual tests. Camouflage net 828107 in the background.

## 3.3 Quantitative Methods - Full Scale Testing

The results from the small scale testing attracted interest for further, more reliable, investigation, which led to that the second half of the quantitative study was conducted on full scale radar systems. The main target with these tests was to gather consistent knowledge of how much a camouflage net impact the radar performance of the radar systems. Focus was also put on the visual perspective to camouflage the GIRAFFE AMB antenna's rotation and glare. The IR signature was left out from investigation as it is more dependable of the camouflage net's material than on the camouflage solution itself.

Following subsections describe the full scale test environment and setups for the radar systems; GIRAFFE AMB, GIRAFFE 4A, ARTHUR and GIRAFFE 1X.

### 3.3.1 GIRAFFE AMB - Test Envrionment

Figure 3.5 visualises two different GIRAFFE AMB antennas that were used during the full scale testing. Figure 3.5a presents the antenna used for radar performance tests and Figure 3.5b presents the antenna used for visual tests.

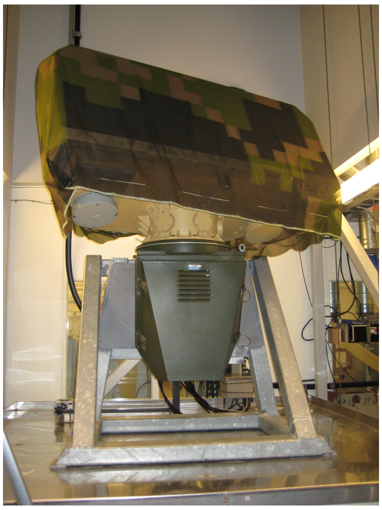
**(a)** GIRAFFE AMB antenna used for radar performance tests. **(b)** GIRAFFE AMB antenna used for visibility tests on Savannen.

**Figure 3.5:** GIRAFFE AMB antennas used during different tests.

The testing of radar performance for the GIRAFFE AMB was performed in a measurement laboratory at the top floor in the Saab Surveillance building. In this laboratory is it possible to mount an antenna on a turntable which is mounted on an elevator, Figure 3.5a, and then lift it through the ceiling to the roof on the building. This enables testing of performance for the antennas. Radar performance was measured towards transponders and a light house. The tests were performed both with and without camouflage at a frequency of approximately 5.5 GHz.

The tests were performed in a clear and sunny weather using a dry and clean camouflage nets.

The testing of visual perspective was performed outside at one of the test sites called "Savannen" nearby the Saab Surveillance building. Savannen is located at the top of a hill and is used for testing and demonstration of the different radar systems. Figure 3.5b visualises the system that was used during this test. In order to save data from this test one of the authors was placed in the Saab building at ninth floor with a view over Savannen 500 m (straight line) from it. From this spot a video camera was mounted and recorded the test procedure and the movement of the antenna. The other author was placed at Savannen with a technician and handled the mounting of different camouflage nets on the antenna and also the control of the system. In order for the camouflage nets to be attached on the antenna a temporary "cap" was created to fit around it. The attached camouflage nets are visualised in Figure 3.6, which presents the attachment during both the radar performance test and the visual test. Both the radar performance and the visibility tests were performed using a dry and clean camouflage net.



**(a)** Attachment of camouflage net 101362 during radar performance tests on GIRAFFE AMB.

**(b)** Attachment of camouflage net 101593 during radar performance tests on GIRAFFE AMB.

**(c)** Attachment of camouflage net 101362 during visibility tests on GIRAFFE AMB.

**(d)** Attachment of camouflage net 101593 during radar performance tests on GIRAFFE AMB.

**Figure 3.6:** Attachment of camouflage net 101362 and 101593 during different tests.

### 3.3.2 GIRAFFE 4A - Test Environment

The full scale tests regarding radar performance for the GIRAFFE 4A Demo Sensor System were performed at the same test site, Savannen, as the visibility test was performed for the GIRAFFE AMB system. For the GIRAFFE 4A the tests were performed both with and without camouflage at a frequency of approximately 3.3 GHz. The radar performance was measured towards a transponder placed on the Saab Surveillance building. This transponder enables the possibility to simulate a target at a fixed distance, in this case the target was simulated to be at a distance of approximately 19 000 m. The radar performance was tested in a stationary system mode, not rotating. Figure 3.7 visualises the radar system with a camouflage net on it. The camouflage net was attached at the top-back of the antenna and hanged in front of it. The tests were performed in a clear and sunny weather using a dry and clean camouflage net.

**Figure 3.7:** Attachment of camouflage net 101593 on the GIRAFFE 4A antenna.

### 3.3.3 ARTHUR - Test Environment

The test environment for the measurement of the radar performance of the ARTHUR reference radar system was similar to the test environment of the GIRAFFE AMB located in the Saab Surveillance building. As visualised in Figure 3.8 different net setups were measured in order to explore if different angles of incidence to the net can affect the radar performance. The tests were performed both with and without camouflage at a frequency of approximately 5.4-5,9 GHz. The frequency varies depending on the elevation since the lobe is controlled by the frequency.


(a) Attachment of camouflage net 101593 on the ARTHUR antenna in straight position.

(b) Attachment of camouflage net 101593 on the ARTHUR antenna in tilted position.

**Figure 3.8:** Different types of attachments of camouflage net 101593 during full scale tests of ARTHUR antenna.

The radar performance for the ARTHUR reference system was measured for five different pre-conditions. First was the camouflage net deployed in front of a straight standing antenna and measurements of how much the camouflage net affected the radar performance were conducted. Then was the antenna tilted, first with an elevation of 10° and then 18°, which corresponds to an antenna that is tilted 3°- 4°. This enabled measurement of an angled camouflage net. It is of interest how the angles of incidence to net affect the radar performance due to aspect of what different geometrical shapes a camouflage structure can take without inflict too much on the radar performance. Last were measurements on a turned antenna conducted with an azimuth of -115° and 115°, which corresponds to an antenna that is laterally turned approximately 40° from the starting position in both directions. These tests were performed in a clear and sunny weather using a dry and clean camouflage net.

On a later occasion further tests were conducted, but this time when the camouflage net was soaked in fresh water before it was deployed in front of the antenna. This was to investigate if a camouflage solution exposed to external conditions, such as rain, might have a negative impact on the radar performance. The same setup was used as for a dry camouflage net even though only three of the five preconditions were investigated. The first test was performed on a straight standing antenna and the second (elevation of 10°) and third (elevation of 18°) tests on a tilted antenna. Measurements were first conducted on an antenna without net, then on an antenna with a wet net in front and then last on an antenna without net again. Same frequency span was used for these tests and the tests were performed during cloudy weather conditions.

### 3.3.4 GIRAFFE 1X - Test Environment

The testing of radar performance for the GIRAFFE 1X system was performed in a measurement laboratory at A15 in Mölndal. In this laboratory it is possible to mount an antenna on a turntable or arm which in itself is mounted on an arm and enables the antenna to rotate freely in the room. Figure 3.9 visualises the area where the antenna and the camouflage net were tested. The tests were performed both with and without camouflage at a frequency of approximately 9 GHz. The tests were performed using a dry and clean camouflage net. [30]

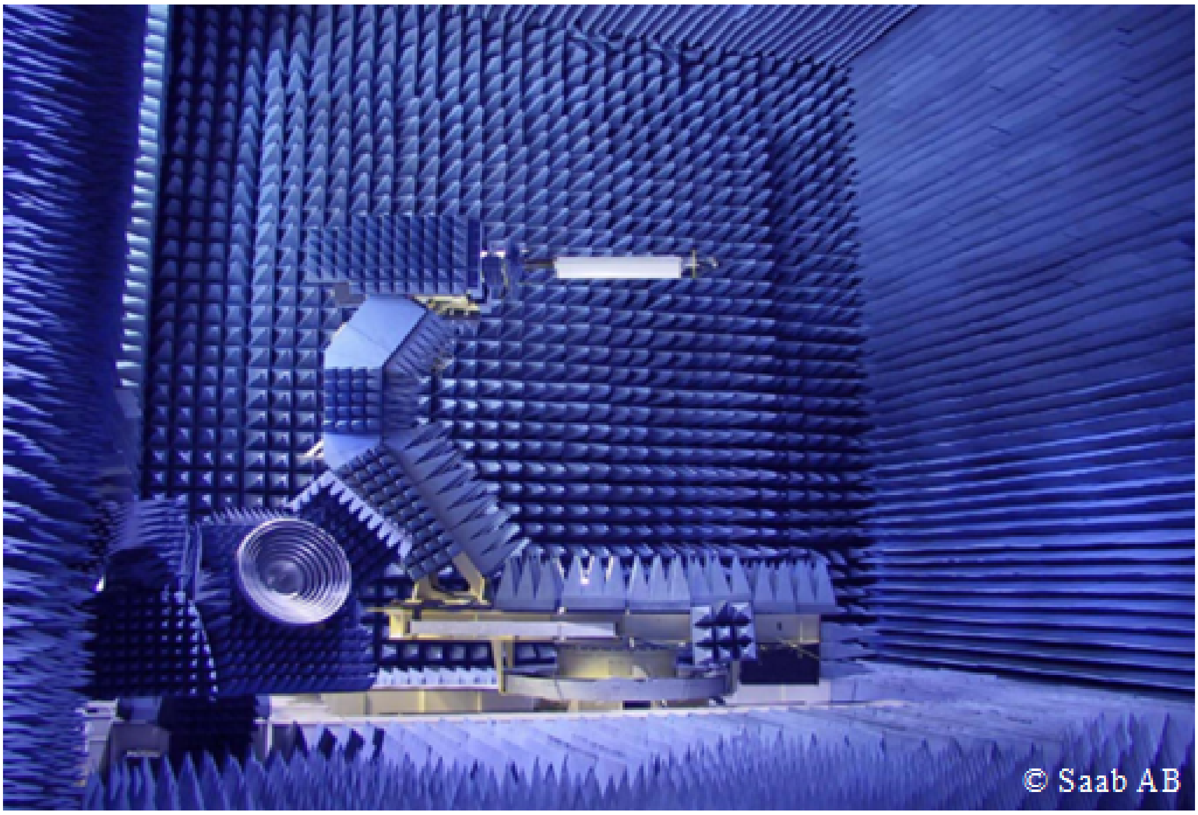
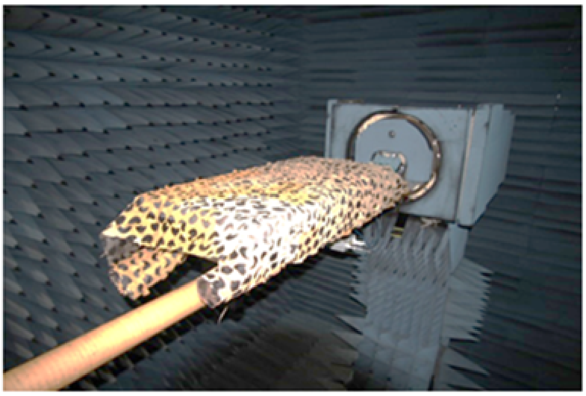



**Figure 3.9:** Radar performance measurement laboratory A15. The figure was provided by Saab AB with their permission.

Since the GIRAFFE 1X still is in the development and testing phase only the antenna plate with slots connected with measuring cables was used. Added between the antenna plate and the camouflage net a layer of ROHACELL® was used in order to not damage the slots and to get a distance between the plate and the net. ROHACELL® is a lightweight foam construction, ideal for high performance sandwich structures and used in the radome inside the antennas developed by Saab. The installation of the antenna plate is visualised in Figure 3.10. Figure 3.10 also visualises how the ROHACELL® was attached on the antenna plate (double-sided tape) and how the camouflage net then was attached outside the ROHACELL®. [9]

**(a)** Attachment of camouflage net and ROHACELL® from behind.



**(b)** Attachment of camouflage net and ROHACELL® from the side.

**Figure 3.10:** Visualisation of how camouflage net 101593 was attached during full scale tests on GIRAFFE 1X.

# 4
# Results

*This chapter presents the quantitative study in terms of results from the two testing phases that were performed during the project. The two phases are small scale testing and full scale testing, as described in Section 3.2 and Section 3.3. These parts are then divided into radar performance and visual aspects.*

## 4.1 Small Scale Testing

The main objects with the small scale tests were to find out basic knowledge about the seven camouflage nets and get an understanding of how they affect the radar performance, visibility of the radar antenna and IR signature. This testing phase can be divided into three main areas where each of the areas responds to the focus areas for this thesis; radar performance, IR- and visual camouflage. All tests were done by using the seven camouflage nets, see Table 3.1 in Section 3.1.3, from Saab Barracuda AB in various setups. The tests were performed one-way.

### 4.1.1 Radar Performance

The tests regarding impact on radar performance were focused on signal attenuation and phase deviation. The impact from the camouflage nets were observed through different conditions such as angle of incidence, distance to the radar horns, environmental conditions.

Results for the frequencies 3 GHz, 5.5 GHz and 9 GHz were of most interest since these frequencies are close to the operating frequencies for the focus antennas in this thesis, presented in Section 2.5.

In order to present the results consistently with the right measurement accuracy this chapter presents attenuation with one significant figure and phase deviation with three significant figures.

#### 4.1.1.1 Attenuation and Radar Range

Attenuation is the power that decreases, limits or prevents oscillations in a system. The first attenuation tests were performed by letting the camouflage nets hang between the antennas on a distance of 0.3 m from the transmitter. These tests were aiming to find out how much a camouflage net affects the attenuation of the transmitted power. It is important that the attenuation is not affected significantly (not more than 1 dB, one-way, according to Lindälv[1]) as a high attenuation decreases the performance (range) of the radar system. The results are presented in Table 4.1. [15]

[1]Erik Lindälv (System Engineer | Saab Surveillance), interviewed by authors February $4^{th}$ 2016.

**Table 4.1:** Summary of attenuation for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with dry camouflage nets as a function of type of net (Art.nr). The measured values are in dB.

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 104408 | **-0.003** | **-0.008** | -0.01 | **-0.02** | -0.03 |
| 101593 | **-0.01** | **-0.02** | -0.03 | **-0.04** | -0.04 |
| 108832 | **-0.0003** | **-0.006** | -0.009 | **-0.01** | -0.02 |
| 828107 | **0.005** | **0.004** | 0.004 | **0.003** | 0.002 |
| 820904 | **0.01** | **-0.002** | -0.01 | **-0.02** | -0.03 |
| 726071 | **-0.0007** | **-0.01** | -0.02 | **-0.03** | -0.04 |
| 101362 | **-0.006** | **-0.005** | -0.005 | **-0.005** | -0.004 |

As can be seen in the table above the attenuation caused by the camouflage nets was not significant. The nets that resulted in higher attenuation where the thickest nets, but the difference in attenuation was small compared to the thinner nets.

Further, similar tests as the one described above were made that aimed to observe if distance of the camouflage nets to the transmitter and different angles of incidence (15° and 30°) of the camouflage nets had any affection of the radar performance. These tests showed no remarkable difference in attenuation from the first test above and can be found in Appendix B.

The nets that had showed to have the lowest attenuation in the previous performance tests and were of most interest regarding the visibility and user-friendliness were sprayed with fresh and salt water. This was done in order to observe how the attenuation can be affected by environmental conditions such as rain. The results from the fresh water measurements are presented in Table 4.2 and show some increase in attenuation compared to dry nets. All values were below the limit of 1 dB.

**Table 4.2:** Summary of attenuation for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with camouflage nets sprayed with fresh water as a function of type of net (Art.nr). The measured values are in dB.

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 101593 | **-0.4** | **-0.5** | -0.6 | **-0.8** | -0.9 |
| 828107 | **-0.02** | **-0.01** | -0.008 | **-0.002** | 0.005 |
| 101362 | **-0.002** | **-0.03** | -0.04 | **-0.06** | -0.09 |

By using the results regarding attenuation for dry and wet camouflage nets made it possible to calculate how the radar range was affected, see Section 3.2.1.2. As can be viewed in Table 4.3 the impact of the radar range is not significant for a dry camouflage net on a distance of 0.3 m from the transmitter. It is almost non-existent for the thinnest camouflage net 828107 where 100 % indicates no decrease in radar range.

**Table 4.3:** Summary of attenuation converted to radar range, where 100 % refers to original range, for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with dry camouflage nets as a function of type of net (Art.nr).

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 104408 | **100 %** | **99.9 %** | 99.8 % | **99.7 %** | 99.6 % |
| 101593 | **99.8 %** | **99.7 %** | 99.7 % | **99.6 %** | 99.5 % |
| 108832 | **100 %** | **99.9 %** | 99.9 % | **99.8 %** | 99.8 % |
| 828107 | **100 %** | **100 %** | 100 % | **100 %** | 100 % |
| 820904 | **100 %** | **100 %** | 99.9 % | **99.8 %** | 99.7 % |
| 726071 | **100 %** | **99.9 %** | 99.8 % | **99.7 %** | 99.6 % |
| 101362 | **99.9 %** | **99.9 %** | 99.9 % | **99.9 %** | 99.9 % |

Wet camouflage nets affect the radar range more which is presented in Table 4.4.

**Table 4.4:** Summary of attenuation converted to radar range, where 100 % refers to original range, for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with camouflage nets sprayed with fresh water as a function of type of net (Art.nr).

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 101593 | **96.1 %** | **94.2 %** | 93.0 % | **91.5 %** | 90.0 % |
| 828107 | **99.8 %** | **99.9 %** | 99.9 % | **100 %** | 100 % |
| 101362 | **100 %** | **99.7 %** | 99.5 % | **99.3 %** | 99.0 % |

#### 4.1.1.2 Phase Deviation and Pointing Errors

This subchapter presents the phase deviation results from the small scale tests and how these results affect the pointing error. In difference to attenuation there is no determined max limit of what the phase deviation can reach as long it is linear over the antenna.

The phase deviation was measured and saved at the same time and in the same way as the attenuation. The same setup regarding the camouflage nets was used as in the attenuation case; distance of 0.3 m and 1.0 m with a dry net (angle of incidence 0°), angle of incidence 15° and 30° with a dry net (distance of 0.3 m), net sprayed with fresh and salt water (angle on incidence 0° at a distance of 0.3 m). The results presented in this subchapter are phase deviation for camouflage nets at a distance of 0.3 m from the transmitter horn and camouflage nets sprayed with fresh water at a distance of 0.3 m from the transmitter horn. Additional results can be found in Appendix B.

Table 4.5 presents the trend values of the filtered signals for chosen frequencies in the span of 2-12 GHz with camouflage nets deployed 0.3 m from the transmitter horn and with an angle of incidence at 0°. As can be viewed in Table 4.5 camouflage net 828107 clearly results in the least impact on the phase deviation compared to camouflage net 726171, which results in the largest impact due to its thicker material structure. Notably, the higher the frequency is the more phase deviation is induced.

**Table 4.5:** Summary of phase deviation for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with dry camouflage nets as a function of type of net (Art.nr).

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 104408 | **-0.729°** | **-1.25°** | -1.57° | **-1.99°** | -2.41° |
| 101593 | **-0.682°** | **-1.19°** | -1.50° | **-1.91°** | -2.32° |
| 108832 | **-0.691°** | **-1.18°** | -1.48° | **-1.87°** | -2.26° |
| 828107 | **-0.0572°** | **-0.169°** | -0.237° | **-0.327°** | -0.416° |
| 820904 | **-0.652°** | **-1.01°** | -1.28° | **-1.64°** | -2.00° |
| 726071 | **-1.24°** | **-2.26°** | -2.87° | **-3.68°** | -4.50° |
| 101362 | **-0.238°** | **-0.463°** | -0.599° | **-0.780°** | -0.960° |

The results show that high frequencies get notable phase deviation from the camouflage nets.

Table 4.6 presents the phase deviation results from the camouflage nets that were sprayed with fresh water. As visualised in the table camouflage nets get considerably higher phase deviation when sprayed with fresh water than they got when they were dry. These tests were only conducted for three camouflage nets as these nets had shown to be of most interest.

**Table 4.6:** Summary of phase deviation for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with camouflage nets sprayed with fresh water as a function of type of net (Art.nr).

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 101593 | **-3.97°** | **-4.69°** | -5.13° | **-5.71°** | -6.28° |
| 828107 | **-0.378°** | **-0.757°** | -0.984° | **-1.29°** | -1.59° |
| 101362 | **-0.753°** | **-1.30°** | -1.63° | **-2.07°** | -2.51° |

Only two materials are presented in this section for the pointing error analysis. The results are based on the phase deviation for camouflage net 828107 and 726071 since they are the nets with the highest and lowest phase deviation. The incidence angle of the camouflage net was set to 10° and 60° relatively the radar horns in order to detect any deviation in pointing errors. Figure 4.1 and Figure 4.2 present the pointing errors for camouflage net 828107 and Figure 4.3 and Figure 4.4 present the pointing errors for camouflage net 726071. As can be viewed in the figures the MATLAB analysis regarding the pointing errors indicated that impact from the phase deviation was insignificant.

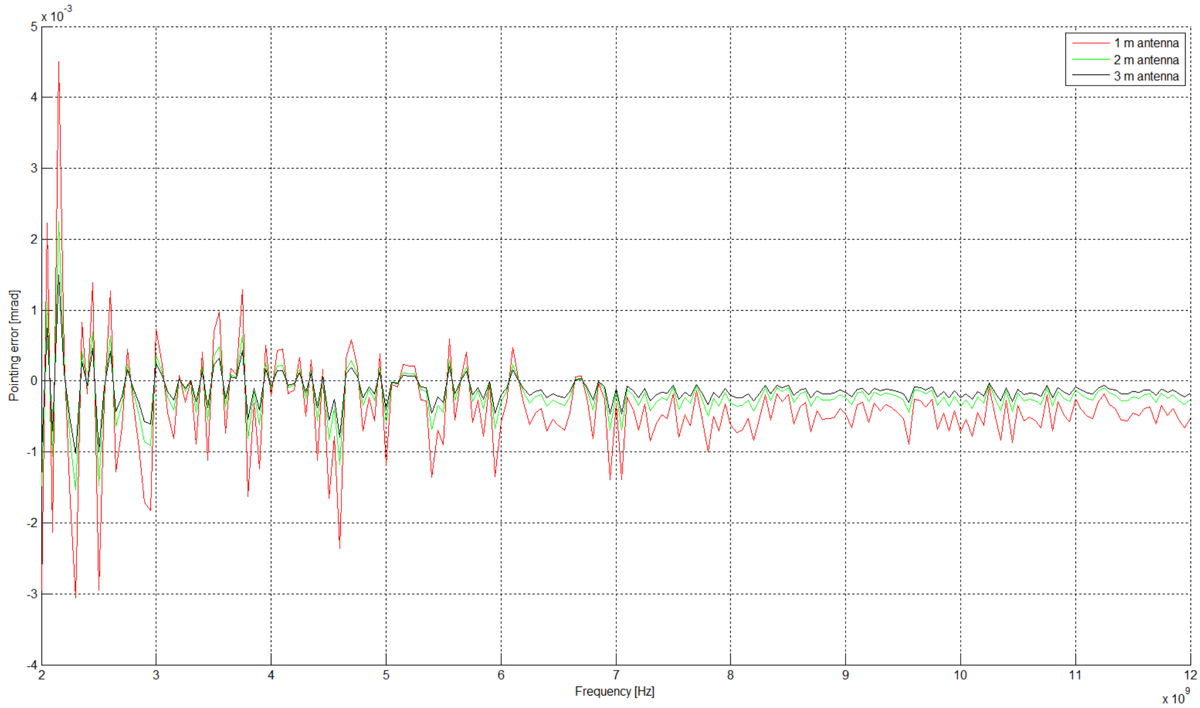



**Figure 4.1:** Pointing error in milli-radians for three sizes of antennas covered by net 828107 at a distance of 0.3 m and an incidence angle of 10° from the radar horns as a function of frequency.

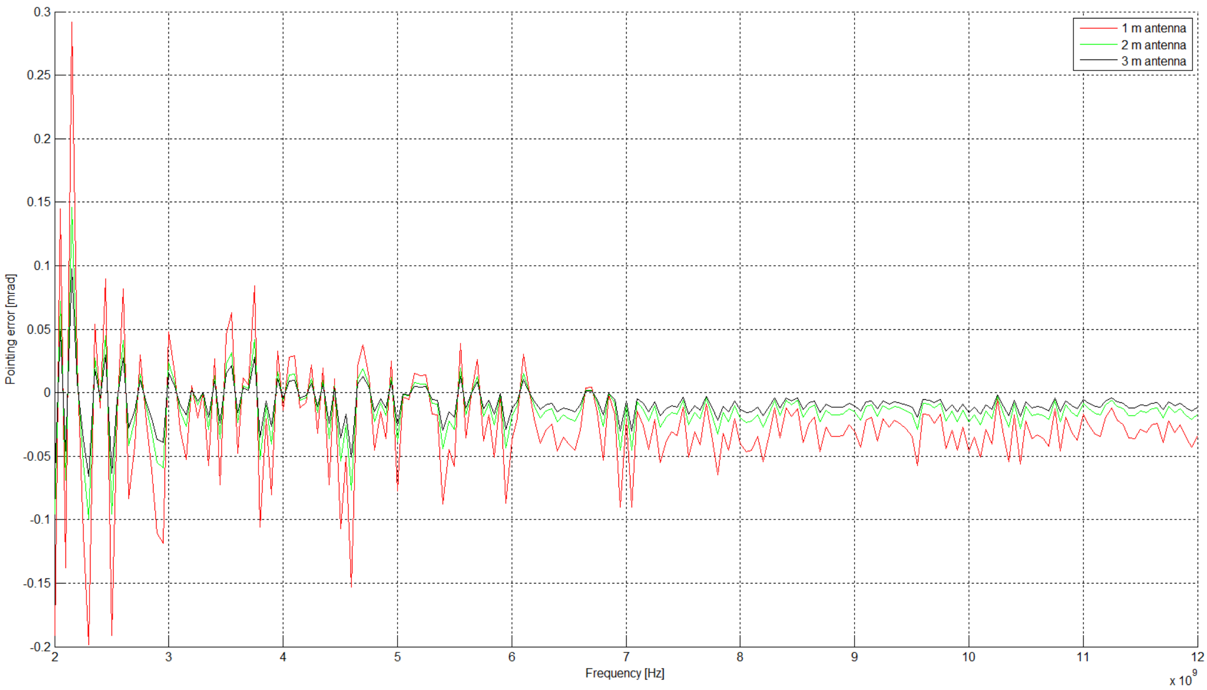



**Figure 4.2:** Pointing error in milli-radians for three sizes of antennas covered by net 828107 at a distance of 0.3 m and an incidence angle of 60° from the radar horns as a function of frequency.

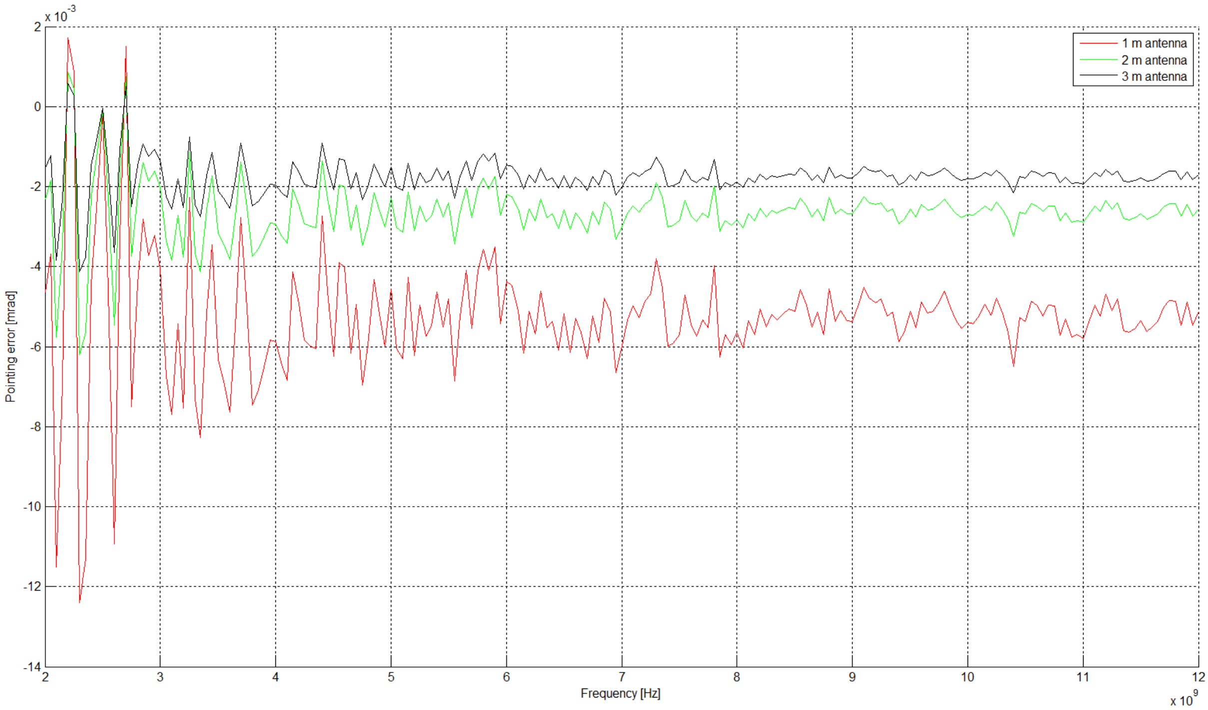



**Figure 4.3:** Pointing error in milli-radians for three sizes of antennas covered by net 726071 at a distance of 0.3 m and an incidence angle of 10° from the radar horns as a function of frequency.

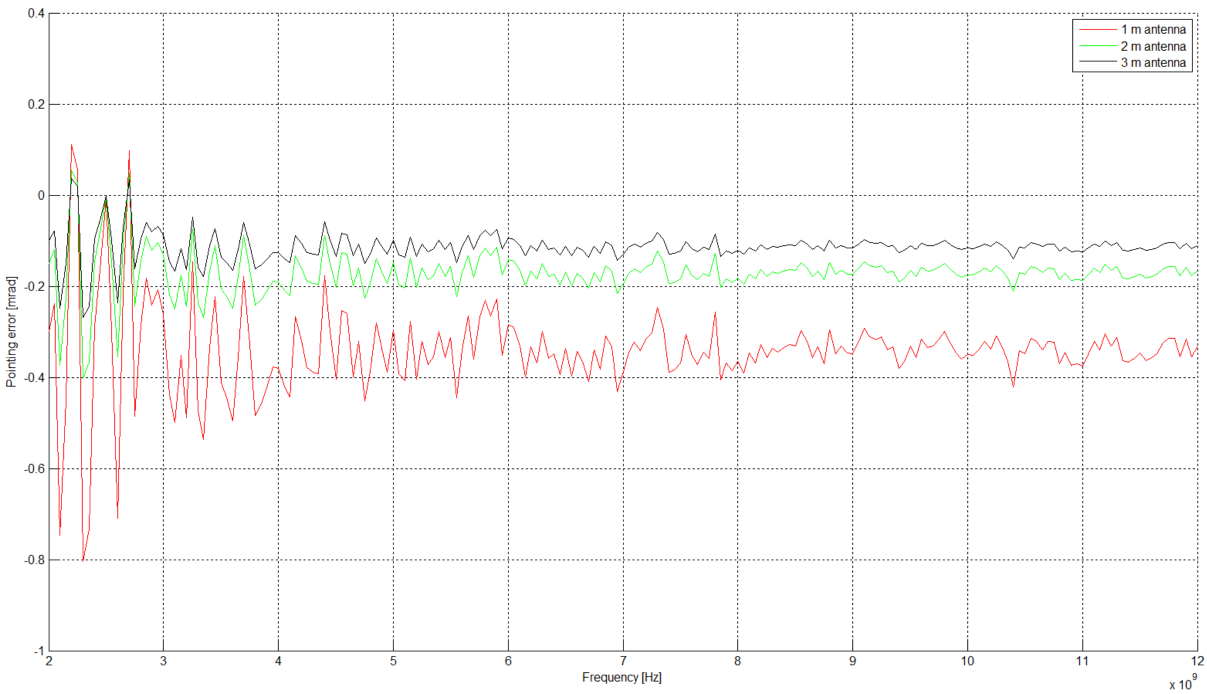


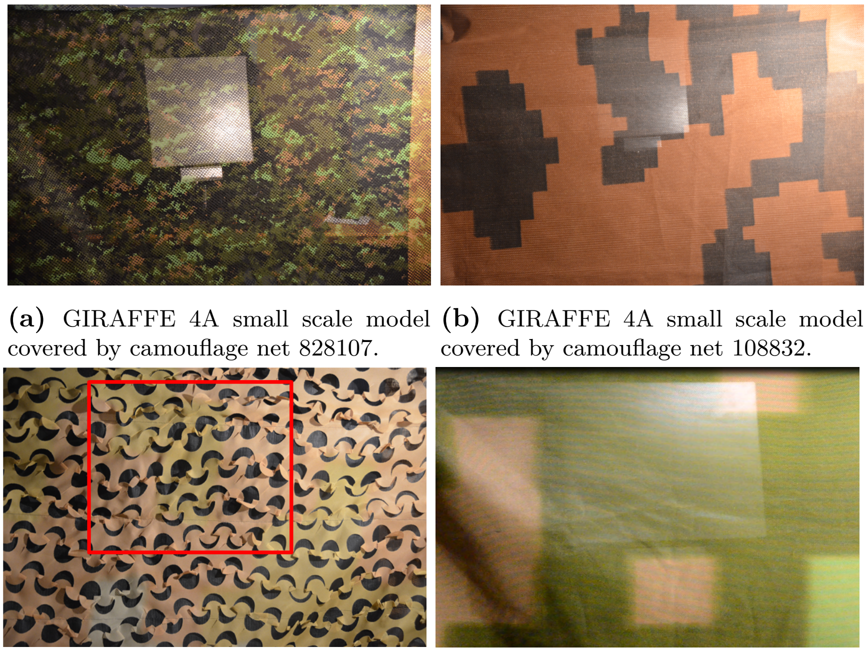

**Figure 4.4:** Pointing error in milli-radians for three sizes of antennas covered by net 726071 at a distance of 0.3 m and an incidence angle of 60° from the radar horns as a function of frequency.

### 4.1.2 IR Signature

In Appendix C the pictures regarding the camouflage nets IR signature are presented. The pictures demonstrate that thicker nets, 726071 and 726074, were hard to see through (low thermal transmission) and their contrast to the surrounding environment became sharper. Thinner nets with larger meshes (high thermal transmission) were not as good in hiding heat and contours of the object behind, but the nets contrast to the surrounding environment was more natural.

### 4.1.3 Visual Perspective

Four of the camouflage nets are demonstrated in Figure 4.5, where different nets were deployed in front of the antenna. As visualised in Figure 4.5c, camouflage net 101593, proved to be the net with best ability to visually conceal the antenna. The red rectangle indicates where the antenna is placed behind the net. A net with structure is accordingly best to use to break up and conceal the signature of the antenna. An observation was made that when a camouflage net, without structure, was put over the antenna as a cap and rotated with the antenna the reflection from the antenna's surface was moved to the surface of the net. So instead of solving the problem the nets without structure are moving the problem. For a stationery camouflage net this is not a problem.



**(a)** GIRAFFE 4A small scale model covered by camouflage net 828107.

**(b)** GIRAFFE 4A small scale model covered by camouflage net 108832.

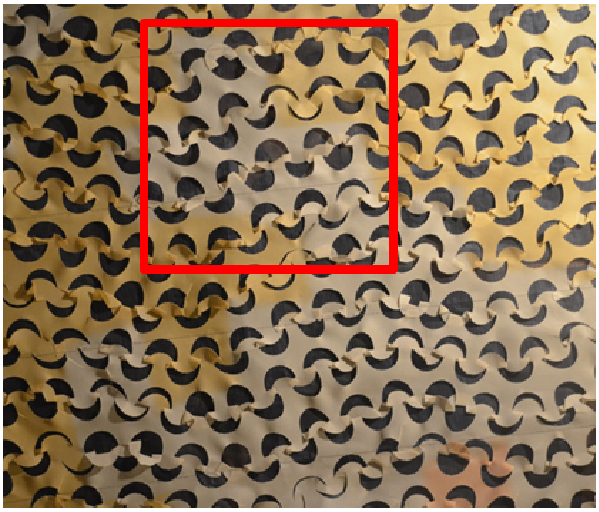
**(c)** GIRAFFE 4A small scale model covered by camouflage net 101593.

**(d)** GIRAFFE 4A small scale model covered by camouflage net 101362.

**Figure 4.5:** Small scale model of GIRAFFE 4A camouflaged by different camouflage nets.

During the visual tests an idea of using two different camouflage nets in different distances to the antenna occurred. The idea was based on using one thin camouflage with small meshes and uniform colour attached close to the antenna with the main task to camouflage the reflection of the antenna. A thicker more conformable camouflage with structure and pattern should then be placed in a short distance from the antenna with the main task to hide the appearance of the antenna. The results from these tests can be viewed in Figure 4.6. In Figure 4.6a net 101362 was used for both layers of camouflage and in Figure 4.6b net 101362 was used as "the inner" camouflage near the antenna and net 101593 was used as "the outer" camouflage a short distance from the antenna. The best observed combination of camouflage was alternative (b), see Figure 4.6b.

(a) GIRAFFE 4A small scale model covered by camouflage net 101362 in two layers.



(b) GIRAFFE 4A small scale model covered by camouflage net 101362 and 101593.

**Figure 4.6:** Small scale model of GIRAFFE 4A camouflaged by different camouflage nets in more than one layer.

Tests similar to previous radar performance tests presented in Section 3.2.1.1 were conducted on two camouflage nets attached between the measurement horns at the same time. The nets were placed approximately 0.3 m apart from each other. Table 4.7 presents the results regarding attenuation and Table 4.8 presents the results regarding phase deviation.

**Table 4.7:** Summary of attenuation for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with two layers of nets as a function of type of nets (Art.nr). The measured values are in dB.

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 101593 101362 | **0.02** | **0.02** | 0.03 | **-0.03** | -0.03 |
| 101593 two layers | **0.002** | **0.02** | 0.03 | **-0.05** | -0.06 |
| 101362 two layers | **-0.02** | **-0.01** | -0.01 | **-0.01** | -0.01 |

**Table 4.8:** Summary of phase deviation for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with two layers of nets as a function of type of nets (Art.nr).

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 101593 101362 | **-0.977°** | **-1.69°** | -2.12° | **-2.69°** | -3.26° |
| 101593 in two layers | **-1.12°** | **-2.05°** | -2.61° | **-3.36°** | -4.11° |
| 101362 in two layers | **-0.552°** | **-0.970°** | -1.22° | **-1.55°** | -1.89° |

These tests prove that the idea of using two nets as camouflage is feasible, as the attenuation and the phase deviation does not get critically affected by the nets. The attenuation is still below the limit of 1 dB and the phase deviation is still constant and linear. The attenuation and the phase deviation is more or less an addition between the two camouflage nets individual attenuation and phase deviation, presented in Section 4.1.1.

### 4.1.4 Usability

The camouflage nets usability was also considered upon during the small scale tests. Some of them were easy to handle and prepare for tests and some of them were heavy and stiff which made them less user friendly. The nets that were easy to handle were in general the ones with lowest phase deviation and the heavier nets resulted in general in a more significant phase deviation. The easiest camouflage nets to work with are presented in Figure 4.7, were Figure 4.7a represents camouflage net 828107 and Figure 4.7b represents camouflage net 101362.

**(a)** Camouflage net 828107.

**(b)** Camouflage net 101362.

**Figure 4.7:** Presentation of the easiest camouflage nets to work with.

The reason why the usability was investigated during the small scale tests was because of possible opportunities regarding further concept development. The investigation resulted in thoughts and ideas of how a camouflage net can affect redeployment of the radar systems.

## 4.2 Measurements Errors

During any kind of tests there are always measurement errors that need to be taken into consideration when analysing the results. Mainly three types of measurement errors were identified during the tests in this project and these are listed and described in this section. [1]

1. *Drift Errors* – Drift errors often cover the test systems changing of performance after a calibration. The network analyser that was used during the first tests had not been properly calibrated for a while, but the old calibration was still valid. The used transmitter and radar horn had not been calibrated for a while and according to Lindälv[2] these can not have a significant effect on the results. An internal calibration through the network analyser's calibration function was made before each camouflage net test in order to stabilise the signals. The small errors/noise that sill occurred can be further reduced through a re-calibration and a more stable test environment.

[2] Erik Lindälv (System Engineer | Saab Surveillance), discussion May 3$^{rd}$ 2016.

2. *Random Errors* – Random errors are unpredictable and cannot be completely removed through any error correction. Random errors for the performed tests are identified as connector/cable wear errors and instrument noise errors. The connectors/cables were controlled and can be ignored after an individual test of the equipment.
    (a) *Instrument Noise Errors* –This type of measurement error is often generated in the components of the network analyser. Noise can be described as unwanted electrical disturbance. When the internal calibration was done the function 'sweep average' was added in order to reduce the generated noise. The noise did not disappear completely but the remaining noise was at an accepted level.
3. *Systematic Errors* – These kind of measurements errors are probably the main reason for eventual errors during the performed camouflage net tests. Systematic errors are mainly caused by imperfection in the test environment/set up and the network analyser. Imperfection in the analyser can be tracked to the need of calibration as mentioned in the first bullet point. After analysis of the results the test environment was identified as a critical cause of errors. Difficulties in performing the tests in exactly the same way for all camouflage nets can affect the results. The test environment had to look the same for all nets and can not be changed during re-attachment of new camouflage net. Critical factors that affected the test environment were the operators, cables, radar horns, metal objects near the area of transmitted energy and the receiver horn. Objects near the transmitted energy can interfere and project false values. The fact that the test were performed in a relatively small space without absorbing material can potentially lead to errors since the transmitted signal can be reflected and take other paths than the straight one between the horns.

As visualised in some of the tables in Section 4.1.1.1, for example Table 4.1 and Table 4.2, negative attenuation appears (increased signal strength), which is not possible. This deviation is probably due to measurement errors. Even during calibration small values of negative attenuation appeared which indicate that drift errors can be the reason to the occurrence of negative attenuation. Also can the test environment be an indicator in itself as no radar absorbers were added to the environment that can intercept certain reflection from the transmitted microwaves.

## 4.3 Summary of Small Scale Testing

All performed tests within the three test areas resulted in a better understanding of how the seven camouflage nets, presented in Section 3.1.3, Table 3.1, appear given different prerequisites. A short summary of all results for each of the test areas are presented below.

Seen to radar performance camouflage net 828107 was the net that had the least impact on radar performance (both attenuation and phase deviation) when deployed in front of the antenna. This camouflage net was also, along with net 101362, the camouflage that was the easiest to handle.

Camouflage net 101593 was advantageous in the visibility tests as it was the net with most structure that can provide best disguise of rotation and glare from the antenna. Net 101593 in combination with net 101362 can improve the concealment even further when net 101362 was deployed close to the antenna covering the reflections and net 101593 was deployed on a short distance to the antenna covering the appearance of the antenna.

Which camouflage net that has the best IR characteristics was difficult to determine as it is advantageous to use a net that performs well in hiding heat and contours at the same time that the net should not risk to create a contrast with the surrounding environment. Net 726071 was disguising the object most but left a black contrast to the background. Net 828107 was nearly not concealing the IR signature at all but did not leave much contrast to the surroundings. Probably nets that have IR characteristics between those two extreme nets would be best to use. For further work during this thesis the IR spectra will not be considered as it is mostly depending on the characteristics of the camouflage nets and this thesis is beyond the scope of developing new camouflage nets.

## 4.4 Full Scale Testing

This chapter presents the second testing phase of this project where full scale tests were performed on four real radar reference systems. The radar systems that were provided and available for these tests were a GIRAFFE AMB, a GIRAFFE 4A, an ARTHUR and a GIRAFFE 1X. The main object with these tests was to verify the results from the smaller scale test and see how well the nets perform together with a real antenna. For the full scale tests the tested and observed areas were the radar performance and the visual aspect. All tests were performed using dry nets. Tests on the ARTHUR were also performed using a wet net in order to investigate in environmental impact.

### 4.4.1 Radar Performance

Measurements on radar performance were only performed with net 101593 due to limited project time and because this net is the most general one in terms of net structure and its construction of a two fabric layer. This decision was made based on opinions from the reference group and the supervisor at Saab.

Bearing [deg], elevation [deg], target strength (SNR) [dB], radar cross section [$m^2$] and distance [m] were the interesting parameters during these tests. Bearing and elevation give an indication of the pointing error of the system when results from a naked and a camouflaged antenna are compared. SNR is equal with attenuation when results from a naked and a camouflaged antenna are compared. It is important that radar cross section and distance to the target are similar when comparing the results; otherwise the measurements can be unreliable.

During the radar performance tests data was stored in a so called etx-file and was later opened in Excel and analysed. The tests were performed both without and with dry camouflage net in order to compare the results. On the ARTHUR system tests were also performed with a wet camouflage net. The results from the full scale tests indicate that it can be of interest to further investigate the possibility to camouflage the antenna of the GIRAFFE AMB system, ARTHUR system and GIRAFFE 4A system.

During the radar performance tests for the GIRAFFE 1X system data was stored and later analysed in MATLAB. The data of interest from these tests were regarding how the camouflage net impacts the attenuation and also the pointing error if it is deployed in front of the antenna. The results are presented in Figure 4.8. The results show that there can be of interest to investigate further into the possibility to camouflage the GIRAFFE 1X antenna.

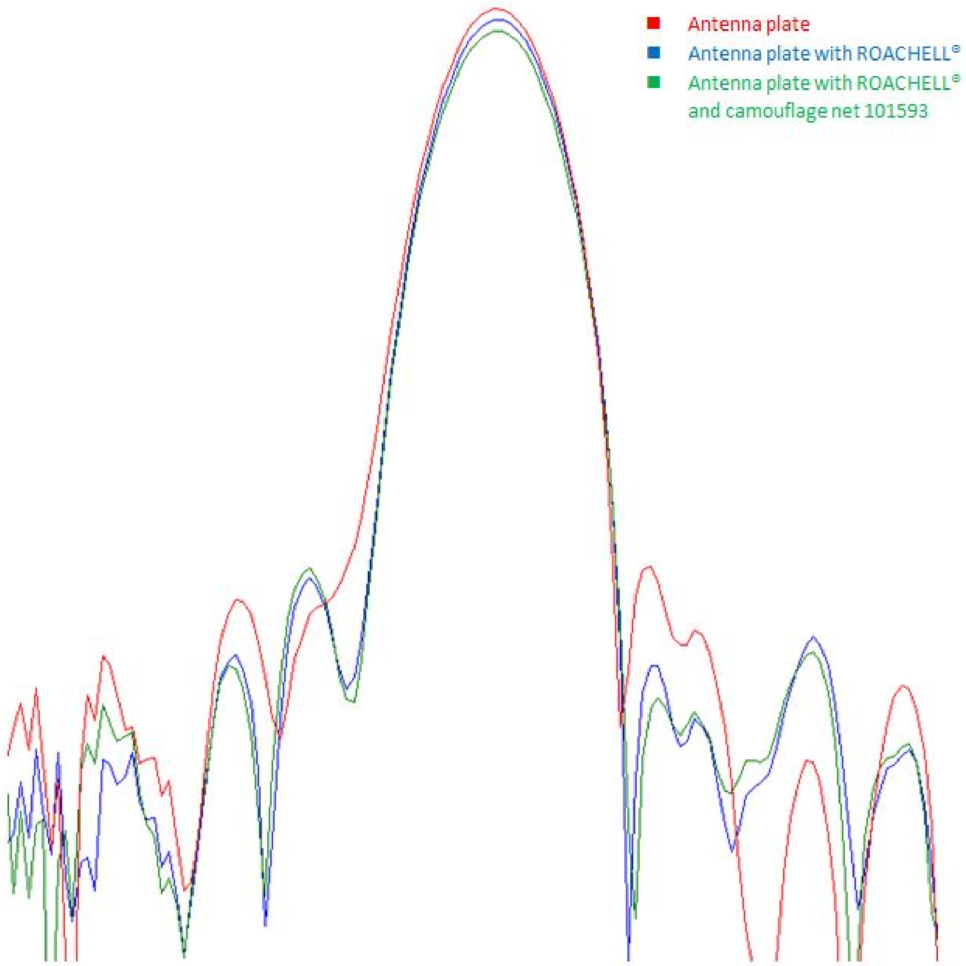



**Figure 4.8:** Results from tests on GIRAFFE 1X.

### 4.4.2 Visual Perspective

Visual tests were only performed on the GIRAFFE AMB system due to limited availability and location of the systems. For the visual tests on GIRAFFE AMB, camouflage net 101362 was also investigated because of its composition of colours that blend well with the Swedish forest. The visual test procedure was recorded with a video camera and then imported into a computer where it was reviewed and analysed. Four different sequences were recorded; one sequence without camouflage net mounted on the antenna and three sequences were one or two camouflage nets were attached on the antenna. Snapshots were taken from the videos in order to present the results from the visual test. These are presented in Appendix D. The visual test showed that it is not enough to drape a rotating antenna with a camouflage net. The net has to also disguise the geometrical shape of the antenna and make it more homogeneous to be able to conceal the rotation and reflection.

# 5
# Requirement Specification

*In this chapter the most important requirements for this project are presented and explained. The section also treats how these were produced and collected. The requirement specification consists of general requirements such as functionality, environment and appearance for both rotating and stationary antennas. Detailed dimensions are not discussed in order to avoid narrowing down and limit the project.*

A requirement specification acts as a structured help to identify what the customer expect of the product. The creation of a requirement specification is an iterative process and it needs to be reviewed several times during the product development process. A general requirement specification was established and aimed to be a guideline for a camouflage solution for all four radar systems, GIRAFFE AMB, GIRAFFE 4A, ARTHUR and GIRAFFE 1X. The specification was based on information gathered from the field trip to Barracuda and discussions with the reference group and the supervisors at Saab. It was also based on observations made by the authors and conclusions from small and full scale testing presented in Chapter 4. In collaboration with two supervisors at Saab and through two rework sessions, the requirement specification was finished. The main target with the requirements was to be able to define design parameters and the factors needed to be considered during the development process. [7]

The most important requirements were put in the beginning of the specification and concerned the performance of the camouflage solution. These requirements include target values that must not be exceeded regarding attenuation, pointing error and visibility. Other important requirements were that the camouflage solution needs to be removable if affected negatively so it never stops the radar system to perform its tasks. It shall be simple to use and has as short mounting time as possible. The camouflage solution shall be designed of interchangeable modules and the net shall be possible to replace (for example to adapt to seasonal changes). The camouflage solution shall also be able to be integrated and transported on the same platform as the radar system. The complete requirement specification can be found in Appendix E.

| Category | | No. | Requirement | Target Value | D/W | Validation |
|---|---|---|---|---|---|---|
| 1. Characteristics | | | | | | |
| *1.1 Performance (Mechanical Structure and Camouflage Net)* | | | | | | |
| | 1.1.1 Damping | | | | | |
| | | 1.1.1.1 | The camouflage solution shall not affect the radar system's performance more than 2 dB in total (two ways) irrespective of the weather conditions. | < 2dB | D | Saab Surveillance |
| | 1.1.2 Pointing Error | | | | | |
| | | 1.1.2.1 | The camouflage solution shall not have a pointing error larger than accepted for the system irrespective of the weather conditions. | | D | Saab Surveillance<br>Saab Barracuda AB |
| | 1.1.3 Reflection, Transmission, IR and Visual | | | | | |
| | | 1.1.3.1 | The camouflage solution shall remove the visual reflection in form of glare from the antenna surface. | | D | Saab Surveillance<br>Saab Barracuda AB |
| | | 1.1.3.2 | The camouflage solution shall remove the visual reflection in form of visual rotation of the antenna. | | D | Saab Surveillance<br>Saab Barracuda AB |
| | | 1.1.3.3 | A rotating antenna shall have as uniform appearance as possible from all angles. | | D | Saab Surveillance |
| | | 1.1.3.4 | A stationary antenna shall blend into the sorrounding environment and be as homgen possible | | | |

**Figure 5.1:** Extract from the full requirement specification presented in Appendix E

# 6

# Concept Generation and Evaluation

*This chapter presents the concept generation phase of the project from brainstorming to concept evaluations. All concepts are presented and assessed according to proven product development methods.*

*Due to limited project time the concept generation and evaluation phase had to be narrowed down to only focus on one radar system. The GIRAFFE AMB was chosen as its elevated rotating antenna was regarded as an interesting challenge to camouflage for the authors. Other radar systems within Saab's portfolio connected to this thesis such as ARTHUR and GIRAFFE 4A have been covered as well in the concept generation phase but not on a detailed level. Conceptual concepts and how problems can be solved for these systems will be presented in Section 7.2 and Section 7.3.*

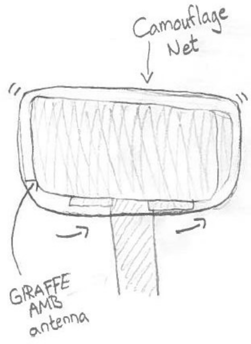
## 6.1 Generating Concepts

After discussions of the results from the quantitative study with technicians, the reference group and supervisors the next phase of the project was started with a brainstorming session conducted by the two authors. Brainstorming is when a group of people generate ideas. Spontaneity is encouraged and it is not allowed to criticise ideas during the session, however it is allowed to build on each other's ideas. It is the quantities of ideas and not the qualities of ideas that is the value. [39]

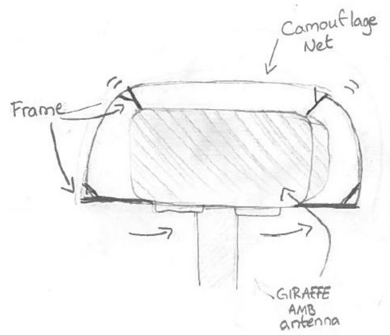
This brainstorming session was focused on the overall camouflage solution and not in technical details on how certain functions can be solved. The session resulted in a creation of three main solutions of how to solve the camouflage challenge for a rotating GIRAFFE AMB antenna. The first concept presented below is suited for a stationary antenna as well. The concepts are concerning the shape of the outer camouflage net. An inner camouflage net can be added to the solutions if a two-layer camouflage net solution is preferred.

Following concepts describes the three overall concept solutions briefly:

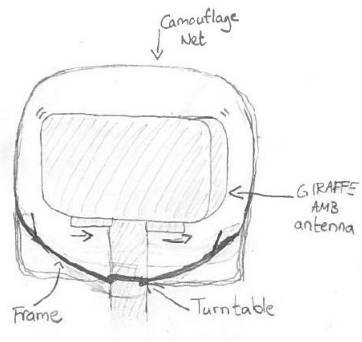
1. *Put net over antenna* – This solution consists, more or less, of a camouflage net that is thrown over the antenna and tied in some way in order to not come off. Investigation if any ribs or fasteners are needed is to be evaluated.




2. *Rotates with the antenna* – This solution consists of a frame which a camouflage net is stretched around and by that form a radome. The frame is meant to be attached in the antenna and by this it rotates with the antenna. This can change the antenna's signature and make it more homogeneous for hiding rotation, see Section 4.4.1.2




3. *Stationary around antenna* – This solution consists of a frame which the camouflage net is stretched around and by that form a radome. The frame is meant to be attached in the turn table or another stationary part near which means that the solution does not rotate with the antenna. This will eliminate the visual rotation as long as the camouflage net not can be seen through.



## 6.2 Selecting Concept

An elimination matrix is often used in early stages of a project's concepts generation phase to be able to exclude concepts that do not fulfil the requirements of the product. All concepts are evaluated according to if they satisfy the requirements in the requirements specification or not. If a concept fails to accomplish any of the requirement's criteria it gets excluded from further investigation in the project. A question mark or an exclamation mark indicates that the known information about the concept is too limited to be able to determine if the concept fulfils the requirements. In this project all requirements are divided into five main areas to get a better overview and easier assessment of the concepts. The elimination matrix can be viewed in Table 6.1. [5]

The three overall concepts, presented in Section 6.1, were evaluated in the elimination matrix:

- A camouflage net is put over the antenna
- A camouflage net rotates with the antenna
- A camouflage net is stationary around the antenna

**Table 6.1:** Elimination matrix of the three overall concepts.

| Concept | Name | Radar Performance | Visability | Ease of Use | Safety | Compatible/Realizable | Decision |
|---|---|---|---|---|---|---|---|
| 1 | Put over antenna | + | - | | | | - |
| 2 | Rotates with the antenna | + | + | + | + | + | + |
| 3 | Stationary in turning table | + | + | ? | + | ? | ? |

Criteria Fulfillment
(+) Yes
(-) No
(?) More information needed
(!) Check with requirement specification

Decision
(+) Further development
(-) Reject
(?) Need more investigation
(!) Check with requirement specification

Concept 1 (Put over) was omitted almost immediately as it failed to fulfil the important visibility requirements. This was discovered during the full scale testing, see Section 4.4, where camouflage nets were draped as caps and threaded on the GIRAFFE AMB antenna. This solution did not manage to remove neither the glare nor the visual rotation of the antenna.

Concept 3 (Stationary) accomplished, like Concept 2 (Rotating), to fulfil all requirements but did get a question mark in Ease of use. This was based on the fact that Concept 3 (Stationary) for GIRAFFE AMB probably would have to be very large. Due to limited project time, as Concept 3 (Stationary) would need further full scale testing, the authors chose to exclude Concept 3 (Stationary) in this project.

A second elimination matrix was created to explore what geometrical shape a camouflage solution that rotates with the antenna should have to disguise the antenna. Each geometrical shape was created in the computer tool PTC Creo Parametric and put in perspective together with a model of the GIRAFFE AMB antenna. PTC Creo Parametric is a 3D modelling software used to take a product from concept to digital prototype and by that simplify and speed up the product development process. These shapes are presented and visualised in Appendix F. 12 different shapes were listed and evaluated according to six main areas of requirements presented in Appendix G. [27]

Six concepts were excluded (cube, cuboid, prisma, sphere and octagon) as they were going to be too large to work as a good visual camouflage.

## 6.3 Selection of Shape of Camouflage Solution

The six geometrical shapes (cylinder, half-sphere, hexagon, rounded cuboid, trapezoid and pentagon) that made it through the second elimination matrix were further evaluated in a Pugh matrix. The Pugh Matrix compares each concept with a reference concept according to predetermined criteria. When all criteria are equated the comparing concept gets a rank in how good it is according to its score against the reference. [6]

In this project the cylinder was put as reference concept and can be found in Appendix H, Table A.11. Both the hexagon and the trapezoid got excluded as neither was advantageous in any criterion.

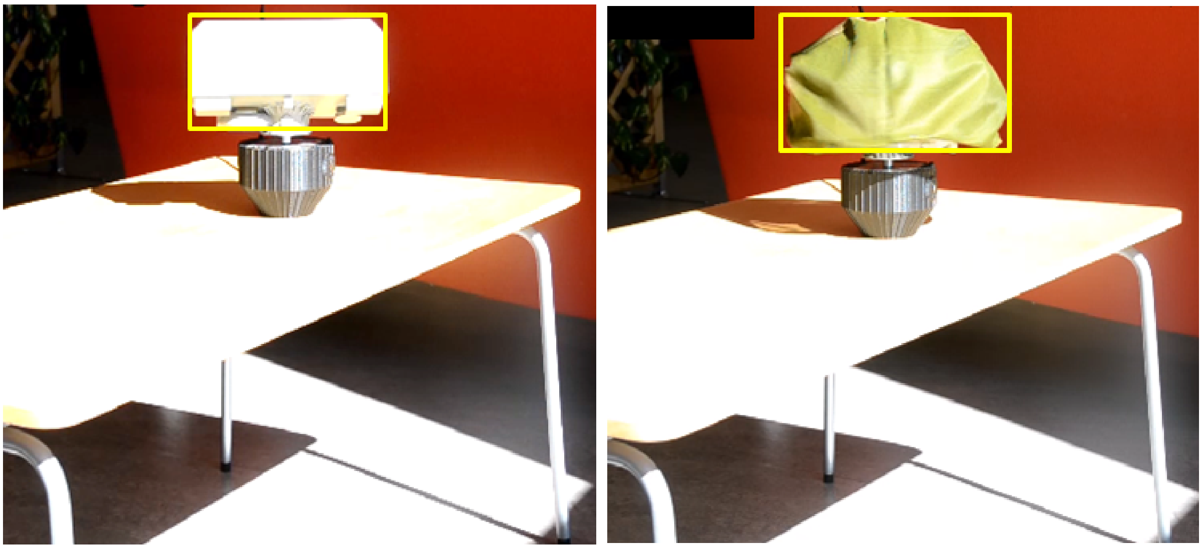
A second Pugh matrix was performed on the remaining geometrical shapes were the rounded cuboid acted as reference concept. This resulted in an exclusion of the pentagon as presented in Appendix H, Table A.12.

The three remaining geometrical shapes were the rounded cuboid, the half sphere and the cylinder. Seen from a visibility perspective, with the aim to conceal the rotation, the half sphere would probably be the best solution as it is the most homogeneous shape. It would probably endure wind the best as well as it has not sharp edges. On the other hand the diameter of the half sphere would have to be significant large to cover the rectangle shaped antenna. This is contradicting the rounded cuboid that would offer the smallest size but would not reach the same level of camouflage in the visual perspective. The cylinder can be hoisted along the sides of the antenna, but risk glare and water collection at the flat top. A conclusion was made that a combination of these three shapes would probably be the best solution for the camouflage.

## 6.4 Light Intensity Analysis in Pixels of Geometrical Shapes

As one focus area of this project is to camouflage the antennas in the visual spectra, further analysis and investigation were made to one of the conceptual geometrical shapes. The analysis and investigation covered perceived difference visually and variance in pixel value for the area when the antenna was rotating. This is of interest because it gives a quantitative value of visibility reduction. The results are based on one rotation sequence for 360°.

A break room in the Saab Surveillance building was used as the test environment where a small scale model (1:12) of the GIRAFFE AMB antenna was placed on a table that was positioned in the sun, as visualised in Figure 6.1. The camouflage prototype of the geometrical shapes was formed by wire and thread. Two sequences were recorded during rotation, 60 rpm, of the antenna: one without camouflage solution shape (naked) and one with the camouflage solution shape covering the antenna. Figure 6.1a presents a snapshot of the first sequence and Figure 6.1b presents a snapshot of the second sequence with a camouflage prototype. The yellow rectangles present the selected area of interesting pixels for the pixel analysis.

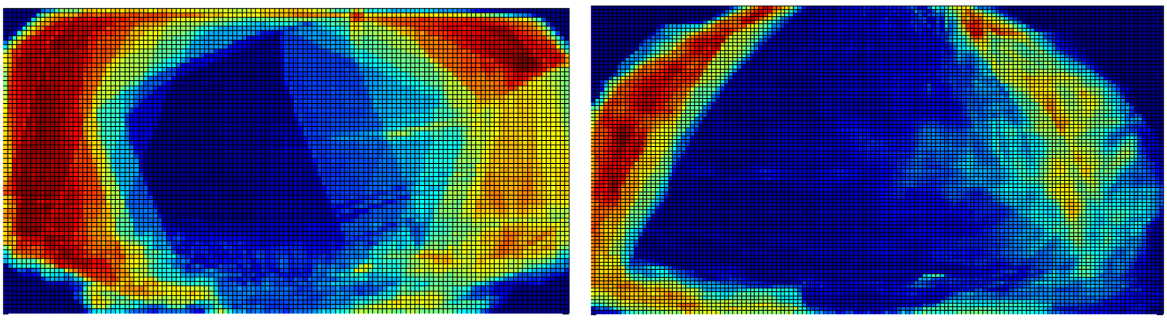


(a) Visualisation of the small scale model without a camouflage prototype.

(b) Visualisation of the small scale model with a camouflage prototype with net 101362.

**Figure 6.1:** Test environment for the light intensity pixel analysis. The areas marked with the yellow rectangles are the areas analysed in MATLAB.

A sequence of one rotating turn with a speed of 60 rpm was divided into 31 frames where each of them were analysed on pixel level. For the sequence without camouflage solution was an area of 68 x 122 pixels selected and for the second sequence with camouflage solution was an area of 84 x 134 pixels selected. The value in each pixel and its change over the 31 frames were summarised and a variance was calculated in MATLAB. Figure 6.2 presents the results from this analysis. Figure 6.2a refers to the marked area within the yellow rectangle in Figure 6.1a and Figure 6.2b refers to the marked area within the yellow rectangle in Figure 6.1b. The figures presents the variance, during one rotation of 360°, over selected pixel area. Red pixels indicates critical areas with a larger light variance. Blue pixels are areas where there are small differences in variance which is preferable. These areas need to be as small as possible in order for the human eye not to detect the movement.



(a) Light intensity pixel analysis of the small scale model without the camouflage prototype.

(b) Light intensity pixel analysis of the small scale model with the camouflage prototype.

**Figure 6.2:** Light intensity analysis of pixels for interesting area.

As visualised in Figure 6.2a and Figure 6.2b there are clear differences between an antenna with a camouflage solution rotating with it and an antenna without a camouflage solution. By calculating the mean variance over the area for the both cases it results in a reduction of 65 % in variance with a camouflage solution. This is an iterative process and the result can be optimised by changing the shape of the camouflage prototype and decrease the shape variance further.

# 7 Solutions

*This chapter presents an overall concept for a camouflage solution for a GIRAFFE AMB and brainstormed alternative solutions for an ARTHUR and a GIRAFFE 4A. The GIRAFFE 1X has been left out as it is not a fully developed product when this report was written.*

*The concept for the GIRAFFE AMB antenna is presented in terms of a general idea (based on decisions from Chapter 6) and suggestions are given for how to handle identified sub-problems and sub-functions of the idea. The suggestions are from the authors' perspective and are based on the gained knowledge within the area from observations, testing and discussions. The section handling GIRAFFE AMB also includes a subsection about solutions discussed on reference group meetings that are out-of-the-box.*

*The subsections regarding solutions for ARTHUR and GIRAFFE 4A presents overall ideas of how a camouflage solution can be applied onto these systems. These ideas are only described briefly in terms of a short description of how each of them can work in practice. The descriptions are supported with simple sketches for a better understanding.*

## 7.1 GIRAFFE AMB

When the overall shape of the product was decided the focused moved on to how to solve the sub-functions that were identified for the product. The sub-functions were generated using the requirement specification as reference, see Chapter 5, and are summarised here.

- It is important that nothing, except the camouflage net, is placed in front of the antenna as it affects the radar system's performance negatively, which means that the structure to support the camouflage net can only be built on the sides, back, top and bottom of the antenna. It is also preferable to design any kind of supporting structure in a non-conducting/non-metallic material in order to reduce the impact on radar performance.

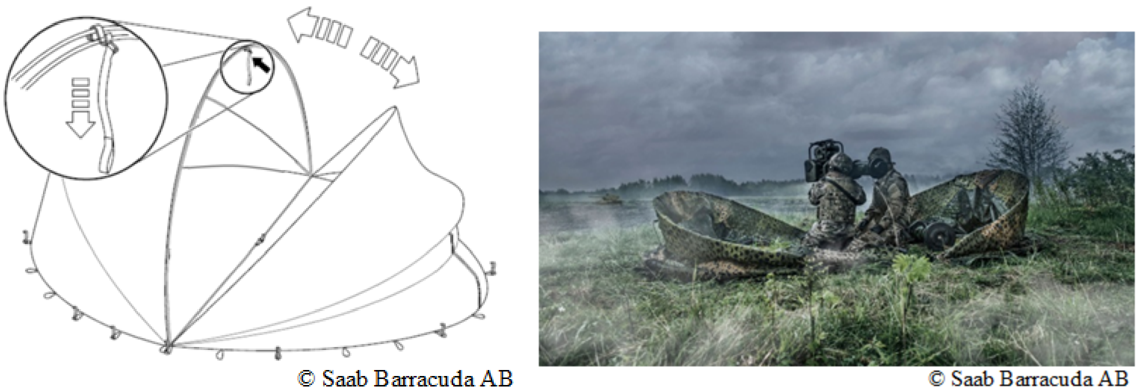
- The camouflage solution shall be easy to remove, so if it breaks it would never risk stopping the radar system to perform its tasks. The system needs to retain the high reliability and availability of approximately 95 – 98 %.[1]

- The camouflage solution shall be light and simple to attach to the system so it does not prolong preparation time substantially before the system can be in use. A request is also that the camouflage solution can stay put on the antenna even during redeployment when the antenna is lowered. This can be a challenge due to extremely limited space during the down position of the radar system. Another reason for a light and simple solution is because of the operating height of 8 or 12 m. If the solution is heavy it can create unwanted oscillations of the system.

[1] Johan Strömquist (Engineer External Provisioning | Saab Surveillance), reconciliation meeting Mars $7^{th}$ 2016.

- It shall be able to be handled by manpower and be stored onto the radar system and can therefore not be too large or too heavy. This is based on short redeployment times and beneficial use.
- The camouflage solution shall endure wind and rain.
- The camouflage net shall be interchangeable.

With the evaluated geometrical shapes and the bullets mentioned above in mind an idea of an overall concept for the camouflage solution was formed. Inspiration was taken from Saab Barracuda AB's Camosphere, see Figure 7.1. Camosphere consists of two equal halves that can be put together to a half-sphere for cover and separated to lie flat on the ground for engagement. The Camosphere changes the signature of the covered system and protect the system and operator from detection[2].




**(a)** Visualisation of a functional draft of Camosphere. **(b)** A contextual visualisation of Camosphere.

**Figure 7.1:** Saab Barracuda AB's Camosphere.

A conclusion was made that the overall solution, see Figure 7.2, has to consist of some kind of frame that can be minimised for storage and enlarged for use, visualised in Figure 7.2a). It also has to consist an interface between the frame and the net that enables interchangeability of nets, visualised in Figure 7.2b). Furthermore there has to be an interface between the frame and the system that enables fast and easy attachment and removal of the camouflage solution, visualised in Figure 7.2c). Each and one of these sub-functions are presented in the following subsections.

[2] Johan Jersblad (Senior Development Engineer, R&D | Saab Barracuda AB), mail conversation Mars 18$^{th}$ 2016.

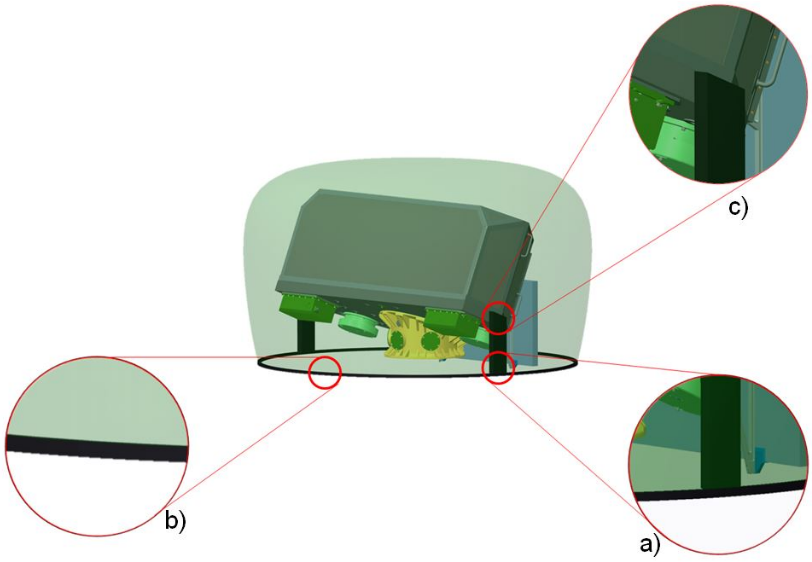



**Figure 7.2:** The overall camouflage solution of the GIRAFFE AMB antenna. Figure (a), (b) and (c) presents the concept's sub-functions.

### 7.1.1 Foldable Frame

The foldable frame would preferably be as thin and light as possible without losing strength. Bendable or unbendable tent poles in a non-metallic material can be of interest. For the folding mechanism several solutions were generated which are presented in Figure 7.3.

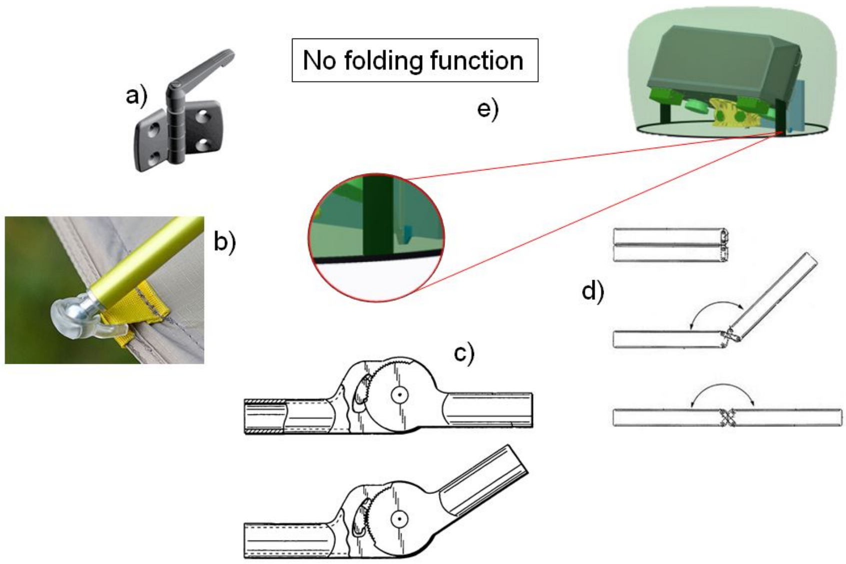



**Figure 7.3:** Ideas of solutions for the foldable frame's sub-function.

(a) A locking hinge that enables the operator to lock the frame in wanted positions.

(b) Free movement in ball joint which enables different positions, locking function needs investigation.

(c) A multi positional hinge that enables the operator to lock the frame in wanted positions. It is also possible to tighten the solution using the locking pawl together with a spring for example. This can result in a more stable solution.

(d) A multi axis hinge that has two locking modes: folded and unfolded. Adding a cotter enables the frame to be locked in these positions.

(e) Should the camouflage solution not be foldable at all?

### 7.1.2 Interface Between Frame and Net

For the interface between the camouflage net and the frame it is important for the net to be interchangeable. Several solutions for the interface were generated which are presented in Figure 7.4.

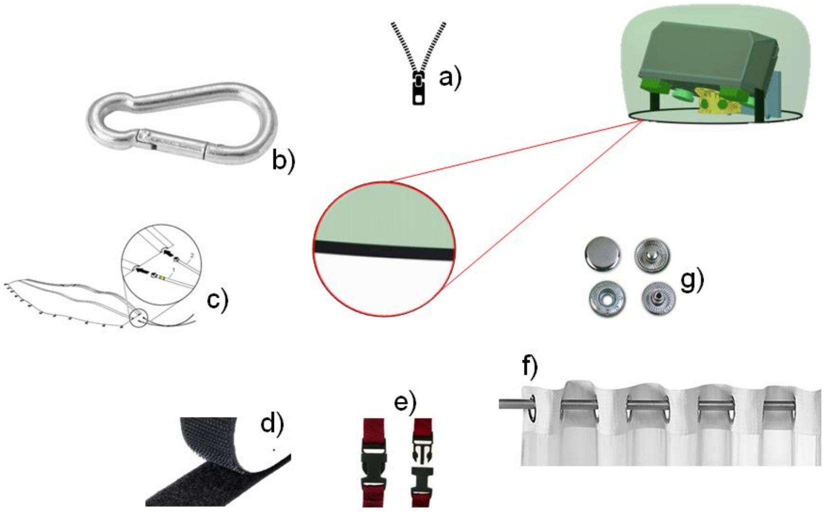



**Figure 7.4:** Ideas of solutions for the interface between the frame and the camouflage net.

(a) A zipper

(b) Snaplinks

(c) A hem

(d) Velcro

(e) Detachable buckles

(f) Curtain rings

(g) Snap fasteners

### 7.1.3 Interface Between Frame and System

An interesting discovery was made when full scale tests were performed on the GIRAFFE AMB. On both sides of the antenna there are four holes, visualised by the red rectangle in Figure 7.5. These holes are used for lifting the antenna when it is to be mounted onto the turning table of the radar system. When the antenna is mounted onto the turning table these holes do not have any tasks which make them interesting to use for attachment of of a camouflage solution.

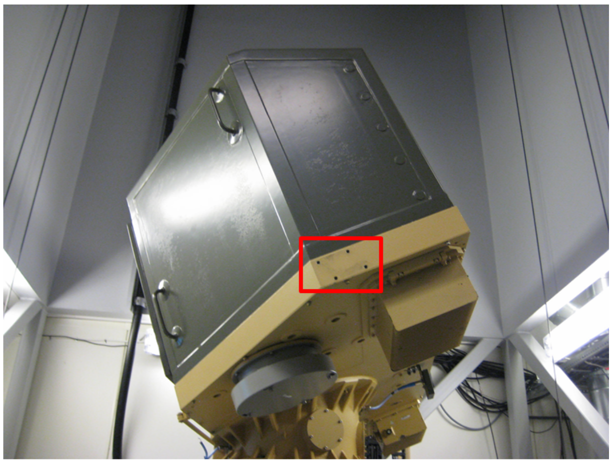


**Figure 7.5:** A GIRAFFE AMB antenna. The red rectangle marks the four lifting holes on the antenna's sides.

It is important that the camouflage solution also covers the IFF antenna at the back of the GIRAFFE AMB antenna as it, like the front of the antenna, reflects lights. A consequence of this is that the camouflage net cannot be attached straight to the antenna it should be attached to something that enables the net to cover further down to enable a homogeneous geometrical shape. An elongated plate attached with screws in the mounting holes on the antenna can be a solution for this. The plate should not override dimensions that prevent it to be attached to the antenna during redeployment when the antenna is fully lowered. Several solutions for the interface between a possible plate and the frame were generated which are presented in Figure 7.6. It is important that this interface enables fast and easy attachment of the camouflage frame to the radar system as, due to limited space when the antenna is lowered (approximately 3 cm), the frame cannot be attached to the system during redeployment.

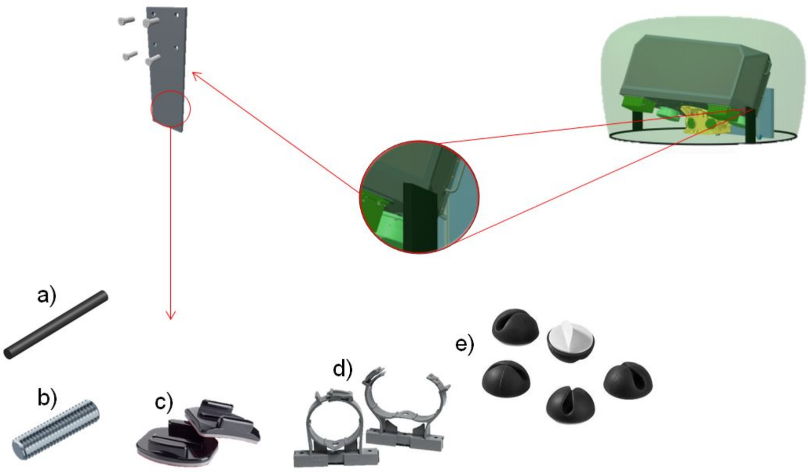



**Figure 7.6:** Ideas of solutions for the interface between the frame and the system.

(a) Axis attachment that enables the operator to click on the frame and fold/unfold it.

(b) Screw attachment that enables the operator to screw the frame onto the plate.

(c) Adhesive mounts that enables the operator to click the frame onto the plate.

(d) Friction clamps that enables the operator to pin the frame to the plate.

(e) Cable holders that enable the operator to press the frame to the plate.

### 7.1.4 Pros- and Cons

A pros- and cons list for each of the sub-solutions was created in order to evaluate the positive and negative attributes of the sub-solutions. This is a subjective method that is simple and fast to use during decision making. These lists are presented in Appendix I. In this section proposals are given by the authors of why certain solutions should be preferable for a camouflage solution. The decisions are based on test experience and the requirement specification, presented in Chapter 4 and Chapter 5. These proposals would have to be investigated further before being applied.

The first sub-function was regarding a bendable or not bendable frame. The pros of a bendable frame are its ability to form, its flexibility and its advantageous storability. The pros of a fixed frame are on the other hand its robustness and easy and fast assembly as a bendable frame need human force and support to stay in bended position. Due to the fact that the antenna is rectangular it would probably be advantageously if the frame was bendable. This can help to prevent the frame from getting stuck when folded over the antenna.

For the folding functionality the multi-positional hinge is preferred as it is flexible when it enables several locking positions which make it easier both to strain to gain a proper, rigid and homogeneous geometrical shape and to fold for compact storage. The only thing that might be negative about this solution when the pros- and cons list was written was that it can be considered as the most complex solution.

The interface between the net and the camouflage solution should enable easy and fast interchangeability between nets even during assembly of the camouflage solution. The hem-solution is preferred as it is the least error prone solution to risk getting stuck during attachment. It is also robust, a proven technique, no extra parts are needed and it is inexpensive. It can withstand harsh climate and it enables maximum cover as the frame is threaded through the camouflage which make the interface invisible and stops the net from embroilment.

The last sub-solution was regarding how to fasten the frame to the plate attached to the system. The authors' suggestion here is the cable holders as they combine the fast and easy attachment of the adhesive mounts with the robustness of the friction clamps.

| Idea | Pros | Cons | Decision |
|---|---|---|---|
| Axis | Inexpensive<br>Withstand high forces | More sensitive to dust | |
| Screw | Inexpensive<br>Withstand high forces | More sensitive to dust | |
| Adhesive Mounts | Easy and fast fastening<br>Requires less space | Do not withstand high forces | |
| Friction Clamps | Easy and fast fastening | Requires more space<br>Cannot stay attached on the system when the antenna is lowered | |
| Cable Holders | Inexpensive<br>Easy and fast fastening<br>Requires less space | Do not withstand high for | |

**Figure 7.7:** Extract from the pros and cons lists presented in Appendix I

### 7.1.5 Alternative Out-of-the-Box Solutions

In discussions with the reference group[3] several out-of-the-box solutions for a camouflage solution for a GIRAFFE AMB system was generated. One of these produced ideas resulted in a solution that inflates the camouflage net to a homogeneous geometrical shape, preferable a sphere. This solution requires a totally solid camouflage net and may lead to problems with cooling of the antenna, which then need to be solved. If the solution is not totally solid the inflated amount of substance needs to be inflated with the same speed as it leaks out. The conceptual solution is sketched in Figure 7.8.

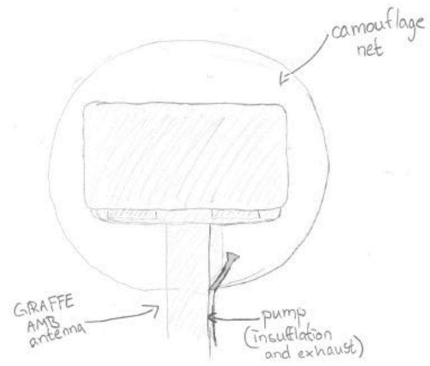



**Figure 7.8:** Draft of the inflatable out-of-the-box solution for the GIRAFFE AMB antenna.

Another idea treated a solution that uses weights in the bottom edge of the camouflage net. The net is put over the antenna and mounted on top of it through an attachment solution. When the antenna starts to rotate the weights help to form the camouflage net to a homogeneous half sphere by the centrifugal power. This solution would remove the need of a structure holding the net, which is beneficial. The conceptual solution is sketched in Figure 7.9.

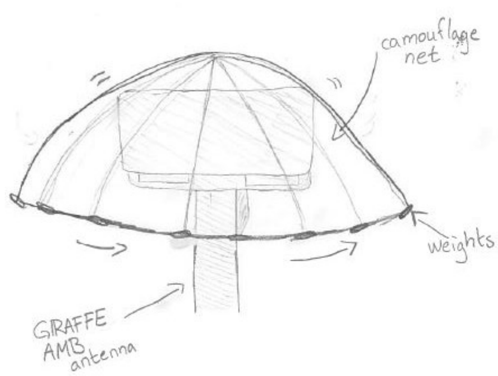



**Figure 7.9:** Draft of the centrifugal force using out-of-the-box solution for the GIRAFFE AMB antenna.

Another more radical solution is to change the outer shell of the antenna by reducing sharp edges and flat surfaces that generate glare. Then perhaps a camouflage solution would be unnecessary. This solution can be something to look into if the demand from the customers of reducing visual rotation and glare increases.

All ideas can be interesting to look further into, but due to limited project time they were not taken into account during this master thesis.

[3]Meeting with reference group April $14^{th}$ 2016.

## 7.2 ARTHUR

This section presents conceptual solutions for an ARTHUR radar system and what obstacles that may complicate any camouflaging of the system.

A simple conceptual solution for an ARTHUR is to put a net over the antenna as it is. The full scale testing did not affect the radar performance significant when a camouflage net was covering the front side of an ARTHUR in different angles of incidence. A solution can then be to let the camouflage solution melt in with the rest of the radar system's camouflage and try to simulate the geometrical shape of e.g. a hill, see Figure 7.10.

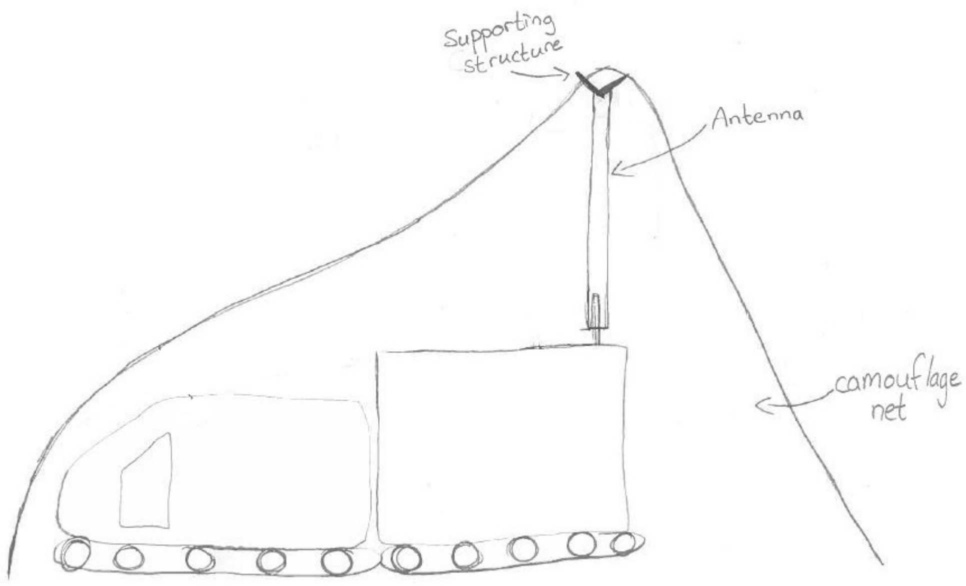



**Figure 7.10:** Draft of a conceptual total camouflage solution for the ARTHUR radar system.

One of the most important functionalities for a camouflage solution for an Arthur system is that it supports fast redeployment as ARTHUR systems have a short instrumented range and often have to be deployed with the front line of the artillery. An ARTHUR has a deployment time of only two minutes which a camouflage solution should preferably not inflict with. Development of a camouflage solution that can be attached even during redeployment would be valuable for an ARTHUR system.

To avoid overheating the system or heating the net through the system, which increases the risk to reveal the system by its IR signature, a structure that keeps a small gap between the camouflage net and the front of the antenna would have to be developed, e.g. a supporting structure in each corner. This structure also has the function to maintain the camouflage net in place in case of strong winds. It is also advantageous to have it during rising of the antenna since it can help the antenna to bring up the net, which means that the operators do not have to throw the net over the markedly high antenna when attaching it.

During lowering of the antenna the camouflage net covering the back of the antenna needs to be taken care of by an operator in order to avoid the net getting stuck in between antenna and shelter roof. The net covering the front can probably hang free as it will not interfere with the rest of the radar system. An alternative solution can be to only camouflage the front of the antenna in order to give the antenna surface more structure to reduce glare. The negative regarding this solution is the distance needed between the antenna front plate and the net because of the heat problem described in previous paragraph. The antenna's signature would not be disguised either as with a fully covering camouflage solution.

## 7.3 GIRAFFE 4A

This section presents conceptual solutions for a GIRAFFE 4A radar system.

One conceptual camouflage solution for a GIRAFFE 4A system can be similar to an ARTHUR created by putting a net over the antenna, trying to create an illusion of e.g. a hill. This solution is only available during transmission in a sector when the antenna is stationary and not rotating. Another solution for a stationary antenna is to only camouflage the front of the antenna (with a short distance in between the net and the antenna plate) in order to get more structure of the surface and reduce glare, same as for ARTHUR.

As a GIRAFFE 4A is 2x2 m a rather large camouflage net would have to be used to disguise the antenna which can inflict with the ease of use and mounting time of the camouflage solution. Perhaps it is not necessary that the camouflage solution is covering the whole radar system. It might be enough if the camouflage solution is attached on the railing of the cab that the turntable of the antenna is attached to. Poles can be attached to the railing that the net can be hoisted up and down or pulled back and forth on, see Figure 7.11. This solution can be applicable on both a stationary and rotating antenna. A rotating GIRAFFE 4A antenna needs probably a new way of thinking than GIRAFFE AMB due to its size. A stationary camouflage solution would be preferable in this case, either put up a tent-like solution on the ground or as described earlier in the paragraph.

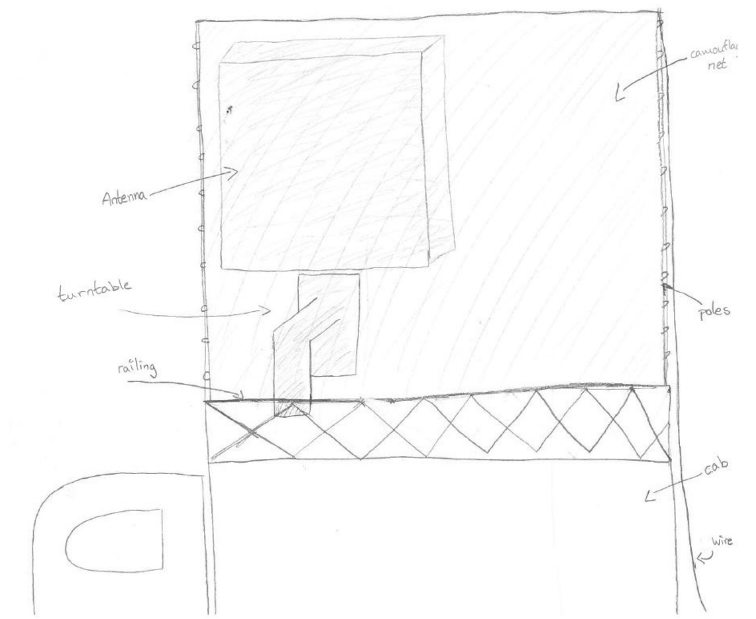



**Figure 7.11:** Draft of a conceptual camouflage solution for the GIRAFFE 4A antenna.

# 8
# Discussion

*This chapter covers the discussion regarding the finished master thesis and what it has resulted in. First are the methods and the approach discussed and analysed. The results from the tests are then discussed and evaluated towards the requirement specification that was set during the thesis. The chapter ends with a discussion regarding possible concepts of how to camouflage the different antennas, the challenges that were faced during the thesis as well as lessons learned.*

## 8.1 Methods

During this master thesis both qualitative methods and quantitative methods have been used. The qualitative methods (interviews, observations, reference group meetings, the field trip to Barracuda and market research) helped to gain an understanding and deeper knowledge about radar systems and the challenge of camouflaging a radar antenna's front side. The information gained from the qualitative methods became a good basis in order to develop hypotheses and plan the testing phase of the thesis. The qualitative methods also assisted in the identification of demands and needs from Saab, their customers and the operators' perspective.

The provided reference group including important people within different areas and departments at Saab was helpful during the thesis. The reference group was used as a sounding board in order to generate ideas and create new approaches for the development of the project. During the meetings an open-minded approach was used to not narrow down or rule out possible approaches and solutions since the thesis is in the start-up phase of an area which has not been investigated earlier. The reference group came up with insightful comments on the work and they also got occasional feedback on what the authors had done. The privilege of having a reference group has resulted in a useful exchange of information and knowledge that benefited all participants.

Interviews, discussions and observations have been important parts of this thesis due to an unexplored research question. These qualitative methods have been ongoing throughout the thesis and even the smallest point of views and ideas have been valuable for the end result. Due to a large interest in the project and the research area a lot of knowledgeable and skilled people have been involved during different phases. They have supported all phases with comments, insights and advices in order to guide the authors in the right way. In order to gather more detailed requirements and demands more interviews should have been conducted with end users of the radar systems.

Since this master thesis focus on camouflage, great emphasis has been put on the nets and therefor support from Barracuda has been vital. They supported the project with different camouflage nets and questions regarding camouflage have been sent to Johan Jersblad.

The quantitative methods (the small and full scale testing) assisted in conducting important data to use as basis for product development work of several overall camouflage solution concepts for Saab Surveillance's ground based radar systems. These methods aimed to seek confirmation of the hypothesis regarding realisation of a camouflage solution and to answer the research question. The different tests were structured and data was gathered through well proven technology in order to give reliable results. The small scale tests showed to be less reliable due to measurement errors and measurement uncertainty, discussed more in Section 4.2. However the full scale tests showed significantly more reliable results.

The research question, answered in this thesis, is more or less based on the test results as this is an unexplored area for Saab and no previous research has been conducted before. It was crucial to perform small scale tests in order to understand the theory and how different camouflage nets actually affect radar signals. The small scale tests brought interest among people at Saab and further investigation was desired. In order to verify and confirm the results and conclusions from the small scale tests it was necessary to perform reliable full scale tests. The tests were inevitable for the project and its outcome. They were also the foundation for the requirement specification of this master thesis.

It is mainly the geometrical shape of the camouflage solution for a GIRAFFE AMB antenna that has been investigated by certain proven product development methods, such as brainstorming, elimination- and Pugh matrixes. No Kesselring matrix was done as it requires a more careful and insightful assessment of the shapes than can be performed at this point of the project. The pros- and cons lists were an important tool for the authors that enabled for them to deliver their point of view to Saab regarding how they can create a camouflage solution for a GIRAFFE AMB antenna.

The overall thoughts regarding chosen methods are that they became well suited for this sort of research project. They all filled their purpose and resulted in a well formulated base for further development of possible ideas and concepts of camouflage solutions for all the focus products.

## 8.2 Results

The achieved results from the small- and full scale testing are discussed in following subsections.

### 8.2.1 Small Scale Testing

During the small scale radar performance tests the focus was on how much a camouflage net affect the attenuation (radar range) and phase deviation (pointing error) when placed between a transmitter and a receiver. An interesting discovery that appeared was that all nets had a negligible impact on the attenuation. Distance to the transmitter and different angles of incidence to the camouflage net from the transmitter did not affect the attenuation either. Wet nets got higher attenuation registered i.e. camouflage net 101593 got a radar range decrease of 10 % for high frequencies when wet. Increased attenuation during rain is a well-known factor, presented in Section 2.4.2, and the camouflage nets did not deviate from these theories. Camouflage nets with finer meshes did absorb more water making them heavier and less user-friendly.

The impact on the phase deviation was more significant than the impact of the attenuation. Since the phase deviations were constant and linear with increasing frequencies for all tests this was not considered an unmanageable problem[1]. Another observation from the tests was that the phase deviation increases for higher frequencies because of shorter wavelengths. Since the

[1]Lennart Steen (Senior Product Manager | Saab Surveillance), meeting February 29$^{th}$ 2016.

wavelength is shorter a disturbing object, such as a camouflage net, affects a larger part of the wavelength and by that the attenuation is increased. For low frequencies the interference in phase deviation is probably more dependent on measurement errors, see Section 4.2.

Thickness and structure of the camouflage nets proved to be the most central elements that affected the results when measures on dry camouflage nets were performed. Not surprisingly, a thin material with large meshes affects the attenuation and phase deviation less than a thicker material with finer meshes. The same conclusion, regarding structure and thickness, can also be applied to the usability of the camouflage nets as a thin material with no structure is much easier to fold than a stiff, thick material.

The pointing error analysis indicated that an increasing antenna size had a reducing effect on the pointing error caused by the camouflage nets. One conclusion that can be drawn from this analysis is that the size of the antenna becomes important if the net is thick and by that affects the phase deviation. The results for the thicker camouflage nets were still satisfying since the pointing errors were insignificant, a maximum of 0.8 mrad.

As the camouflage nets were not optimised for the IR spectra the IR tests were conducted to get an idea of what performance the different nets had in the IR spectra. The thicker nets were found to be hard to see through in the IR spectra and the thinner nets with most structure were found to wipe out contours of the hiding object the best. Thick nets are as presented advantageous to use to hide what is behind but the disadvantage is that these nets get heated by the sun faster[2]. Thinner nets got the opposite properties compared to thicker nets, which results in a constant trade-off between them. Another important aspect to consider regarding the nets IR characteristic is the ability to melt into the surrounding environment without any sharp contrasts. This can be done through adaptation to air temperature and not allow thermal radiation to pass for example as described in Section 2.6.2.

The combination of two camouflage nets in two layers during the visual tests proved to create the best camouflaging effect of the rotation and glare of the antenna. A suggestion is to deploy the first layer of camouflage upfront the antenna to disguise the glare of the antenna. The second layer of camouflage can be deployed in a short distance from the antenna in order to disguise the appearance of the rotating antenna. The first layer should then be a thinner more lightweight camouflage net with smaller meshes and uniform colour, i.e. net 101362, and the second layer should be a camouflage net with more structure and pattern, i.e. net 101593.

A camouflage net with structure is to prefer compared to a net without structure if the camouflage solution shall consist of only one net. This is because the structure helps to break up the signature of the antenna and reduces glare. A net without structure that is rotating with the antenna is moving the reflection from the antenna's surface to the surface of the net instead.

### 8.2.2 Full Scale Testing

The full scale tests were performed in order to verify the results from the small scale tests and have resulted in a clearer view of how camouflage nets actually impact the radar performance. The performed full scale tests on the four radar systems, GIRAFFE AMB, GIRAFFE 4A, ARTHUR and GIRAFFE 1X, can be seen as high quality and reliable tests. Since the tests on GIRAFFE 1X were performed on A15 in a measurement laboratory the results are considerably more reliable than for the other systems. In this measurement laboratory there are no disturbing objects in the surrounding environment and possible impact from different weather phenomena

[2]Johan Jersblad (Senior Development Engineer, R&D | Saab Barracuda AB), mail conversation May $3^{rd}$ 2016.

is eliminated. For the tests on the other systems some disturbing object or weather changes might have had an impact on the results. In order to confirm the results with high accuracy more tests need to be done for each of the radar systems to get a statistical value and an average value of the results. For this around ten measurements are needed. The reason why this few is needed is because of the small differences in performance from system to system and small differences every time each system is running.

Neither of the systems showed any critical values regarding impact of attenuation and pointing direction during the radar performance test when a dry net was put in front of the antenna. The ARTHUR system did not show any critical impact on radar performance when a wet net was deployed in front of the antenna, except the decreased SNR value. This is due to the fact that water is a critical factor when it comes to signal attenuation. This led to the conclusion that it is possible to cover the front of the antenna with a camouflage net. The fact that the attenuation results for the GIRAFFE 1X antenna were significantly higher than for the other antennas can be explained by their wavelengths. As mentioned in Section 2.4.2, regarding factors affecting the radar range, the wavelength of the radar reveals its sensitiveness. A GIRAFFE 1X is more sensitive to disturbing objects than i.e. a GIRAFFE 4A due to its higher operating frequency and shorter wavelength.

The information regarding that different angles of incidence of the camouflage net covering the antenna do not have any remarkable impact on the radar performance was interesting. This observation means that the possibilities of different geometrical shapes of the camouflage solution do not have to be narrowed down with respect to radar performance. The visual test on the GIRAFFE AMB system showed, that it is not enough to drape a rotating antenna with a camouflage net. The net also has to disguise the geometrical shape of the antenna making the antenna more homogeneous in all directions to be able to conceal the rotation and reflection.

During the full scale tests valuable insights regarding usability came to the authors. As long as the camouflage net is dry it is easy to handle but as soon it becomes really wet the characteristic change considerably. The camouflage net becomes considerably more unmanageable and heavy, which affects the usability. Another insight was that the wet camouflage net dried extremely fast if it was attached on an antenna placed in the sun. These measurements on a wet camouflage net had to be conducted two times since the first results did not become reliable as the camouflage net dried too fast in the sun. At the first occasion the antenna had been standing in the sun for a while before the tests were conducted and by putting the hands on the antenna plate the authors can estimate the temperature to 50°-60° Celsius. As soon as the camouflage net was placed tight in front of the antenna it started to dry and the water started to evaporate. This is a great property of the net if it starts to rain and then stops during operation of the systems. This theory can be applicable on all the systems according to several skilled employees at Saab as Erik Lindälv[3], Stellan Karlsson[4], Sven-Olov Brattström[5] and Anders Höök[6]. At the second occasion the weather conditions were cloudier and the net was wet throughout the measurements.

Another thought that came up during evaluation of the tests with a wet camouflage net was the creation of a solid water surface on the antenna front plate when a net was hanged in front of it. During discussions with Anders Höök[6] it appeared that a solid surface of water on the antennas front plate is critical to the radar performance. A surface of water may result in attenuation of the signals at 10 dB or more. This might only be a problem for a short time since the weather

[3] Erik Lindälv (System Engineer | Saab Surveillance), discussion May $16^{th}$ 2016.
[4] Stellan Karlsson (Technician | Saab Surveillance), discussion during tests May $16^{th}$ 2016.
[5] Sven-Olov Brattström (Subsystem Engineer | Saab Surveillance), meeting May $17^{th}$ 2016.
[6] Anders Höök (Specialist of Antennas | Saab Surveillance), meeting May $18^{th}$ 2016.

and the transmitted signals help to dry the surface, see Section 2.4.2. According to Höök[6] small water droplets is to be preferred over a solid surface of water since the droplets not interferes on the systems radar performance as much.

The conclusion from tests with a wet camouflage net is that the net can create a surface of water and because of that it can cause problems in term of attenuation. This can be countered by using a surface with structure (punched leaf surface) creating tiny cavities, which prevents creation of a solid surface between the net and the antenna front side. Another solution is to not place the camouflage net closely to the antenna as presented in Chapter 7 regarding conceptual solutions for the different systems. Full scale tests on GIRAFFE 4A with a wet camouflage net attached in front of it were not performed due to limited project time. According to Erik Lindälv[7] and Sven-Olov Brattström[8] the GIRAFFE 4A should get less affected as it operates in a lower frequency band, see Section 2.5. GIRAFFE 4A has a low atmospheric attenuation, which makes it less sensitive to rain.

## 8.3 Solutions

The chapter presenting possible solutions for the GIRAFFE AMB system, the ARTHUR system and the GIRAFFE 4A system is only conceptual and not final.

The light intensity pixel analysis was valuable as it assisted the authors to present a quantitative value of how much a camouflage solution can decreases the visual glare of a rotating antenna. The results are an indication of what is possible to camouflage in terms of reflecting light. It was not easy to get a perfectly homogeneous shape of the functional prototypes of the camouflage solution when using wire and thread as frame. A harder, more robust material (radar transparent) for the frame would probably have been better to use for these tests.

One aspect that has to be considered if decisions are made to go ahead with the GIRAFFE AMB concept is that the antenna is rectangular and in order to be able to deliver a homogeneous shaped camouflage solution the diameter of this solution would have to be rather large. This fact is also substantiated by the circumstance that to be able to fold and unfold the frame of the antenna the diameter has to be large enough to not get stuck in the antenna when folded back and forth.

Even as the homogeneous shape is desirable to achieve for the camouflage solution as it helps to reduce the visual rotation and the impact of the wind, a completely homogeneous shape would probably be difficult to reach. A question that was constant through the project was therefore *"What is good enough?"* The light intensity pixel analysis showed a value of 65 % in reduction when the small scale model was covered with the not completely homogeneous prototype. It is probably a trade-off that has to be made between the homogeneous shape of the camouflage solution and the size and ease of use. The same trade-off has to be made when discussing the use of two layers of camouflage that was observed to be advantageous to use during the small scale testing. The use of two nets would probably disguise the antenna better but would increase the size and aggravate the ease of use.

The conceptual solutions for ARTHUR and GIRAFFE 4A are vague and more investigation is needed in order to identify what is possible for each of the systems. All systems have different properties and their individual requirements differ. It is important to identify possible options for each system and also identify what the individual requests from the customers are.

[7] Erik Lindälv (System Engineer | Saab Surveillance), discussion May $16^{th}$ 2016.
[8] Sven-Olov Brattström (Subsystem Engineer | Saab Surveillance), meeting May $17^{th}$ 2016.

# 9

# Conclusion

The research question for this master thesis was:

"*How can the transmitting and receiving side of ground based radar systems antenna be camouflaged with a camouflage net without influence on radar performance?*"

The results from the small scale testing indicated that it is realisable to camouflage ground based radar system's antennas front side in the frequency span of 2-12 GHz without critical effects on the radar system's performance. The results from the full scale testing confirm these results.

The goal was also to present practical solutions on how a camouflage solution can be designed for stationary and rotating antennas in the visual and IR spectra. The geometrical shape evaluation and the light intensity pixel analysis showed that a homogeneous geometrical shape helps to decrease the visual rotation of the antenna the most. The reduce of glare can be improved by the use of two camouflage nets or with a camouflage net with much structure as it helps change the surface signature of the antenna.

# 10

# Further Development and Recommendations to Saab AB

The result of this master thesis is not a finished product it is more an indication of that it might be possible to camouflage a radar system's antenna's front.

Further development should concern how different environmental conditions affect the characteristics of a camouflage solution. This thesis covers dry and wet camouflage nets where full scale testing have been conducted with good weather conditions and outside temperatures of approximately 5°-20° Celsius. The wet net testing was only performed on the ARTHUR system but should be performed on all systems.

Another important aspect to test is what happens if the camouflage solution is covered in a layer of ice. A known phenomenon when an antenna is covered of ice is so called total reflection that can appear, which means that the transmitted signals do not get pass the ice and everything gets reflected back to the receiver. The radar antennas are nowadays designed to withstand those errors in terms of not being damaged. It is important to have this occurrence in mind.

The criterion to fasten the camouflage net in the turntable can also be investigated further. It was due to limited project time that this master thesis had to reject that option. It can be an advantage to be able to attach the camouflage net in the turntable as a stationary solution can eventually decrease the rotation considerably more than a solution that rotates with the antenna. A stationary solution would probably, though, get larger than a rotating solution, so it is a trade-off between ease of use and decrease in visual rotation that has to be made.

The individual requirements and demands for each system need to be further investigated. More observations and interviews with end users can give a better understanding of challenges with a camouflage solution.

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# A
# Appendix

# A Path Deviation MATLAB Code

```
function pathAndPointingError(filename,description,camoAngle)
    %Analyses phase deviation from camo nets
    %filename=filnamn
    %description='Text describing the net'
    %cameAngle=Deviation from normal incidence angle

    %Calculates how the thickness varies over the net
    scale=1/cos(degtorad(camoAngle))-1;
    close all
    c = 3*10^8;

    %Loads the selected file
    data= loadNetworkAnalyserData(filename,description);
    freq=data.data(:,1);
    phase=data.data(:,2);
        %Plots phase versus frequency
    figure(1);
    plot(freq,phase);
    title(description);
    xlabel('Frequency [Hz]');
    ylabel('Phase deviation [mrad]');     grid on

    %Plots phase deviation versus frequency (scales phase to distance)
    dist=c./freq.*phase/360*scale*1000;

    figure(2)
    plot(freq,dist);
    title(description);
    xlabel('Frequency [Hz]');
    ylabel('Path deviation over antenna [mm]');
    grid on

    %Plots pointing error versus frequency for 1,2 and 3 m high antennas
    figure(3)
    hold on
    plot(freq,1000*atan(dist/1000),'r');
    plot(freq,1000*atan(dist/2000),'g');
    plot(freq,1000*atan(dist/3000),'k');
    title(description);
    xlabel('Frequency [Hz]');
    ylabel('Pointing error [mrad]');
    legend('1 m antenna','2 m antenna','3 m antenna');
    grid on


end
```

# B Small Scale Testing

**Table A.1:** Summary of damping for chosen frequencies between 2-12 GHz at a distance of 0.3 m and an incidence angle of 30° from the transmitting horn during tests performed with dry camouflage nets as a function of type of net (Art.nr). The measured values are in dB.

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 104408 | **0.004** | **-0.003** | -0.007 | **-0.01** | -0.02 |
| 101593 | **-0.02** | **-0.02** | -0.01 | **-0.01** | -0.01 |
| 108832 | **-0.004** | **-0.01** | -0.01 | **-0.02** | -0.02 |
| 828107 | **0.004** | **0.008** | 0.01 | **0.01** | 0.02 |
| 820904 | **-0.01** | **-0.02** | -0.03 | **-0.04** | -0.05 |
| 726071 | **-0.008** | **-0.01** | -0.01 | **-0.02** | -0.02 |
| 101362 | **-0.008** | **-0.006** | -0.004 | **-0.002** | 0.0002 |

**Table A.2:** Summary of damping for chosen frequencies between 2-12 GHz at a distance of 0.3 m and an incidence angle of 15° from the transmitting horn during tests performed with dry camouflage nets as a function of type of net (Art.nr). The measured values are in dB.

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 101593 | **-0.01** | **-0.02** | -0.02 | **-0.03** | -0.03 |
| 828107 | **0.004** | **0.006** | 0.007 | **0.009** | 0.01 |
| 101362 | **0.0004** | **-0.0007** | -0.001 | **-0.002** | -0.003 |

**Table A.3:** Summary of damping for chosen frequencies between 2-12 GHz at a distance of 1.0 m from the transmitting horn during tests performed with dry camouflage nets as a function of type of net (Art.nr). The measured values are in dB.

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 101593 | **-0.01** | **-0.01** | -0.02 | **-0.02** | -0.02 |
| 828107 | **-0.002** | **-0.003** | -0.003 | **-0.003** | -0.004 |
| 820904 | **0.02** | **-0.002** | -0.02 | **-0.03** | -0.05 |
| 101362 | **-0.001** | **-0.002** | -0.002 | **-0.002** | -0.003 |

**Table A.4:** Summary of damping for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with camouflage nets sprayed with salt water as a function of type of net (Art.nr). The measured values are in dB.

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 108832 | **0.2** | **-0.5** | -0.6 | **-0.9** | -1 |
| 828107 | **-0.04** | **-0.03** | -0.02 | **-0.01** | 0.005 |
| 101362 | **-0.05** | **-0.08** | -0.1 | **-0.1** | -0.2 |

**Table A.5:** Summary of phase deviation for chosen frequencies between 2-12 GHz at a distance of 0.3 m and an incidence angle of 30° from the transmitting horn during tests performed with dry camouflage nets as a function of type of net (Art.nr).

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 104408 | **-0.722°** | **-1.34°** | -1.72° | **-2.21°** | -2.71° |
| 101593 | **-0.718°** | **-1.26°** | -1.59° | **-2.02°** | -2.45° |
| 108832 | **-0.802°** | **-1.35°** | -1.67° | **-2.11°** | -2.54° |
| 828107 | **-0.0352°** | **-0.291°** | -0.444° | **-0.648°** | -0.850° |
| 820904 | **-0.825°** | **-1.09°** | -1.24° | **-1.45°** | -1.66° |
| 726071 | **-1.48°** | **-2.47°** | -3.06° | **-3.85°** | -4.64° |
| 101362 | **-0.280°** | **-0.494°** | -0.623° | **-0.795°** | -0.966° |

**Table A.6:** Summary of phase deviation for chosen frequencies between 2-12 GHz at a distance of 0.3 m and an incidence angle of 15° from the transmitting horn during tests performed with dry camouflage nets as a function of type of net (Art.nr).

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 101593 | **-0.722°** | **-1.26°** | -1.59° | **-2.02°** | -2.46° |
| 828107 | **-0.0995°** | **-0.255°** | -0.348° | **-0.472°** | -0.596° |
| 101362 | **-0.312°** | **-0.512°** | -0.632° | **-0.792°** | -0.952° |

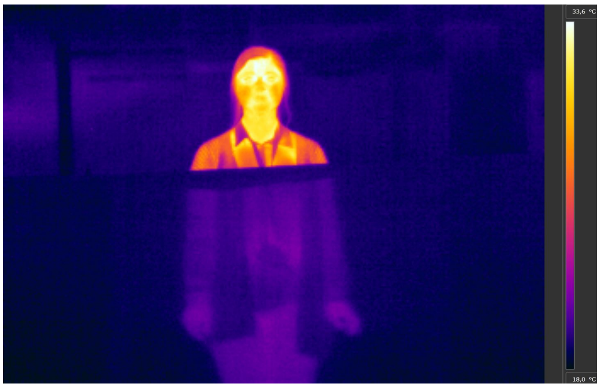
**Table A.7:** Summary of phase deviation for chosen frequencies between 2-12 GHz at a distance of 1.0 m from the transmitting horn during tests performed with dry camouflage nets as a function of type of net (Art.nr).

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 101593 | **-0.724°** | **-1.30°** | -1.64° | **-2.10°** | -2.56° |
| 828107 | **-0.106°** | **-0.289°** | -0.399° | **-0.546°** | -0.693° |
| 820904 | **-0.627°** | **-1.037°** | -1.28° | **-1.61°** | -1.94° |
| 101362 | **-0.234°** | **-0.417°** | -0.527° | **-0.674°** | -0.820° |

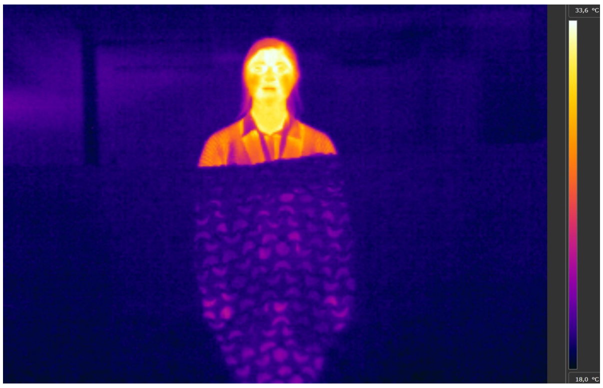
**Table A.8:** Summary of phase deviation for chosen frequencies between 2-12 GHz at a distance of 0.3 m from the transmitting horn during tests performed with camouflage nets sprayed with salt water as a function of type of net (Art.nr).

| **Art.nr** | **3 GHz** | **5.5 GHz** | 7 GHz | **9 GHz** | 11 GHz |
|---|---|---|---|---|---|
| 108832 | **-5.76°** | **-9.01°** | -11.0° | **-13.6°** | -16.2° |
| 828107 | **-0.702°** | **-0.988°** | -1.16° | **-1.39°** | -1.62° |
| 101362 | **-1.07°** | **-1.90°** | -2.39° | **-3.05°** | -3.70° |

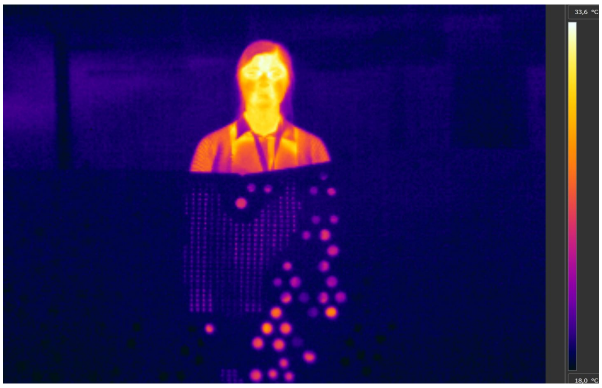
# C Thermal Photos - IR Signature



**(a)** Camouflage net 101362.

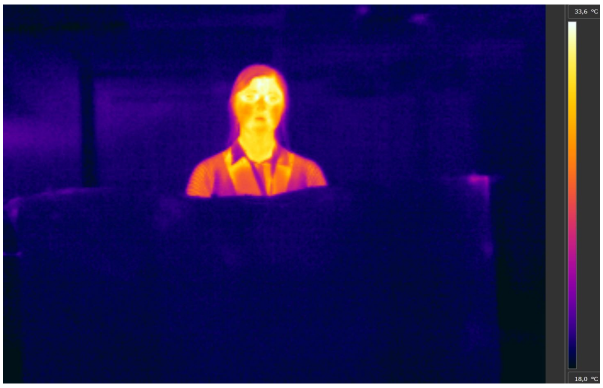


**(b)** Camouflage net 101593.

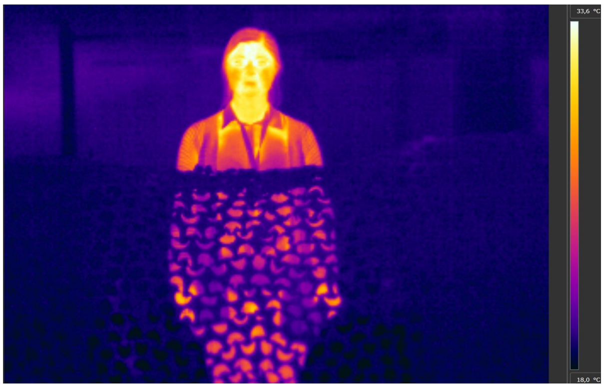


**(c)** Camouflage net 104408.

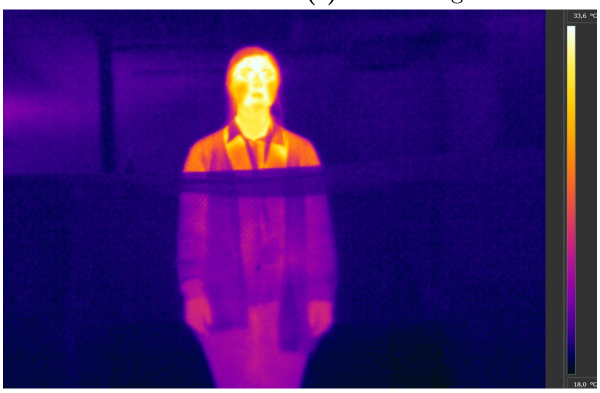
**(d)** Camouflage net 108832.



**(e)** Camouflage net 726071.



**(f)** Camouflage net 820904.



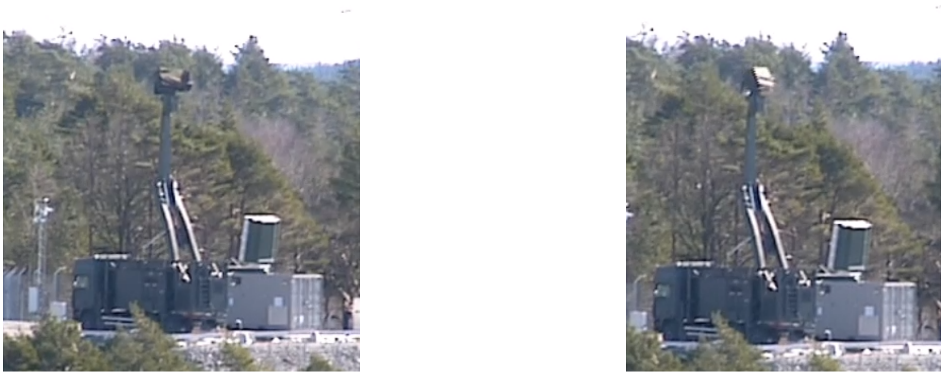
**(g)** Camouflage net 828107.

**Figure A.1:** Thermal Photos illustrating the camouflage nets IR signature. Colour scale from 1.0° Celsius to 33.6° Celsius.

# D Full Scale Testing - Visibility

**(a)** Front side of antenna no glare. **(b)** Front side of antenna with glare. **(c)** Back side of antenna including IFF antenna.

**Figure A.2:** GIRAFFE AMB antenna without camouflage net.



**(a)** Front side of antenna with no glare. **(b)** Front side of antenna with glare.

**Figure A.3:** GIRAFFE AMB antenna with camouflage net 101362.

**(a)** Front side of antenna with no glare. **(b)** Front side of antenna with glare.

**Figure A.4:** GIRAFFE AMB antenna with camouflage net 101593.

(a) Front side of antenna with no glare.

(b) Front side of antenna with glare.

**Figure A.5:** GIRAFFE AMB antenna with camouflage net 101362 and 101593.

# E Requirement Specification

**Table A.9:** Requirement specification.

| Category | No. | Requirement | Target Value | D/W | Validation |
|---|---|---|---|---|---|
| 1. Characteristics | | | | | |
| *1.1 Performance (Mechanical Structure and Camouflage Net)* | | | | | |
| 1.1.1 Damping | | | | | |
| | 1.1.1.1 | The camouflage solution shall not affect the radar system's performance more than 2 dB in total (two ways) irrespective of the weather conditions. | < 2dB | D | Saab Surveillance |
| 1.1.2 Pointing Error | | | | | |
| | 1.1.2.1 | The camouflage solution shall not have a pointing error larger than accepted for the system irrespective of the weather conditions. | | D | Saab Surveillance<br>Saab Barracuda AB |
| 1.1.3 Reflection, Transmission, IR and Visual | | | | | |
| | 1.1.3.1 | The camouflage solution shall remove the visual reflection in form of glare from the antenna surface. | | D | Saab Surveillance<br>Saab Barracuda AB |
| | 1.1.3.2 | The camouflage solution shall remove the visual reflection in form of visual rotation of the antenna. | | D | Saab Surveillance<br>Saab Barracuda AB |
| | 1.1.3.3 | A rotating antenna shall have as uniform appearance as possible from all angles. | | D | Saab Surveillance<br>Saab Barracuda AB |
| | 1.1.3.4 | A stationary antenna shall blend into the sorrounding environment and be as homgeneous as possible. | | D | Saab Surveillance<br>Saab Barracuda AB |
| 1.1.4 Weight | | | | | |
| | 1.1.4.1 | Added weight for the antenna shall not exceed 20 kg. | < 20 kg | D | Saab Surveillance |
| 1.1.5 Size | | | | | |
| | 1.1.5.1 | The camouflage solution's total size shall minimum cover the antenna front plate. | | D | Saab Surveillance |
| 1.1.6 Robustness | | | | | |
| | 1.1.6.1 | The camouflage solution shall be able to carry its own weight and a reasonable amount of wind/water/snow/ice/ hail. | | D | Saab Surveillance |
| | 1.1.6.2 | If the functionality of the camouflage solution is affected negatively it should have the possiblity to be removed. | | D | Saab Surveillance |

*2. Operational Time*
*2.1 Handling by Operator*

| | | | | | |
|---|---|---|---|---|---|
| 2.1.1 Ease of use | | | | | |
| | 2.1.1.1 | The camouflage solution shall be simple to use and not affect other tasks. | | D | Saab Surveillance |
| 2.1.2 Ease of learning | | | | | |
| | 2.1.2.1 | The camouflage solution shall be intuitive. | | D | Saab Surveillance |
| 2.1.3 Operator training | | | | | |
| | 2.1.3.1 | A mounting instruction shall be provided with the camouflage solution. | | D | Saab Surveillance |
| 2.1.4 Mounting time | | | | | |
| | 2.1.4.1 | Mounting time of the camouflage solution during regrouping shall not be more than 0-5 minutes onto the radar system. * | < 0-5 min | D | Saab Surveillance |
| | 2.1.4.2 | Unmounting time of the camouflage solution during regrouping shall not be more than 0-5 minutes onto the radar system. * | < 0-5 minutes | D | Saab Surveillance |
| | 2.1.4.3 | Mounting time of the camouflage solution from storage onto the radar system shall not be more than 20-30 minutes. * | < 20-30 minutes | D | Saab Surveillance |
| | 2.1.4.4 | Unmounting time of the camouflage solution from the radar system including packaging shall not exceed 20-30 minutes. * | < 20-30 minutes | D | Saab Surveillance |

* depending on system

| | | | | | |
|---|---|---|---|---|---|
| *3. Environmental Requirements* | | | | | |
| *3.1 Climatic Environment* | | | | | |
| | 3.1.1 General | | | | |
| | | 3.1.1.1 | Aspects of different climate conditions should be investigated. | D | Saab Surveillance |
| | 3.1.2 Wind | | | | |
| | | 3.1.2.1 | Impact of wind on the camouflage solution shall be investigated, especially considering the risk to damage the radar system. | D | Saab Surveillance |
| | 3.1.3 Salt water resistance | | | | |
| | | 3.1.3.1 | Shall be resistant to salt water. | D | Saab Surveillance |
| | 3.1.4 Resistance to corrosion | | | | |
| | | 3.1.4.1 | Shall be resistant to corrosion. | D | Saab Surveillance |
| | 3.1.5 Dust | | | | |
| | | 3.1.5.1 | The camouflage solution shall be designed to minimize the negative effects of dusty weather conditions. | D | Saab Surveillance |
| *4. Reliability* | | | | | |
| *4.1 Availability* | | | | | |
| | | 4.1.0.1 | The risk of negative impact on the radar system's availability caused by the camouflage solution shall be investigated. | D | Saab Surveillance |
| *4.2 Operational* | | | | | |
| | | 4.2.0.1 | The camouflage solution shall have the possibility to be operated manually. | D | Saab Surveillance |

*5. Maintainability*

*5.1 Interchangeability*

| | | | |
|---|---|---|---|
| 5.1.0.1 | The camouflage solution shall have a modular design with interchangable modules that is easy to replace during field operation. | D | Saab Surveillance |
| 5.1.0.2 | The camouflage solution shall enable use of various camouflage nets. | D | Saab Surveillance |
| 5.1.0.3 | The camouflage solution should act as a compliment to the rest of the systems camouflage. | W | Saab Surveillance |

*5.2 Cleanness*

| | | | |
|---|---|---|---|
| 5.2.0.1 | The camouflage solution shall be designed for easy cleaning with low pressure water and mild detergent. | D | Saab Surveillance |

*6. Safety*

*6.1 General*

| | | | |
|---|---|---|---|
| 6.1.0.1 | The camouflage solution shall be designed with necessary safety to avoid personal injuries, environmental damage, antenna damage or system damage. | D | Saab Surveillance |

*7. Interfaces*

*7.1 Interface Between Radar System and Camouflage Solution*

| | | | |
|---|---|---|---|
| 7.1.0.1 | The camouflage solution shall have as little impact as possible on the antenna and radar system design. | D | Saab Surveillance |

*8. Design Rules*

*8.1 Packaging*

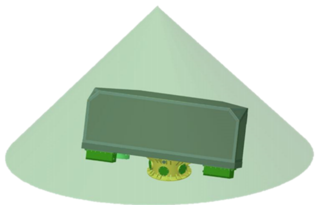
| | | | |
|---|---|---|---|
| 8.1.0.1 | The camouflage solution shall be able to be integrated and transported on the same platform as the radar system. | D | Saab Surveillance |

*9. Cost*

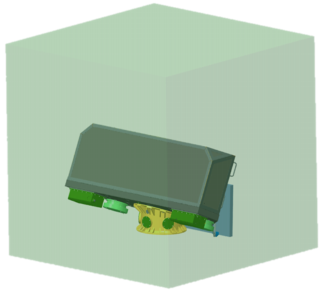
*9.1 Total Cost in Series After Development*

| | | | |
|---|---|---|---|
| 9.1.0.1 | Production cost should be approximated. | W | Saab Surveillance<br>Saab Barracuda AB |

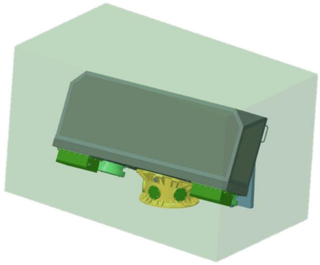
# F Generated Concepts - Geometrical Shapes



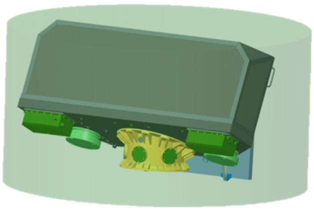
**(a)** Cone.



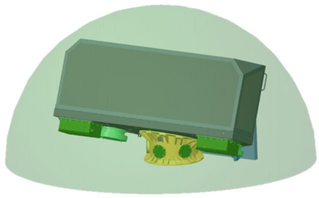
**(b)** Cube.



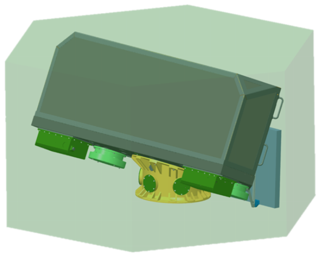
**(c)** Cuboid.



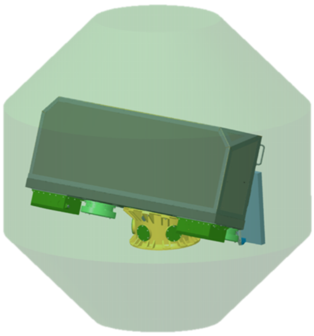
**(d)** Cylinder.



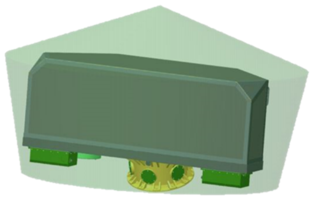
**(e)** Half Sphere.



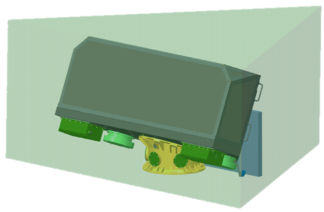
**(f)** Hexagon.



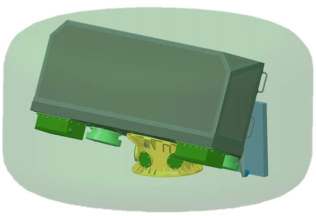
**(g)** Octagon.



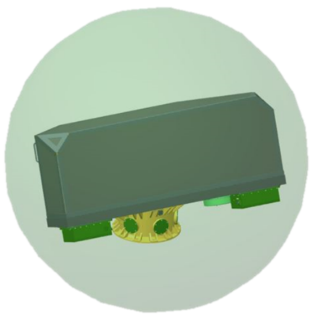
**(h)** Pentagon.



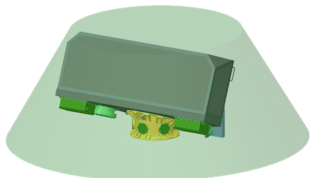
**(i)** Prisma.



**(j)** Rounded Cubiod.



**(k)** Sphere.



**(l)** Trapezoid.

**Figure A.7:** Generated concepts in terms of different geometrical shapes.

# G Elimination Matrix

**Table A.10:** Elimination matrix of geometrical shapes.

| Concept | Name | Radar Performance | Visability | Size | Ease of Use | Safety | Compatible/Realizable | Decision |
|---|---|---|---|---|---|---|---|---|
| 1 | Cylinder | + | + | + | + | + | + | + |
| 2 | Cone | + | + | - | | | | - |
| 3 | Cube | + | - | | | | | - |
| 4 | Cuboid | + | - | | | | | - |
| 5 | Prisma | + | - | | | | | - |
| 6 | Sphere | + | + | - | | | | - |
| 7 | Half-Sphere | + | + | + | + | + | + | + |
| 8 | Hexagon | + | + | + | + | + | + | + |
| 9 | Rounded Cubiod | + | + | + | + | + | + | + |
| 10 | Octagon | + | + | - | | | | - |
| 11 | Trapezoid | + | + | + | + | + | + | + |
| 12 | Pentagon | + | + | + | + | + | + | + |

| Criteria Fulfillment |
|---|
| (+) Yes<br>(-) No<br>(?) More information needed<br>(!) Check with requirement specification |
| **Decision** |
| (+) Further development<br>(-) Reject<br>(?) Need more investigation<br>(!) Check with requirement specification |

# H Pugh Matrix

**Table A.11:** Pugh matrix of geometrical shapes with the cylinder as reference concept.

| Criteria | Cylinder (ref) | Half Sphere | Hexagon | Rounded Cubiod | Trapetzoid | Pentagon |
|---|---|---|---|---|---|---|
| Size | 0 | - | 0 | 0 | - | - |
| Weight | 0 | + | 0 | 0 | - | - |
| Visability | 0 | + | - | + | 0 | + |
| Ease of Use | 0 | 0 | 0 | 0 | - | - |
| Safety | 0 | 0 | - | 0 | 0 | 0 |
| Robustness | 0 | + | - | + | - | + |
| Reliability | 0 | 0 | - | + | 0 | 0 |
| Operational Time | 0 | + | 0 | - | - | - |
| Maintainability | 0 | 0 | 0 | 0 | 0 | 0 |
| Modularity | 0 | + | - | 0 | - | - |
| Storability | 0 | 0 | - | 0 | - | 0 |
| Sum + | 0 | 5 | 0 | 3 | 0 | 2 |
| Sum - | 0 | 1 | 6 | 1 | 7 | 5 |
| Sum 0 | 11 | 5 | 5 | 7 | 4 | 4 |
| Rank | 3 | 1 | 5 | 2 | 6 | 4 |

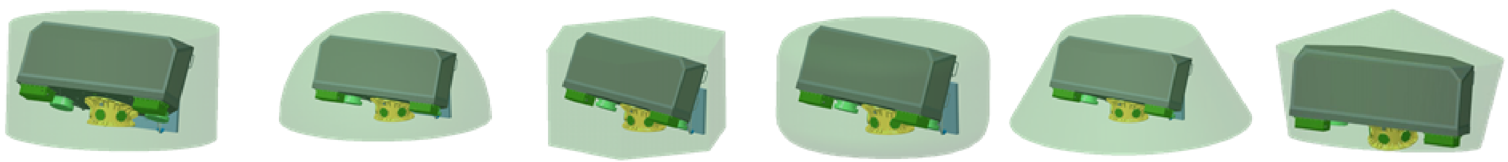
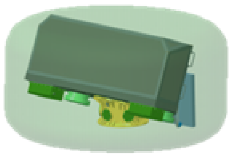
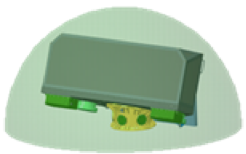
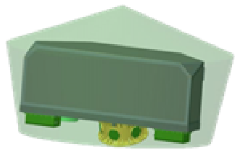


**Table A.12:** Pugh matrix of geometrical shapes with the rounded cuboid as reference concept.

| Criteria | Rounded Cubiod (ref) | Half Sphere | Pentagon | Cylinder |
|---|---|---|---|---|
| Size | 0 | - | - | 0 |
| Weight | 0 | 0 | - | 0 |
| Visability | 0 | + | + | - |
| Ease of Use | 0 | + | 0 | 0 |
| Safety | 0 | 0 | 0 | 0 |
| Robustness | 0 | + | + | - |
| Reliability | 0 | - | - | - |
| Operational Time | 0 | + | 0 | + |
| Maintainability | 0 | + | 0 | 0 |
| Modularity | 0 | + | - | 0 |
| Storability | 0 | 0 | - | 0 |
| Sum + | 0 | 6 | 2 | 1 |
| Sum - | 0 | 2 | 5 | 3 |
| Sum 0 | 11 | 3 | 4 | 7 |
| Rank | 2 | 1 | 4 | 3 |


# I Pros and Cons Lists

**Table A.13:** Frame ideas.

| Idea | Pros | Cons | Decision |
|---|---|---|---|
| Bendable frame | Advantageous storage<br>Ability to form<br>Flexible | Need human force<br>Need support to in bended position | |
| Not bendable frame | Robust<br>Easy and fast assembly | Not flexible<br>Require more space during storage | |

**Table A.14:** Folding/unfolding ideas.

| Idea | Pros | Cons | Decision |
|---|---|---|---|
| Ball Joint | Flexible<br>Low weight | Less robust<br>Tedious to get in right position<br>Dust sensitive | |
| Locking Hinge | Flexible<br>Enables several locking positions | Need human force to be locked | |
| Multi Positional Hinge | Flexible<br>Less storage space<br>Enables several locking positions | Complex | |
| Multi Axis Hinge | Intuitive<br>Less storage space | Only two positions | |
| Not able to fold/unfold | Robust<br>Less moveable parts<br>Inexpensive<br>Low weight | Require more space during storage<br>Tedious assembly<br>Longer assembly time<br>Less flexible | |

**Table A.15:** Interface between frame and camouflage net ideas.

| **Idea** | **Pros** | **Cons** | **Decision** |
|---|---|---|---|
| Hem | Maximum cover<br>Easy and fast fastening<br>Robust<br>No extra parts needed<br>Inexpensive<br>Withstand harsh climate | Not modular<br>Difficult to maintain | |
| Curtain rings | Robust<br>Break structure and prevent glare | Not fully covered frame<br>Tedious fastening<br>Need locking device | |
| Zipper | Easy and fast fastening<br>Maximum cover<br>Robust<br>Withstand harsh climate | Difficult to maintain<br>Not modular<br>Prone to stuck | |
| Velcro | Maximum cover<br>Easy and fast fastening<br>Inexpensive<br>Durable | Difficult to maintain | |
| Snap fasteners | Modular<br>Easy to maintain<br>Easy fastening<br>Inexpensive | Less robust<br>Time consuming fastening | |
| Snap link | Easy to maintain<br>Modular<br>Easy fastening<br>Robust | Tedious fastening<br>Not fully covered frame<br>Need locking device<br>Time consuming fastening | |
| Detachable buckle | Easy to maintain<br>Modular<br>Easy fastening<br>Robust | Not fully covered frame<br>Tedious fastening<br>Need locking device | |

**Table A.16:** Interface between frame and radar system ideas.

| Idea | Pros | Cons | Decision |
|---|---|---|---|
| Axis | Inexpensive<br>Withstand high forces | More sensitive to dust | |
| Screw | Inexpensive<br>Withstand high forces | More sensitive to dust | |
| Adhesive Mounts | Easy and fast fastening<br>Requires less space | Do not withstand high forces | |
| Friction Clamps | Easy and fast fastening | Requires more space<br>Cannot stay attached on the system when the antenna is lowered | |
| Cable Holders | Inexpensive<br>Easy and fast fastening<br>Requires less space | Do not withstand high forces | |