Degree Thesis

Computer Science and Engineering 300 credits / Electrical Engineer 180 credits

A systematic approach to quantitatively compare antenna measurements with simulations.

Degree thesis 15 credits

Elin Andersson and George Kiarie

HALMSTAD UNIVERSITY

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Andersson, Elin
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& Kiarie, George
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Abstract

The objective of this paper is to compare antenna simulations to actual measurements using a simulation software tool. This comparison is done using statistical methods in the far field region where the radiation patterns of antennas are plotted on a polar diagram. Actual antenna measurements are carried out in an anechoic chamber. The residual, correlation and sum of squares between simulated data and measured data are calculated. The theoretical directivity value of an antenna is compared to a calculated simulated directivity value. Different methods of creating a vector norm polarplot are outlined and discussed. The numerical method used by the simulation program is outlined. The results achieved will be presented and analyzed. They will also be compared to what we expected to find. The result provided high calculated values, these depend on how the simulated and measured data are matched.

Sammanfattning

Syftet med denna rapport är att jämföra antennsimuleringar med mätningar med hjälp av ett simuleringsprogramverktyg. Denna jämförelse görs med hjälp av statistiska metoder i fältet där strålningsmönstren av antenner ritas i ett polardiagram. Antennmätningar utförs i en ekofri-kammare. Residualen, korrelationen och kvadrat summan mellan simulerad data och uppmätta data beräknas. Det teoretiska riktningsvärdet för en antenn jämförs med ett beräknat simulerat direktivitetsvärde. Olika metoder för att skapa en normaliserad polarplot diskuteras. Den numeriska metoden som används av simuleringsprogrammet beskrivs. De uppnådda resultaten presenteras och analyseras. De kommer också att jämföras med vad som förväntas att hitta. Resultatet gav höga beräknade värden, dessa är beroende på hur den simularde och den uppmätta datan är matchad.

Contents

1 Introduction

In this modern era of wireless communication, more and more products are being developed and are connected wirelessly, such as cars and watches. This requires knowledge of fundamental communication concepts such as types of antennas, electromagnetic radiation and various phenomena related to propagation. In case of wireless communication systems, antennas play a prominent role since there is no wireless communication without them. Over the past years there has been increased growth in the antenna industry. Dating back from when Heinrich Hertz developed a wireless communication system in which he forced an electrical spark to occur in the gap of a dipole antenna to when Marconi was sending information across the Atlantic. In the 1890s, there were only a few antennas in the world. By World War II, antennas became widely used in radio and television reception. In the early 21st century, the average person carried one or more antennas on them wherever they went. This significant rate of growth is more likely to increase, as wireless communication systems become a larger part of everyday life. Over a billion devices use antennas today. According to Internet Of Things (IOT), there are predictions that the number of connected devices is going to be 31 billion in 2025 [1]. Hence, learning about antennas contributes to one's overall understanding of the modern world [2]. Nowadays, making antennas smaller, particularly in communications for personal wireless communication devices has become the way forward. A good example is the cell mobile systems which have evolved from analog systems, called the first-generation (1G) systems, to digital systems, called the second-generation (2G) systems. Afterwards came the third-generation (3G) systems, which are capable of multimedia transmission to the fourth-generation systems (4G) (LTE advanced) and soon fifth generation (5G). This is noticeable in the change of size in mobile phones, which went from big to small partly due to the change in antenna size. All people who grew up during the last 40 years can recognize the development.

Electronics Center Halmstad (ECH) is located at Halmstad University. ECH is an innovation arena that collaborates with regional industries and with the slogan *"For the future of electronics in Halmstad"*. At ECH, companies are offered contact with the university's researchers in electronics development and the possibility to run Electromagnetic Compatibility (EMC) tests.

1.1 Phonak and their products

Phonak is a company with an office in Halmstad whose headquater is located in Switzerland. They have launched several hearing aids that will help people with impaired hearing [3]. Phonak is the architect for this bachelor thesis, done by students at Halmstad University. There are different styles of hearing aids, such as, behind-the-ear and in-the-ear. Behind-the-ear is the most common type in Sweden and it suits most hearing losses. All functions are placed in the device that is located behind the ear. The sound travels through a thin plastic tube that runs from the device to an ear-mold which is located in the ear canal. A behind-the-ear hearing aid has more functionalities than an in-the-ear hearing aid. In-the-ear suits mild to severe hearing loss, this hearing aid is located in the ear canal. All the functions are placed in an individual mold cast. One of the big differences, between in-the-ear and behind-the-ear, is that the microphone is located in the ear canal and the sound is recorded more naturally. In both hearing aid types there are different models, behind-the-ear and in-the-ear are collective names [4].

Bluetooth connected hearing aids have been an area of study recently. They are hearing aids designed to recognize radio signals that have been sent from other devices and wirelessly communicate in the 2.45 GHz band. The wireless hearing aids are usually paired directly with a streamer which is often worn around the neck and then the streamer can be paired with external devices. The nature of the 2.45 GHz band allows signals to propagate easily through air, thus reducing signal degradation. The disadvantage of this band is that it results in a short wavelength that does not propagate well through and around the human head and body. Most Bluetooth devices are being built to improve propagation of the signal around the human head and body. This is done to be able to send signals from a phone/streamer to both ears and make sure that the signals can be received by both ears at the same time.

There are many experiments required to be able to develop antennas and more and more companies have started relying on simulations instead of practical testing. The current method of verifying their simulations is an unquantifiable way of comparing measured data to simulations. Essentially all current companies is subject to the use of different scales and ways of plotting. This is the reason why companies such as Phonak are looking for a quantitative method of making comparisons between measured data and simulations. To be able to trust their simulations.

1.2 Project aim and goals

This project aims to shed light on how to quantify the comparison between measurements and simulations. This is done by comparing 2D data between the measured data and simulated data.

The second goal, is to try to turn a 3D simulation to fit a 2D measurement. This is done by comparing measured data with simulated data that have tilted angles. It can be demonstrated with help of a balloon, it is not perfectly spherical. If a line is drawn around an inflated balloon, a 2D area that is created inside the balloon can be seen, with the limitation of the line as area one. After tilting the balloon a few degrees and drawing a new line that will cross the first line, there will be two lines and two areas. If both areas are taken out and laid on each other, an observation of their difference in size is seen, as well as their similarities. By turning the balloon, an estimation of the plane where the 3D simulation fits as good as possible with the 2D measurements is done. See figure 1 and 2.

Questions

- Which statistical methods are suitable to compare simulations to measurements?
- Can we systematically detect antenna angles using common statistical tools?

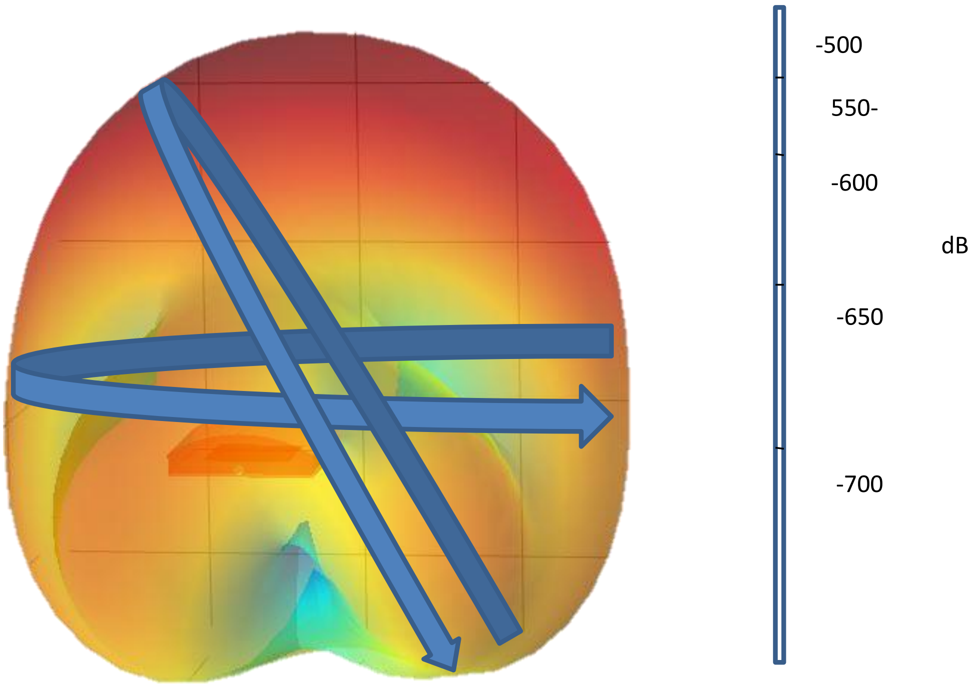


Figure 1: A 3d simulation of a patch antenna's radiation pattern. The arrow pointing downwards indicates a tilted vertical plane while the arrow pointing towards the right indicates the horizontal plane.The scale is in dB.

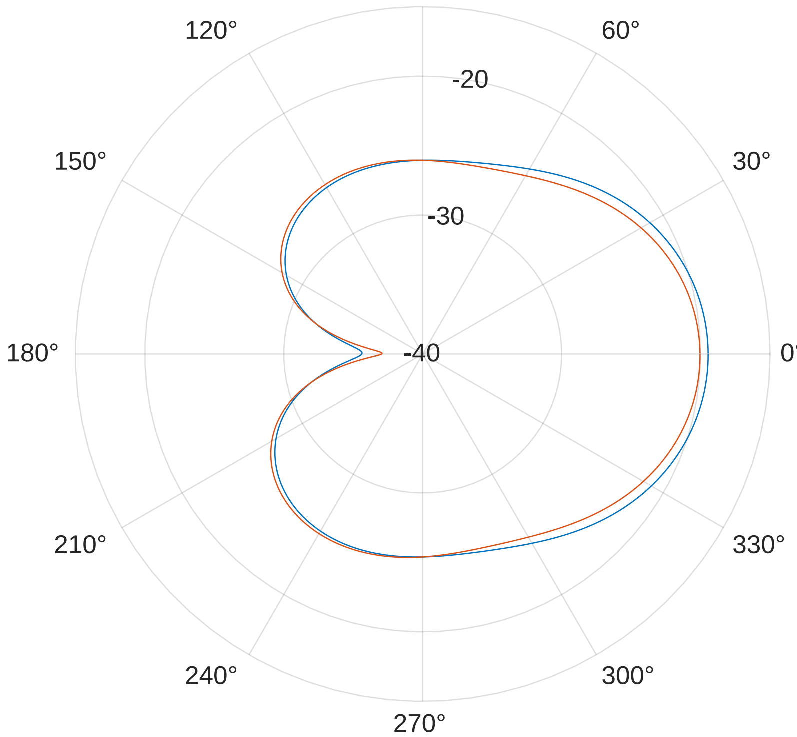


Figure 2: The norm of the E field that is obtained from figure 1. The blue polarplot is 30 dBm, the red polarplot is 30dBm with 5 deg tilt

1.3 Limitation

In this project we limit ourselves to COMSOL, a simulations program which uses the Finite Element Method. The antenna measurment were performed by Per-Olof Karlsson, head research engineer at ECH, Halmstad university.

1.4 Previous work

There have been various research conducted previously to try to quantitatively compare antenna simulations with measurements. This is done using numerical methods and statistical methods. In one of the research, they try to draw a comparison of antenna simulations to measurements using the scale model of a ship. In the past decades, scale brass model measurement has been the most extended methodology to assist in the on board antennas design and in the selection of their optimal placement. The scale model of a ship is a detailed brass model linearly downscaled from the original dimensions of the vessel. The scaling factor is determined by the manageable size of the model and the frequency capabilities of the measuring equipment.The frequency must be suitably scaled in order to maintain the size of the brass model in terms of the wavelength. The objective of this research was to highlight the convenience of using electromagnetic simulation software as an alternative to the traditional scale model measurement when dealing with the design of antennas on real complex platforms. The experiment was developed during the building process of a real vessel. Since the vessel length was over 240 meters, a scaling factor of 1/50 was chosen so as to obtain an accurate model of the superstructure.

The antenna measurements (Voltage Standing Wave Ratio (VSWR) and reflection coefficient(S_{11})) carried out onboard the real platform were compared with the antenna simulations VSWR and S_{11} obtained by the M^3 software and with those obtained after measuring the scale model in a semi-anechoic chamber. It was noted that the VSWR and S_{11} from the scale model differed slightly from the other two results corresponding to the measurements on the real platform and those derived from the simulations with M^3. It demonstrated that more accurate results can be obtained when using an adequate electromagnetic simulation code, which offers advantages in flexibility and usability [5].

The second research was in comparing simulations to measurements in the near field region. Here, the antenna measured peak directivity was compared to the antenna simulated peak directivity from different simulation programs such as CST, Savant and FEKO. The measured data differed to simulations by a maximum value of 0.25 dB and thus deemed that simulations were reliable [6].The average correlation between simulations with the measured source and the reference measurement of the final scenario was found to be 30dB, which is comparable to what is achievable with a full-wave simulation of the scenario. It confirms the accuracy of proposed approach, based on the link between measurement and simulation.

2 Theory

In this project we are only interested in the far field measuring technique, the difference between near- and far-field is shown in figure 3. Generally the far field represents antenna radiation, and is responsible for signal propagation. Therefore the antenna measurements and simulations are presented in the far field.

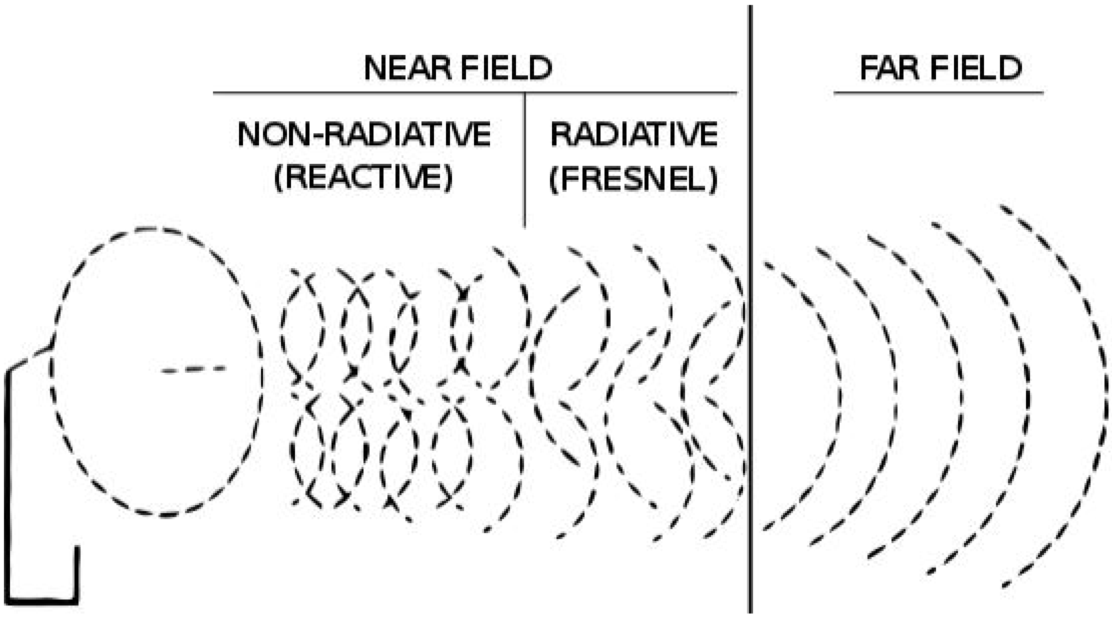


Figure 3: Differences between Fresnel diffraction in the near field area and Fraunhofer diffraction in the far field area

2.1 Development of the antenna industry

In the past, companies relied mostly on build and test procedures when making antennas. This proved to be a costly method in the design process due to time loss and misuse of resources. Many companies have decided to speed up the production cycles by improving the design with simulations, all to minimize cost and save time. Currently, there is no actual standard in quantifying antenna simulations with measurements.

The antenna industry standard has developed from open testing to anechoic testing over the years. An anechoic chamber is a room where the walls, ceiling and floor are lined with EM-absorbent foam to minimize electromagnetic (EM) radiation being reflected. Fifty years ago, the most accurate antenna measurements tests were conducted in Open Area Test Sites (OATS), where there was minimal electromagnetic wave activity. This method was relatively imprecise and impractical. The weather and the amount of sunlight dictated when the OATS could be used, and there were few measures in place to restrict the number of wave reflective objects at the sites such as wires, lights, and walls.

One way to eliminate some of the problems with the OATS was to conduct tests in a radio-frequency (RF) shielded chamber which was based on the Faraday cage principle. This method unfortunately opened up issues with cavity resonances and internal surface reflections. In the 1970's and 80's, regulatory agencies began implementing new testing standards for products that emitted or were susceptible to RF waves. Electronic devices faced the threat of being taken off the shelf for not meeting international standards and the economic drawback of this spurred large multi-national corporations to look for better and more reliable alternatives for vetting their products.

Thus, many companies opted to invest in an absorber material to attenuate (weakening in force or intensity) the waves and inhibit internal reflection in anechoic chambers. The biggest breakthrough came in the application of "ferrite", a great absorber, which could be made into tiles only a few millimeters thick. Today, the hybridized anechoic chamber is the standard for EMC testing. They are versatile enough to emulate a wide variety of test conditions to be a reasonable investment for companies, labs, and universities [7].

2.2 Radiation pattern

Previous work on comparisons between measured data and simulated data is studied. Usually, only the shape of the radiation pattern is compared, no statistical analysis on differences and errors is done. To accurately observe power propagation, the antenna's radiation pattern is plotted in the far field which allows a comparison between the actual and theoretical values.

A radiation pattern [8] defines the variation of the power radiated by an antenna as a function of the direction away from the antenna. It's the most significant property of an antenna and is plotted on a polar diagram. In case of a transmitting antenna, this is a plot that shows the strength of the power field radiated by the antenna in various angular directions. The radiation pattern reflects the sensitivity of the antenna in different directions and due to this the antenna can be orientated in the optimum direction to ensure the required performance. Polar diagrams are used to indicate the response of antennas.

The radiation pattern of an antenna is typically represented by a two dimensional graph. Its most common representation is in the Azimuth (horizontal) and Elevation (vertical) patterns. Radiation plots are usually shown in relative dB (decibels). An example of a simulated antenna radiation pattern is shown in figure 4 below.

There are three types of antennas. Those that have a pattern which is "isotropic", that is, if the radiation pattern is the same in all directions (this is solely theoretical, do not exist in real life). They are sometimes discussed as a means of comparison with real antennas. The second is the "omnidirectional" antennas. They are antennas whose radiation pattern is isotropic in a single plane. Lastly is the "directional" antenna, which does not have symmetry in the radiation pattern. These antennas typically have a single peak direction in the radiation pattern; this is the direction where the bulk of the radiated power travels.

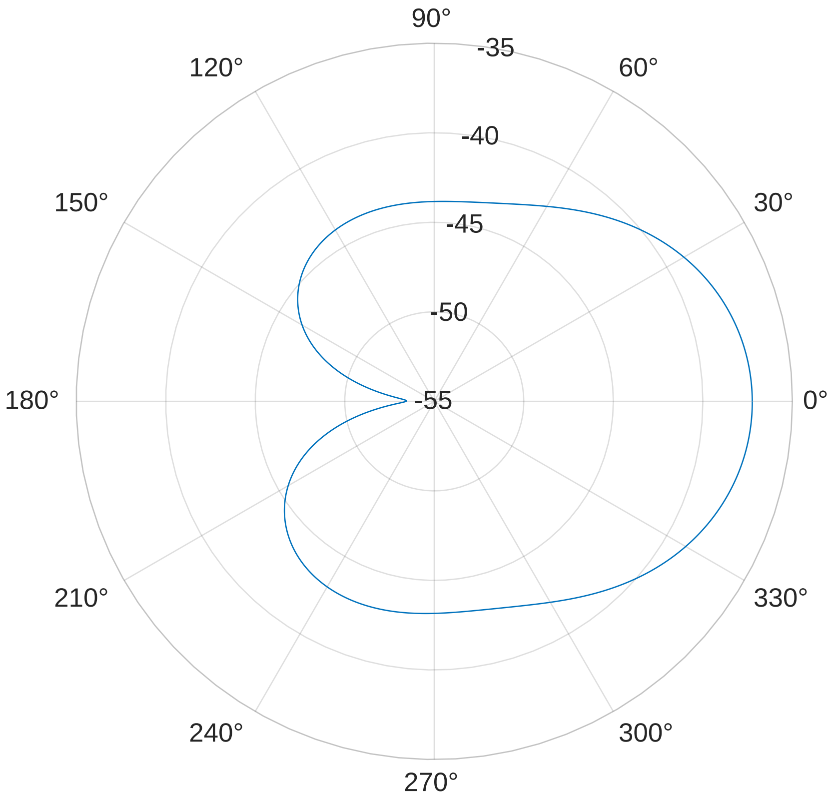


Figure 4: A vertical polar plot representation of a simulation of an antennas radiation pattern. Radial scale in dBi.

2.3 Antenna properties

Antennas are constantly being enhanced and improved to ease communication between people and ease transmission and reception of signals between devices. To move the project forward, an understanding of how different antennas work is crucial [9], [10] so as to be able to identify the right type of antenna to use for different frequencies and different situations.

Various terms are also important to understand such as polarization, which is one of the fundamental characteristics of any antenna. It is the polarization of the radiated fields produced by an antenna, evaluated in the far field. Antennas are usually classified as “Linearly Polarized” or a “Right Hand Circularly Polarized Antenna”. Due to the reciprocity theorem [11], [12], antennas transmit and receive in exactly the same manner. This means that the horizontal transmitting antenna cannot communicate with the vertical receiving antenna. Polarization Loss Factor (PLF), also known as antenna receiving factor, polarization efficiency or antenna mismatch factor is the factor that arises when two linearly polarized antennas are rotated from each other’s angle. The most desirable type of polarization for antennas is the circular polarization. This is because of no signal loss due to polarization mismatch if two antennas are both circularly polarized. It is advantageous since a RHCP wave will reflect off a surface and be LHCP. This means that an antenna designed to receive RHCP waves will have some immunity to the signal- fading effects of reflected waves interfering with the desired wave [13].

Antenna efficiency is a ratio of the power delivered to the antenna relative to the power radiated from the antenna. It's a number between zero and one though which is usually put as a percentage and frequently presented in decibels (dB). A low efficiency antenna has most of the power absorbed as losses within the antenna, or reflected away due to impedance mismatch. A high efficiency antenna has most of the power present at the antenna's input radiated away. Antenna efficiency is the same whether we are using the antenna to transmit or receive signals, also known as antenna reciprocity. The total efficiency of an antenna is the radiation efficiency multiplied by the impedance mismatch loss of the antenna, when connected to a transmission line or receiver. Antenna efficiency losses are typically due to conduction losses (due to infinite conductivity of the metal that forms the antenna), dielectric losses (due to conductivity of a dielectric material near an antenna) and impedance mismatch loss [13]. Antenna efficiency can be measured in terms of directivity and gain.

Directivity is a measure of how "directional" an antenna's radiation pattern is. An antenna would have effectively zero directionality if it radiates equally i all directions. This directivity would be one (or 0 dB). A high directivity value implies a more "focused" or "directional" antenna. The directivity of an antenna can vary over several orders of magnitude. Directivity can be a s low as 1.76 dB for a real antenna. It can theoretically be less than 0 dB [14].

Antenna gain is how much power is transmitted in the direction of peak radiation to that of an isotropic source. It's more common to find it on an antenna's specification sheet than directivity since it takes into account the actual losses that occur. It's sometimes discussed as a function of an angle. A radiation pattern can be plotted in terms of gain as shown in figure 4. The gain of a real antenna can be as high as 40-50 dB. The peak gain of an antenna can be arbitrarily low because of losses or low efficiency [14].

2.4 Types of antennas

There are various types of antennas in the market today [15]. Some of the examples are:

The wire antennas - They are the simplest and cheapest available and are used in a wide range of applications. Examples are the dipole antenna, monopole antenna and loop antenna.

The dipole antenna is one of the most straight forward antenna alignments. It consists of two thin metal rods with a sinusoidal voltage difference between them. For very small dipole antennas, the input impedance is capacitive, which means the impedance is dominated by a negative reactance value. If the dipole's length becomes close to a one wavelength, the input impedance becomes infinite. The full-wavelength dipole antenna is more directional than the quarter-wavelength dipole antenna. It is symmetric when viewed azimuthally. Its directivity increases with length.

Monopole antennas see figure 5 are attractive when a smaller antenna is needed. It is one half of a dipole antenna and its impedance is one half of a full dipole antenna. Its directivity is is twice that of a dipole antenna of twice its length. Its radiation pattern is strongly affected by a finite sized ground plane. The fields of the short dipole antenna are a function of the polar angle. They have no azimuthal variation and therefore it can be characterized as omnidirectional. The polarization of this antenna is linear and its impedance depends on the radius of the dipole. They are usually used in narrow-band applications because their input impedance varies wildly with frequency because of the reactance component of the input impedance.

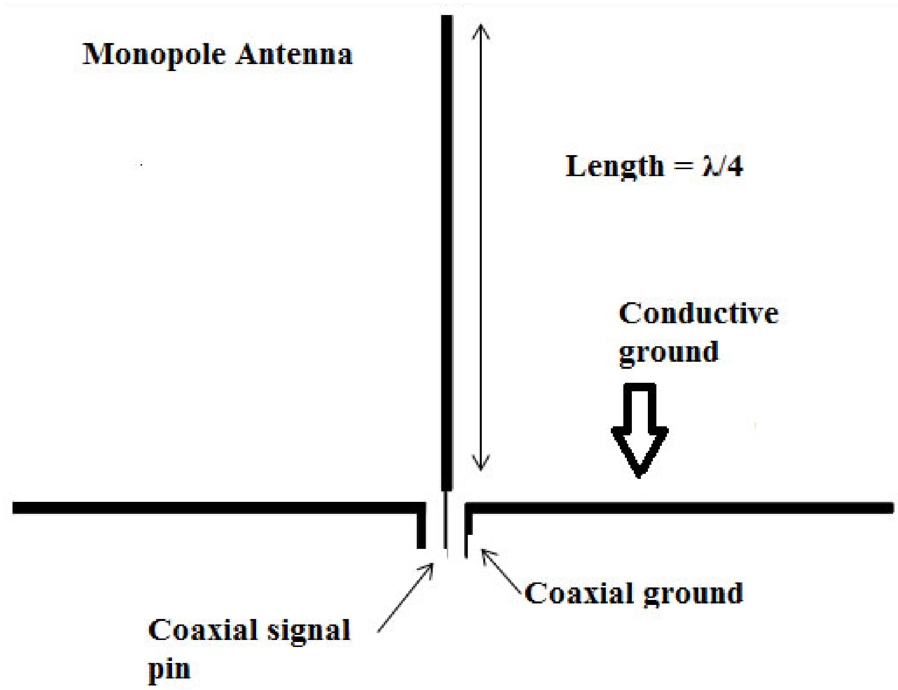


Figure 5: Dimensions of the monopole antenna

The microstrip antenna - It's mostly used at microwave frequencies. Examples are the rectangular microstrip (Patch) antennas and the Planar Inverted F Antennas (PIFA). The width of the patch antenna controls the input impedance and the radiation pattern. The directivity (a measure of how "directional" an antenna's radiation patter is) of patch antennas is approximately 5-8 dB. The Planar Inverted F Antenna see figure 6 is resonant at a quarter-wavelength and has good Specific Absorption Rate (SAR) which is usually between 1.9-3 W/kg at 0.9 GHz. SAR is a measure of the rate at which energy is absorbed by the human body when exposed to a radio frequency (RF) electromagnetic field. SAR is set by determining the lowest level of exposure known to cause health hazards [16] and then adding a safety margin. A patch antenna's impedance can be controlled via the distance of the feed to the short pin. The impedance decreases the closer the feed is to the shorting pin and increases by moving it farther from the short edge.

There are some differences between a patch antenna and a dipole antenna that have been noted by [18]. When conducting an experiment for a wi-fi application, the patch antenna was found to be more superior when it came to measured radiation and gain. The measured download speed performance was similar compared to the dipole antenna. The patch's measured upload speed performance started deteriorating at a distance of 200 meters from the wireless router compared to 240 meters for the dipole antenna. Even though the patch antenna was better in certain aspects,

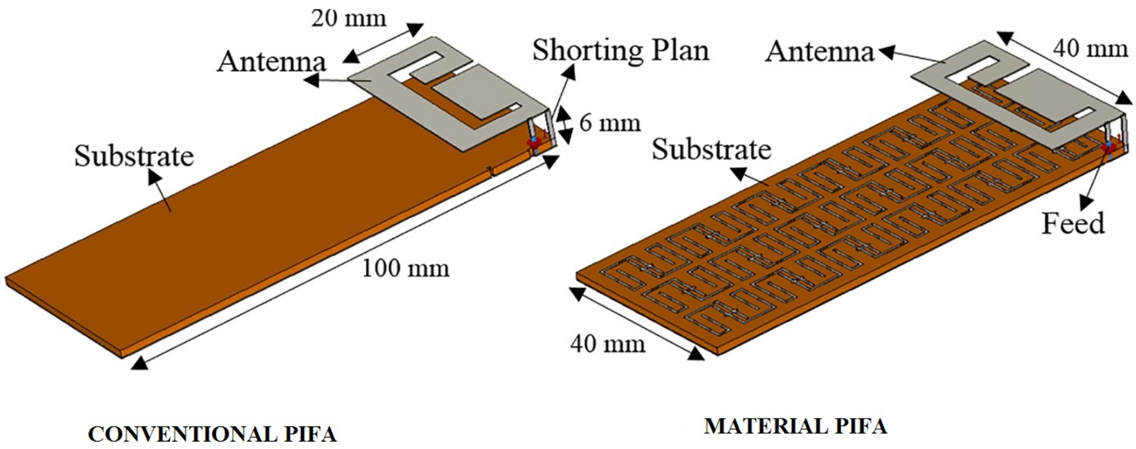


Figure 6: On the left is the geometry of the conventional PIFA and on the right is the metamaterial- embedded PIFA for cellular phones [17]

the result showed that the dipole antenna proves to be more superior compared too the directional patch microstrip antenna when it comes to wi-fi application.

In this project the focus was on the patch antenna. A patch antenna (also known as a rectangular microstrip antenna) is a type of radio antenna with a low profile, which can be mounted on a flat surface. It offers the advantages of thin profile, light weight, low cost, conformability to a shaped surface and compatibility with integrated circuitry. It is a direction sensitive antenna. It's used in military applications, mobile satellite communications, the direct broadcast (DBS) system and global positioning system (GPS). One way of improving the bandwidth in a patch antenna is to use parasitic patches, either in another layer [19] (stacked geometry) or in the same layer [20] [21] (coplanar geometry).

Availability of an anechoic chamber in the university enables us to carry out far field measurements.

3 Method

Lips is a project model that is very common, there are three stages in the model. Before, during and after. In the before stage, the execution of the project is being planned as well as the time to be allocated and resources to be used. This stage is very important, and must be performed carefully. If the before stage is done incorrectly the whole project will not succeed. In the during stage, is where the project is performed. Everything is documented and in this stage a deeper knowledge and more details are noted and tested. In the after stage, the project ends and an evaluation is done. The after stage is also an important part, it might be the most difficult part in a project, to actually end it [22].

In this project lips were used, In the early stages, similar work was sought and research on various articles containing the relevant information to the project was done. Different programming languages were investigated and decisions were made as to which ones would be used. Various statistical and numerical methods were looked in to in order to carry out the project. During the actual process, a lot of work was done. A deeper understanding of the chosen programming tools and how to use them was achieved. Different calculations resulted in different results. A new way of analyzing data and critical thinking emerged. One example may be how the angles from the horizontal and vertical measurements were handled. During the after stage, all results have been analyzed and discussed, for example how one result affects the other. A conclusion has been drawn that there have been good methods used as they are influenced by how the data is matched. Most of the report has been written during the final phase of the stage and in the after-stage.

3.1 Computer software tools

There are numerous software applications available for computing statistic analyzes, such as:

MATLAB - MatLab is a language of technical computing that is developed by the company MathWorks. MathWorks produces many different mathematical computing software. MatLab is one of them, and it's a programming environment for example algorithm development and data analysis [23]. MatLab uses different algorithms that can be computed on the users data. It combines an environment tuned for design processes and analysis with a programming language. Furthermore it is a language that express mathematics directly, such as matrices and arrays. MatLab is professionally built, which means that the toolboxes are professionally developed, tested and well documented [24].

R - R is a language that computes statistics and graphs. The R language is similar to the language S. According to their website *"R can be considered as a different implementation of S. There are some important differences, but much code written for S runs unaltered under R."* R has facilities for data manipulation, calculation and showing graphs. They have effective data handling and storing, different operators for calculating on for instance arrays and tools for data analysis [25]. They are useful in plotting polarization graphs which are essential in representing radiation patterns.

IDL - IDL is a programming language from Harris Geospatial Solutions. The company say this about IDL. *"IDL is the trusted scientific programming language used across disciplines to extract meaningful visualizations from complex numerical data. With IDL you can interpret your data, expedite discoveries, and deliver powerful applications to market."* IDL is a language that gives the user flexibility in the programming, and allows them to focus on the data. The IDL language is easy to learn and to use, it also requires less lines of code. They want to make it easy and fast to find out the result. The users can fast add different mathematical function and statistics, and also visualize the data [26].

Choice of software Due to the wide range of tools, both to calculate and plot, a comparison must be made to find the program that is most suitable. After studying the programs above, and looking for differences and similarities. According to Jules Kouatchou, that have done a comparison between Python, Julia, R, MatLab and IDL. He tested both simple and difficult mathematics. When a comparison between only R, MatLab and IDL examinees from the result, a trend can be seen. In 6 of 8 different problems, that are being solved with these programs, MatLab has the shortest execution time [27].

In an Technical Report done at Department of Mathematics and Statistics, University of Maryland, Baltimore County. A Comparative Evaluation of Matlab, Octave, FreeMat, Scilab, R, and IDL has been done. They tested for instance Gaussian Elimination and Conjugate Gradient Method. Even here only MatLab, R and IDL is analysed. The conclusion is that MatLab was faster than R. Unfortunately IDL does not compute the conjugate problem and does not have a time measuring function without the license. Which leads to that it is not the easiest program to use. From their result a conclusion is made that MatLab is a better toll to use [28]. With this information, MatLab is the program that we want to look closer at.

Halmstad University has a collaboration with MathWorks. This enables the university to give all students a student-version and a license key that works for one year. Together with all these facts and results, and the fact that MatLab has been taught in some courses at the University. MatLab is a given choice to use and to learn more about.

3.2 Numerical techniques

3.2.1 Finite Element Method (FEM)

The Finite Element Method (FEM), is a numerical method of solving engineering problems such as structural analysis, fluid flow, heat transfer and electromagnetic potential [29]. The analytical solution of these problems generally require the solution to boundary value problems for differential partial equations. Its formulation of the problem results in a system of algebraic equations.

The laws of physics for space- and time-dependent problems are usually expressed in terms of partial differential equations (PDEs). For most geometries and problems, these PDEs cannot be solved with analytical methods. Thus, an approximation of the equations can be constructed based upon different types of discretization. These discretization methods approximate the PDEs with numerical model equations, which can be solved using numerical methods.

The finite element method offers great freedom in the selection of discretization, both in the elements that may be used to discretize space and the basis functions. Its theory is well developed. This is mainly due to the close relationship between the numerical formulation and the weak formulation of the PDE problem. For example, the theory provides useful error estimates, or bounds for the error, when the numerical model equations are solved on a computer.

It's a systematic way to convert the functions in an infinite dimensional function space to first functions in a finite dimensional function space and then finally ordinary vectors (in a vector space) that are tractable with numerical methods. One of the advantages of the finite element method is its ability to select test and basis functions. It's possible to select test and basis functions that are supported over a very small geometrical region.

The finite element method gives an approximate solution to the mathematical model equations. The difference between the solution to the numerical equations and the exact solution to the mathematical model equations is the error: $e = u - u_h$. In most cases, the error can be estimated before the numerical equations are solved. For example, if the problem is well posed and the numerical method converges, the norm of the error decreases with the typical element size h according to $0h_\alpha$, where α denotes the order of convergence. This simply indicates how fast the norm of the error is expected to decrease as the mesh is made denser [30].

3.2.2 Types of FEM

The are different types of FEM [31]. The first is the Extended Finite Element Method (XFEM) - The Bubnov-Galerkin method requires continuity of displacement across elements. XFEM was born in the 1990's and it works through the expansion of the shape functions with Heaviside step functions. Extra degrees of freedom are assigned to the nodes around the point of discontinuity so that the jumps can be considered.

The second is the Generalized Finite Element Method (GFEM),[32]. It was introduced in the 90's. It combines the features of the traditional FEM and meshless methods. Shape functions are primarily defined by the global coordinates and further multiplied by partition-of-unity to create local elemental shape functions. It's advantage is the prevention of re-meshing around singularities.

The third is the Mixed Finite Element Method - In several problems, like contact or incompressibility, constraints are imposed using Lagrange multipliers. These extra degrees of freedom arising from Lagrange multipliers are solved independently. The system of equations is solved like a coupled system of equations [33].

The fourth is the hp-Finite Element Method – It's a combination of automatic mesh refinement (h-refinement) and an increase in the order of polynomial (p-refinement). When automatic hp-refinement is used, and an element is divided into smaller elements (h-refinement), each element can have different polynomial orders as well [34].

Lastly we have the Discontinuous Galerkin Finite Element Method (DG-FEM) - It has shown significant promise for utilizing the idea of finite elements to solve hyperbolic equations, where traditional finite element methods have been weak. It has also shown improvements in bending and incompressible problems which are typically observed in most material processes [35]. Here, additional constraints are added to the weak form that includes a penalty parameter (to prevent interpenetration) and terms for other equilibrium of stresses between the elements.

In this research, we use the Helmholtz equation formula 1. It's a three-dimensional, elliptic partial differential equation, which can be solved either by analytical or numerical methods or by a combination of the two. Helmholtz boundary value problems are usually categorized into one of three categories: direct, eigenvalue or inverse. Direct problems require the solution of the Helmholtz partial differential equation for given boundary conditions, whereas eigenvalue problems involve the determination of the natural frequencies of the system. Alternatively, the solution is given for inverse problems, and appropriate boundaries must be located that satisfy it. The most convenient method is determined by the complexity of the medium properties and of the boundary conditions for the actual problem. The equation is as follows:

$$\nabla * (\mu_r^{-1} \nabla \times E) - k_0^2 \times \epsilon_{rc} \times E = 0 \tag{1}$$

3.3 Statistical method

Different statistical methods will be used, such as sum of squares. It helps to calculate different parameters by comparing two types of data sets. This will show how accurate the result is and to draw conclusions of the results achieved. From the parameters and the data, both from measuring and simulated, a plot can be drawn.

Sum of square - Sum of squares is a mathematical function that helps to determinate the mismatch by calculating the variance. This is done by taking the difference between the measured data and the simulated data, at the same angle value. The formula 2 is used. Where $x_{i,r}$ is the measured norm matrix, at r degrees and with the i value. The $y_{i,r}$ is the simulated data matrix, with the same degrees, r and with the i value. When it's calculated it will tell if a model (the simulated data) is a good match. The closer to zero the result is, the better the results. It indicates that the mismatch is not that big [36]. A value close to zero is expected.

$$\sum_{i=1}^{n} (x_{i,r} - y_{i,r})^2 \tag{2}$$

Correlation coefficient - Correlation is a statistic function that estimate how much the next value is depended on the previous. It gives an estimation of how incorrect the shapes are, when the are compared to each other. There is both positive and negative correlation, if one value is high and the next one also is a high number, then it's a positive correlation. The opposite is a negative correlation, first a high value and then a lower. The output from correlation is a value that lies between one and negative one, the closer to zero the better the result. If the result is zero, the conclusion may be that the values are linear independent from each other[37] [38]. A value close to zero is expected.

Correlation estimation is a special case of correlation. The correlation between two variables X and Y can be seen in formula 3.

$$r(X, Y) = \frac{\operatorname{cov}(X, Y)}{\sqrt{V(X) \times V(Y)}} \tag{3}$$

Where $\text{cov}(X, Y)$ is the covariance of X and Y, $V(X, Y)$ is the variance of X and Y

3.4 Vector norm

To be able to use and compare measured with simulated data, a vector norm has to be done by using the horizontal and vertical matrices. This converts the two matrices into one matrix. First a calculation has to be done that calculates the dBm value into Volts. When both matrices has been calculated into volts, a new formula is used to calculate the two values into one. This formula is the same as Pythagoras equation. The result is put in a new matrix. To be able to understand the data, it is calculated back into dBm and plotted.

3.5 Measurements in an anechoic chamber

The chamber provides a platform to measure an antenna behavior in the outside world by rotating a receiver antenna normally connected to a signal generator through different angles. In order to test an equipment inside the anechoic chamber, a transmitting source that emits an electromagnetic signal and a device under test (DUT) as a receiver is required to receive the transmitted signal. The transmitted signal field strength is sampled by the receiver antenna that can be used for calculating the desired results. Measurements are done in two planes. First is the horizontal plane and the second is the vertical plane. An example of an anechoic chamber is shown in figure 7.

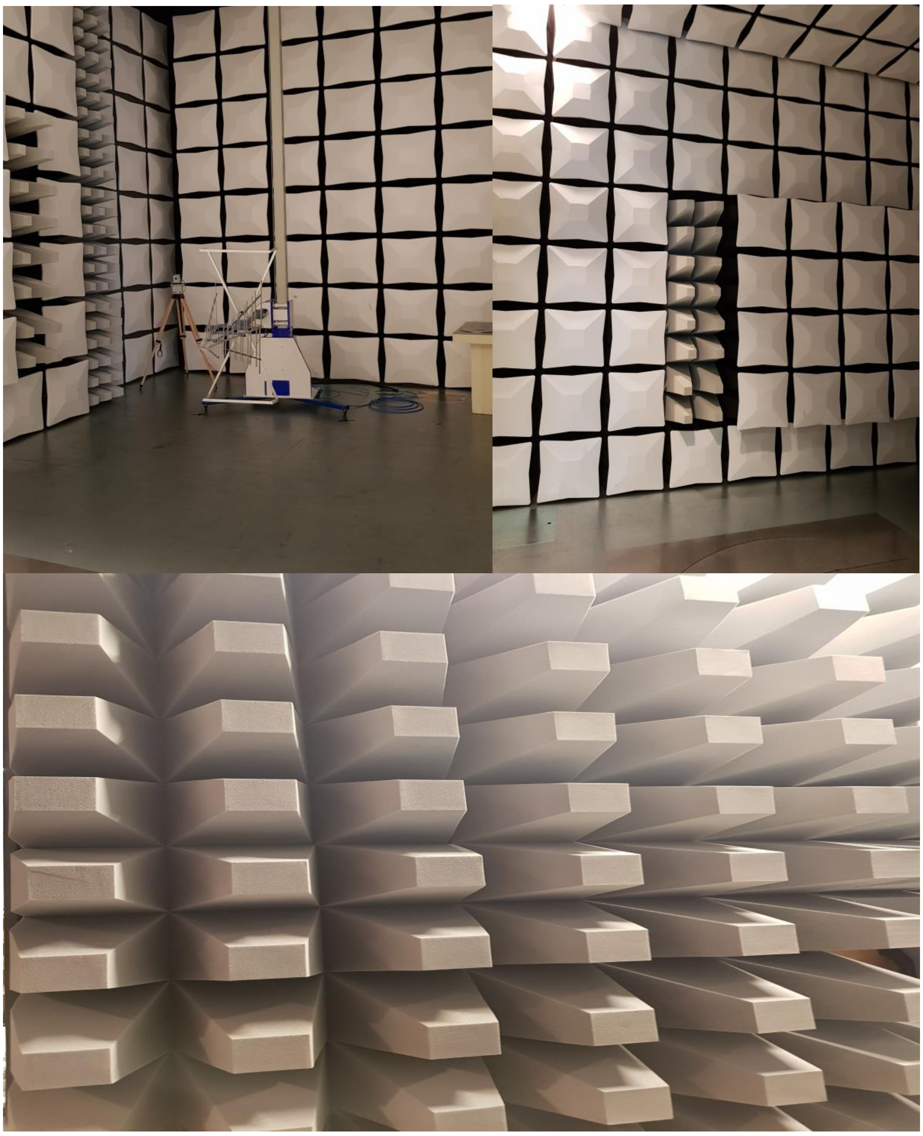


Figure 7: An anechoic chamber located in Halmstad university. A receiving antenna which is usually connected to a signal generator is shown. EM-absorbent foam is placed around the room to minimize EM-radiation being reflected.

4 Result

A flowchart over the process can be seen in figure 8.

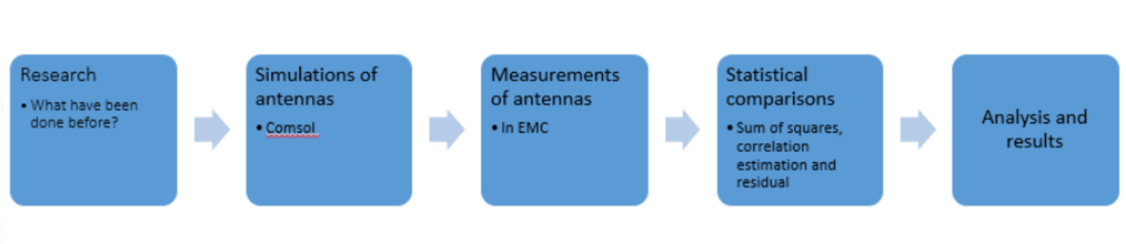


Figure 8: A flowchart over the process.

4.1 Approach and code

The data that are collected is in two matrices (127,2), that has 127 rows and 2 columns. The measurement is effect radiated as a function of the angle of the radiated antenna. Since the antennas that are being used radiates in different directions, data from the vertical and horizontal planes have been collected. One matrix contains the vertical angles and its values in dBm, and the other one the horizontal angles and its values in dBm. The first column contains the values of the angles (in degrees) and the second contains the value of the radiation (in dBm). Unfortunately there has been an incident where some of the measured data has lost one or two data points at the end. To be able to still use the data, interpolated data have been added to the end so that every matrix has the same amount of rows. In this case the interpolated data, in the first column it's the same angle value as the completed matrix has. In the second column, is the last registered value. By looking at the matrices row by row, an overview of what radiation exists at what angle. With these matrices a polar plot can be drawn in MatLab. MatLab has a function that is called *polarplot()* that is being used.

When the measured data is examined more carefully, it was discovered that the angles from the vertical and horizontal matrices, did not have the same values and there was unequal distances between the them. If the angle is not handled the result would be that the calculations that are going to be done won't be as accurate as it could be. In other word the norm data won't be completely correct. To solve this, three suggested solutions emerged. The first one was to only take the measurement data as it is, the other is to find the angles that are close to each other. The last one is to interpolate.

4.1.1 Vector norm on the data

To norm the data, several steps haves to be done. First, the data have to be normed from two matrices into one. To do this, three formulas are being used. The first one (4) is used to calculate the dBm value into Volt. A loop is used in MatLab where each value is calculated to volts. The calculated values are stored in a matrix. When both matrices has been transformed, a new formula is used to norm the data. In (5) the matrices that contains the value in volt are being used. The output is stored in a new matrix. When the norm of the data is done, it's calculated from volt to dBm by using (6).

$$10^{\frac{dBm-13}{20}} \tag{4}$$

$$normV = \sqrt{horV^2 + verV^2} \tag{5}$$

$$20 \times \log(normV) + 13 \tag{6}$$

4.1.2 Averaging of the angles

To get the most accurate radiation calculation, the angles have to be controlled and possibly calculated before the calculation of the norm begins. In this section, the second solution will be described. Therefore a new/different way of thinking has emerged, a way to work with the angles. Firstly, that after the angles is compared it won't be as many as it was before, some of the angles and the dBm values will be sorted out. Secondly, a subtraction will be done to see if the angles are close enough. During this investigation a mismatch of absolute 1.5° is acceptable. Lastly, both matrices have been given an index that symbolize their rownumber. To begin with an if statement is done. If the difference between the matrix values is acceptable, both values will be added to a new matrix. One column is for the horizontal angle and one is for the vertical angle. There is also two columns that are given the dBm values, both from the horizontal and the vertical. Lastly, both row numbers will increase by one.

But if the first condition is not fulfilled it will go to a new if state. In this statement a comparing will be done and the matrix with the smallest value will add one to their row number. After this the outer loop will go over and over again, as long as the row indexes are smaller than 128. It's 128 because all 127 rows must be read. A pseudo code of this can be seen in algorithm 1.

Result: Finding the angles that are near each other
$i = 1\%horizontalrownumber$;
$j = 1\%verticalrownumber$;
while $i \neq \&\&j \neq 128$ **do**
  if *absolute (horizontal data (at i) - vertical data (at j))* ≤ 1.5 **then**
    The angles, the mean of the angles and the measured data values is added to a matrix.;
    Both row indexes increases;
    $i = i + 1$;
    $j = j + 1$;
  else
    if *(horizontal data (at i)* $>$ *vertical data (at j))* **then**
      $j = j + 1$;
    else
      $i = i + 1$;
    end
  end
end

Algorithm 1: A systematic way of finding angle values that are close, absolute 1.5°, and placing the values in a matrix.

The matrix holds angle values (vertical, horizontal and mean). The mean value it calculated because the norm data has to have angles, otherwise it won't be correctly plotted. The mean is taken because it's easy and it gives an approximate value. In figure 9 three plots can be seen. Every polar plot has the same norm data that comes from a 0dBm measurement. The blue line is plotted with the angles from the horizontal dataset, and the red is from the vertical dataset. The yellow line is plotted with the mean angles. By looking at the figure, a conclusion can be made that there are no big differences between the three polar plots. The mean value are an acceptable approach.

4.1.3 Simulated data

The data is given in dB but to be able to compare it to the measured data it has to be converted into dBm which means, how much effect one has related to a mW measured in a dB scale. If the signal is 1 mW, it corresponds to 0 dBm, 10mW equals 10dBm, 100mW corresponds to 20dBm and 1000mW or 1W corresponds to 30dBm. This comes from the definition of dB scale that is: $10 \times log_{10}(P)$, where P is power (W).

If the signal is 1W, we should compare it with the "reference" signal 1mW. It is 1000mW and if 1000 is inputted in the formula for the dB scale $(10 \times log_{10}(1000))$, the result is 30. This is the factor that can be used to convert between dB related to W and dB related to dBm.

4.1.4 How to use it

Sum of squares is calculated based from data gathered from an antenna in 2 dimensions. The data (a norm radiation pattern) will be analyzed and compared to

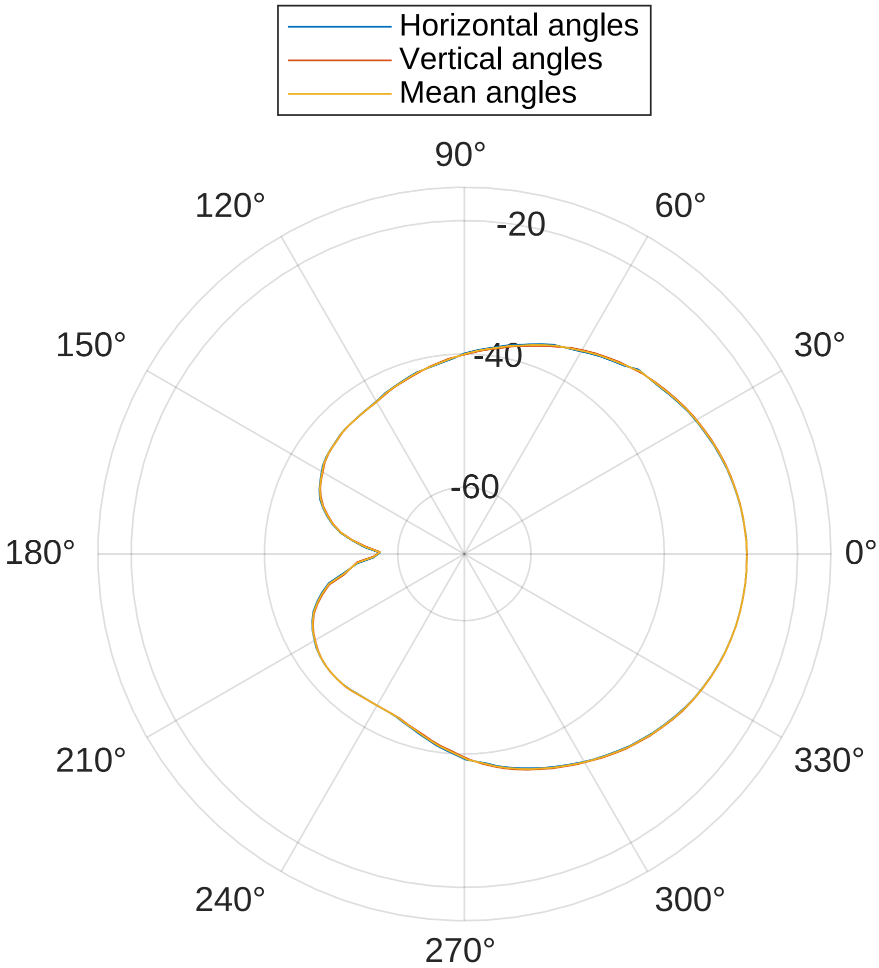


Figure 9: In this graph, vector norm data (0dBm) is plotted with three different angles as input.

simulated data from COMSOL. Sum of squares will be calculated by taking the sum of the simulated data subtracted with the vector norm measured data. But before taking the sum, the difference will be squared. By squaring the difference it won't matter if the simulated data is first or last in the subtraction. To be able to get the most accurate sum of squares, the angles are important. The angles from the vector norm measured data will be compared with the angles from the simulation. This is done by an if statement i MatLab, since the angles is not exactly the same. The statement compares the angles and find the best match with an interval of absolute 0.5°. After this is done, the calculation of sum of squares is done.

Correlation is calculated in MatLab by a function that is called *corrcoef*. *Corrcoef* takes two vectors as an input and calculate the correlation estimation.

The residual are the simulated data subtracted with the measured vector norm. It's the difference between two data points. To get the most accurate result the subtraction has to be made in consideration of the close angles. The residual will be plotted in a linear graph, trends and differences can be easy spotted. It's desirable that the residual lies around zero, that indicated that there are the values are close and it's an good match.

4.2 Dimensions of the simulated patch antenna

Below is a a patch antenna in which measurements for the simulation are obtained. (see figure 10)

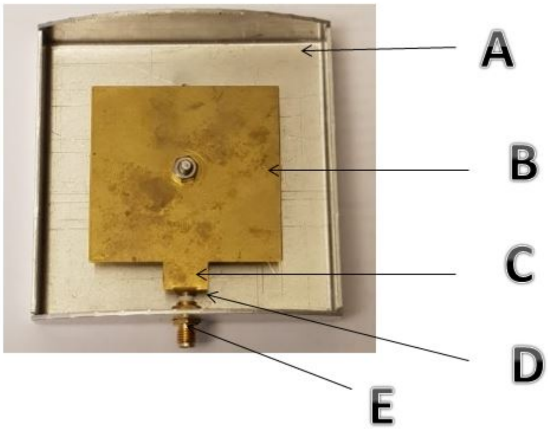


Figure 10: Patch antenna

A patch antenna with the following measurements see table 1 , table 2, was used to create a simulation in COMSOL as seen in figure 11 and figure 12 where a polar plot of the far field radiation pattern was calculated.

Table 1: Block measurements

	BLOCK A	BLOCK B	BLOCK C	BLOCK D
Width	88 mm	56 mm	13 mm	0.55 mm
Length	88 mm	53 mm	7 mm	7 mm
Height	14 mm	1 mm	1 mm	4 mm

Table 2: Cylinder measurements

CYLINDER E	OUTER CYLINDER	INNER CYLINDER	MIDDLE CYLINDER
Radius	2.8 mm	0.5 mm	2 mm
Height	8 mm	15 mm	8 mm

Measurements ranging from 0-20 dBm and some with with 10 degrees tilt and 20 degrees tilt was added to the simulation in order to compare the data with the actual measurements from an anechoic chamber.

4.3 Simulated patch antenna

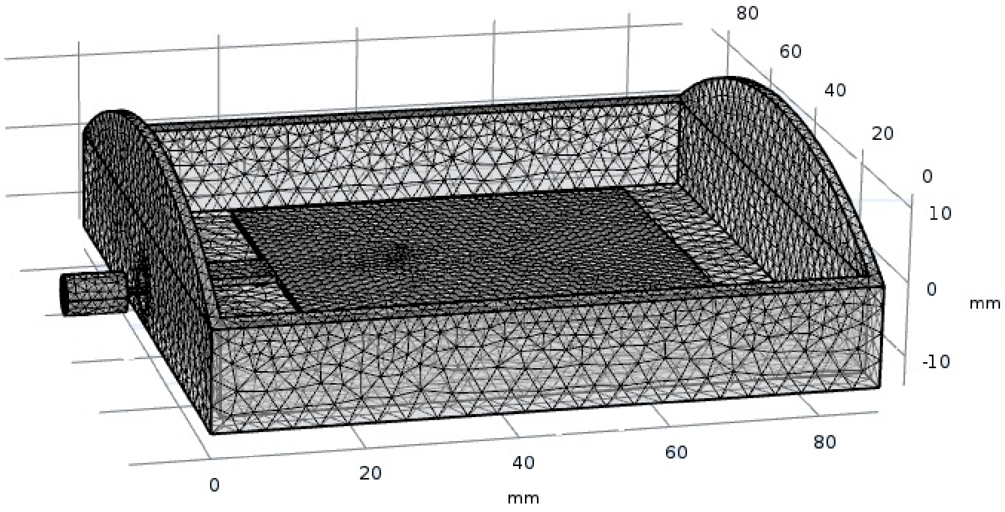


Figure 11: simulated horizontal Patch antenna with mesh from comsol

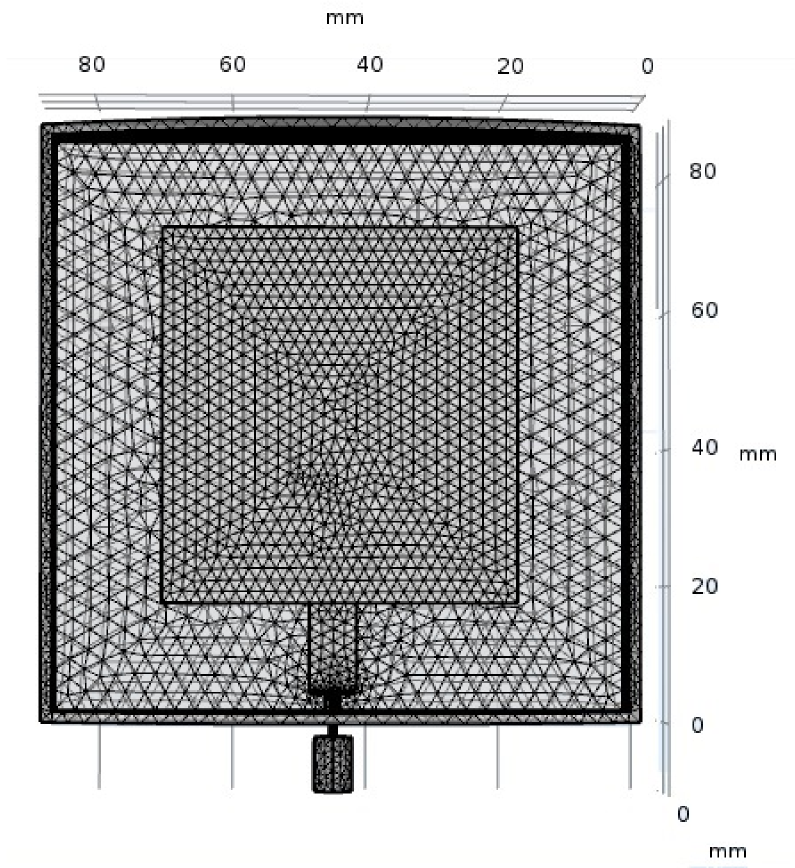


Figure 12: simulated vertical Patch antenna with mesh from comsol

The input signal is led through a coaxial port(cylindrical part of the patch antenna). The electromagnetic radiation propagates downwards through the center of the patch antenna.

In COMSOL simulation software, the default solver is determined based on the number of degrees of freedom and physics interface settings. If the model is large, the linear iterative GRMES solver with multigrid conditions is used. Since our simulated patch antenna is not that huge, the PARDISO is in effect. PARDISO is used when solving for small number degrees of freedom. One of the numerical method used by this program is the discontinuous Galerkin method which solves wave equations in the first order derivatives in time and space.

Mesh nodes enables the discretization of the geometry into small units of different shapes, referred to as mesh elements. The mesh is a result of building of meshing sequence. A meshing sequence corresponding to a geometry, consists of meshing operations and attributes. The attribute nodes store properties that are used by the operation nodes when creating the mesh

The mesh generator discretisizes the domains into tetrahedral, hexahedral prism, pyramid or mesh elements whose faces,edges and vertices are called mesh faces, mesh edges and mesh vertices respectively. This is the reason as to why the mesh sizes are different in the geometry. The boundaries in the geometry are discretized into triangular or quadrilateral boundary elements. The geometry edges are discretized into edge elements. Geometry vertices are represented by vertex elements.

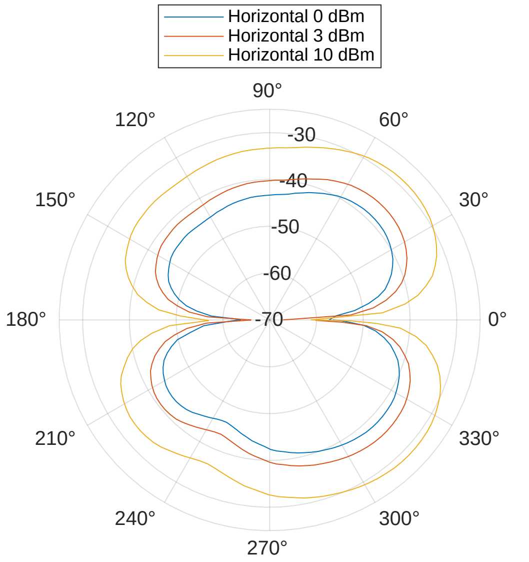
We match antenna measurements to antenna simulations so that they both have the same resulting effect straightforwards. We match antenna measurements to antenna simulations so that they both have the same resulting effect straightforwards.

4.4 Polar plots and residual

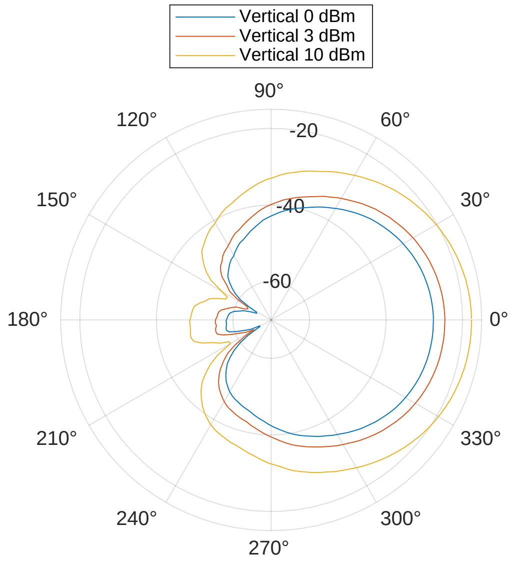
The measured data with varying input effect are shown in figure 13. In figure a), are the measured horizontal radiation pattern with input powers 0dBm, 3dBm and 10dBm. In figure b), are the measured vertical radiation pattern in with the same input power. In figure c) are the simulated vector norm. In all figures a similarity can be seen in the shape, however the size differ. The same process have been done to which can be seen in figure 14. In there figures are the polar plot from 10dBm, 10dBm with 10 tilt and 10dBm with 20 tilt. These figures differ more in shape, than in size. That is because the radiation from an antenna differs depending on the angle of measurement, which can be seen in figure 1.

Since the measured 0dBm had the best match with the simulated 22dBm, the differences between the simulated 22dBm and 0dBm are interesting. This can be seen in figure 15a and figure 15b. In these figures, also the simulated 3dBm, 10dBm, 25dBm and 32dBm are plotted to be able to compare and see the differences. The shapes are similar however, the size is different. The measured 10dBm with 10 tilt had the best match with 30dBm with 10 tilt. Therefore, the simulated data with tilt been plotted in figure 16. A larger difference between these two figures can be spotted. Figure 16a has the same dBm and tilt as the measured. There polar plots are similar, except at 180° where the differences can be easy seen. The polar plots that matched the measured is plotted in figure 16b, between these polar plot a bigger differ can be seen. By looking at this figure and figure 14c a larger match can be seen. For instance both blue polar plots are furthest to the right at 0°, and the yellow are furthest to the left at 0°. The match at 0° were prioritized, and both yellow polar plots have values that are slightly smaller than -20.

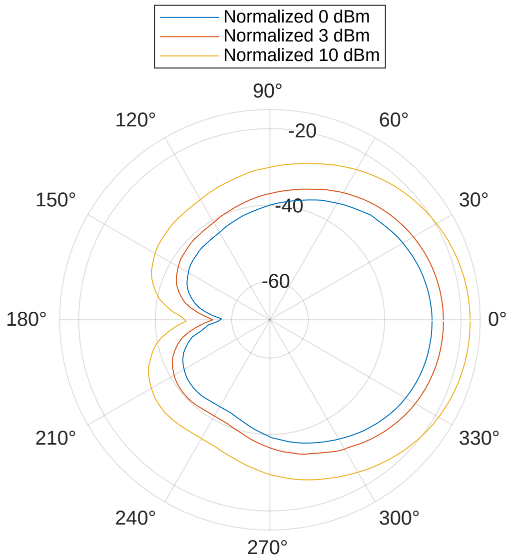
To get an overview of how every plot differs, all the residuals have been plotted together in figure 17. The similarity between the residual of figure 18a, figure 31a, and figure 32a can now be easily seen. The similarities in shape only shifted a little to the right. Between the data point $0 - 15$ and $110 - 126$ all the residuals is very close to each other. To be able to match the simulated data to the measured data, the effect in the simulated data had to be changed in the port in which the signal entered the patch antenna. It was prioritized that the values at $0°$ were as close as possible. This is because a same resulting effect between antenna measurements and antenna simulations was desired. This lead to that the match, at about $180°$, the difference between the two begins to show. The largest mismatch can be seen as a spike around $55 - 70$.



(a) Horizontal radiation pattern from 0dBm, 3dBm and 10dBm

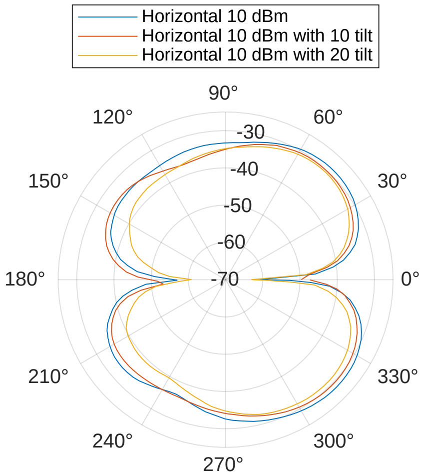


(b) Vertical radiation pattern from 0dBm, 3dBm and 10dBm

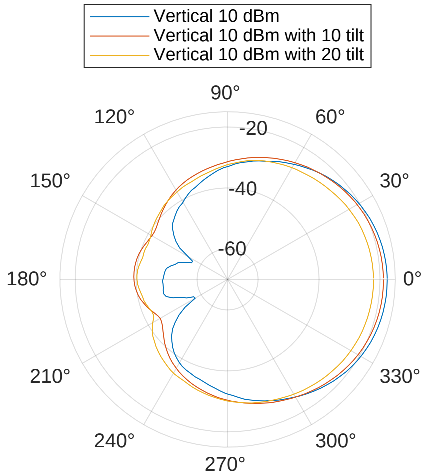


(c) Vector norm of the radiation pattern in 0dBm, 3dBm and 10dBm

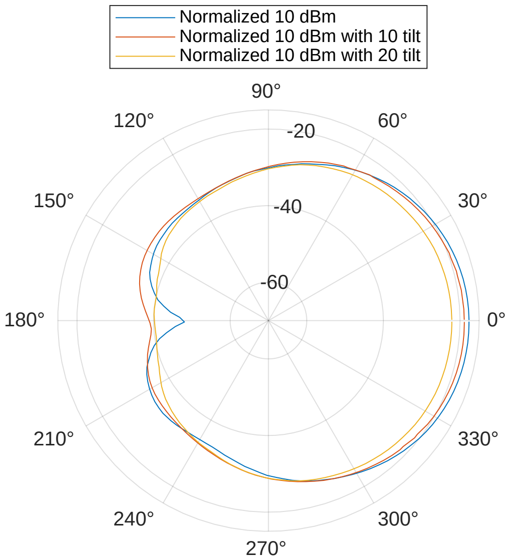
Figure 13: Graphs of measured data at 0dBm, 3dBm and 10dBm that has been plotted. a) is the horizontal radiation patterns and b) is the vertical radiation patterns. c) is the norm data with angles that are the mean of vertical and horizontal.



(a) Horizontal radiation pattern 10dBm, 10dBm with 10tilt and 10dBm with 20tilt

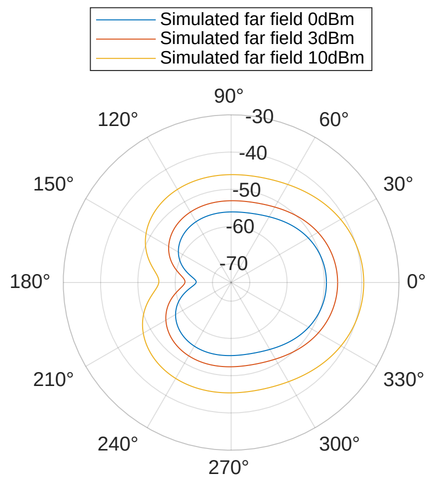


(b) Vertical radiation pattern 10dBm, 10dBm with 10tilt and 10dBm with 20tilt

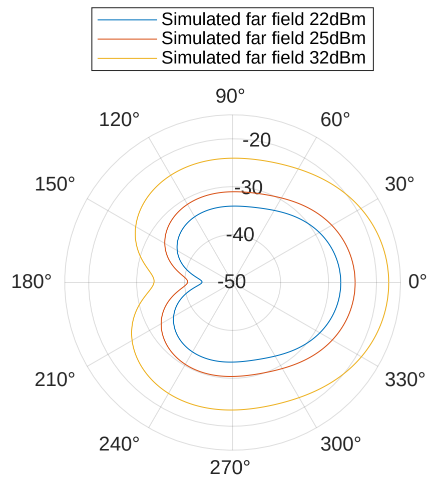


(c) Vector norm of the radiation pattern in 10dBm, 10dBm with 10tilt and 10dBm with 20tilt

Figure 14: Graphs of measured data at 10dBm, 10dBm with 10 tilt and 10dBm with 20 tilt that has been plotted. a) is the horizontal radiation patterns and b) is the vertical radiation patterns. c) is the norm data with angles that are the mean of vertical and horizontal.

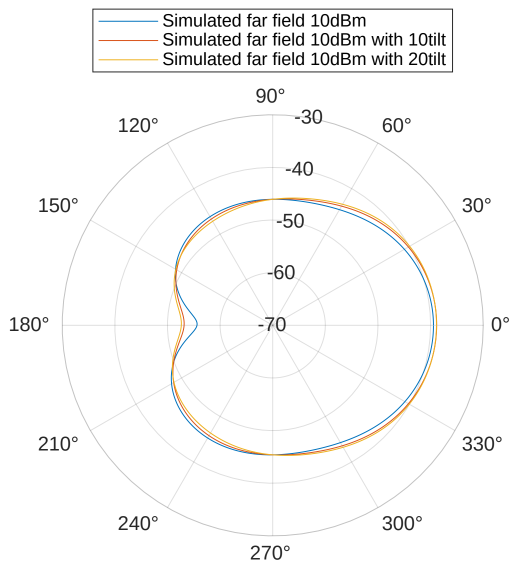


(a) Graphs of simulated data at dBm values 0,3 and 10.

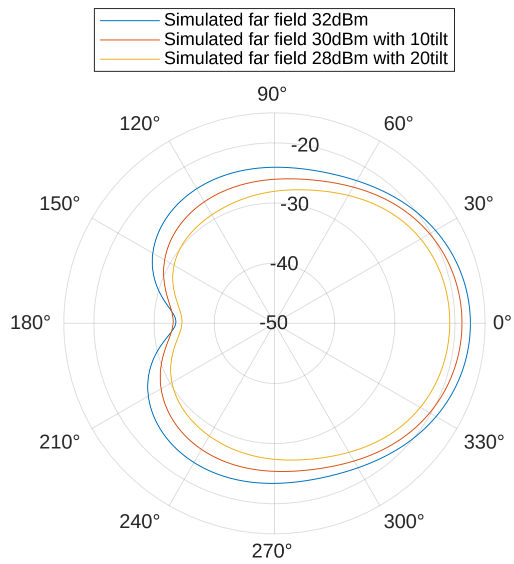


(b) Graphs of simulated data at dBm values 22,25 and 32.

Figure 15: Simulated data, to compare with each other and see the differences and similarities. This is done because the measured 0dBm, 3dBm and 10dBm has the best match at 0° with the simulated 22dBm, 25dBm and 32dBm. a) Graphs of simulated data at dBm values 0,3 and 10. b) Graphs of simulated data at dBm values 22,25 and 32.



(a) Graphs of simulated data at dBm values 10,10 with 10tilt and 10 with 20tilt.



(b) Graphs of simulated data at dBm values 32,30 with 10tilt and 28 with 20tilt.

Figure 16: Simulated data, to compare with each other and see the differences and similarities. This is done because the measured 10dBm, 10dBm with 10 tilt and 10dBm with 20tilt has the best match at 0° with the simulated 32dBm, 30dBm with 10 and 28dBm with 20 tilt. a) Graphs of simulated data at dBm values 10,10 with 10tilt and 10 with 20tilt. b) Graphs of simulated data at dBm values 32,30 with 10tilt and 28 with 20tilt.

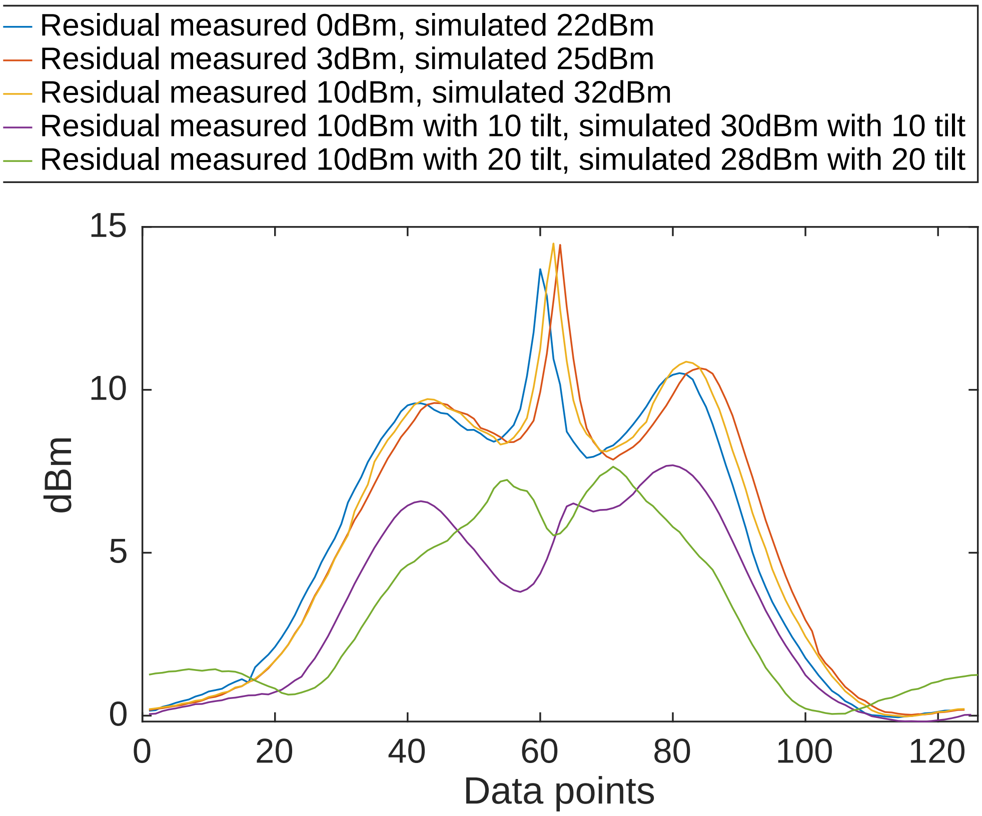
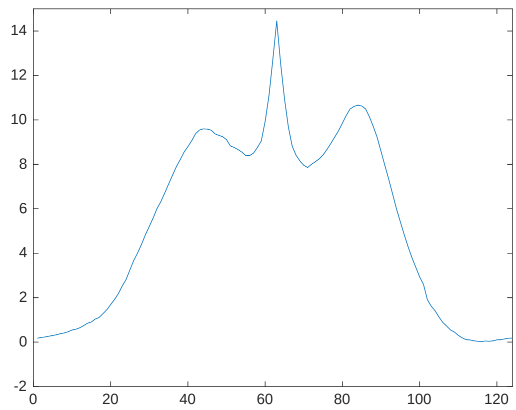


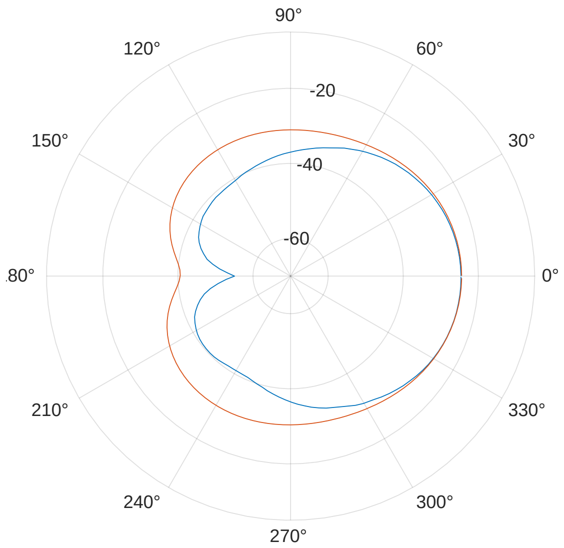
Figure 17: In this figure all residuals have been plotted together. This is done to be able to spot similarities and differences. The residuals have between 122-126 data point. Every data point is an difference between simulated data and measured data at an specific angle.

4.5 Differences in simulated data and measured data

Measured vector norm is compared with simulated data, both vector norm and a residual can be seen in figure 18. In figure 18a the residual is drawn, which is the differences between the simulated norm data and the measured norm data. A spike can be seen around data points 55-70 which can be seen as the same difference in figure 18b at 180°. A compilation of all correlation estimation and sum of squares values can be seen in table 3 and table 4.



(a) Residual of a 3dBm measured data and 25dBm simulated data



(b) The blue polar plot indicates a 3dBm vector norm measured polar plot and the red polar plot indicates a 25dBm vector norm simulated polar plot.

Figure 18: Showing two different ways to see differences in simulated data and measured data. a) Shows the residual between the simulated and measured. It can be seen in both a) and b) that between data point 0-20 $0° - 20°$ and between data point 110-126 $300° - 360°$ The graphs are nearly the same value. b) shows measured 3dBm in the same graph as simulated 25dBm.

Table 3: correlation

Differences between measured and simulated data	Value in dBm
Measured 3 dBm data vs 25dBm simulated data(Figure 18a)	0.9523
Measured 0 dBm data and 22 dBm simulated data (Figure 31a)	0.9522
Measured 10 dBm data vs 32 dBm (Figure 32a)	0.9512
Measured 10 dBm10tilt data vs 30dBm10 tilt simulated data (Figure 33a)	0.9618
Measured 10dBm20tilt data vs 28dBm20tilt simulated data (Figure 34a)	0.9725

To be able to compare the residuals of the data (see table 4), all data has been refereed to actual plots

Table 4: Sum of squares

Differences between measured and simulated data	Value
Measured 0 dBm data and 22 dBm simulated data (Figure 31b)	5403.1
Measured 3 dBm data vs 25dBm simulated data(Figure 18b)	5580.6
Measured 10 dBm data vs 32 dBm (Figure 32b)	5616.2
Measured 10 dBm10tilt data vs 30dBm10 tilt simulated data (Figure 33b)	2264.9
Measured 10dBm20tilt data vs 28dBm20tilt simulated data (Figure 34b)	2034

4.6 Trying to fit a 3D simulation to 2D measurement

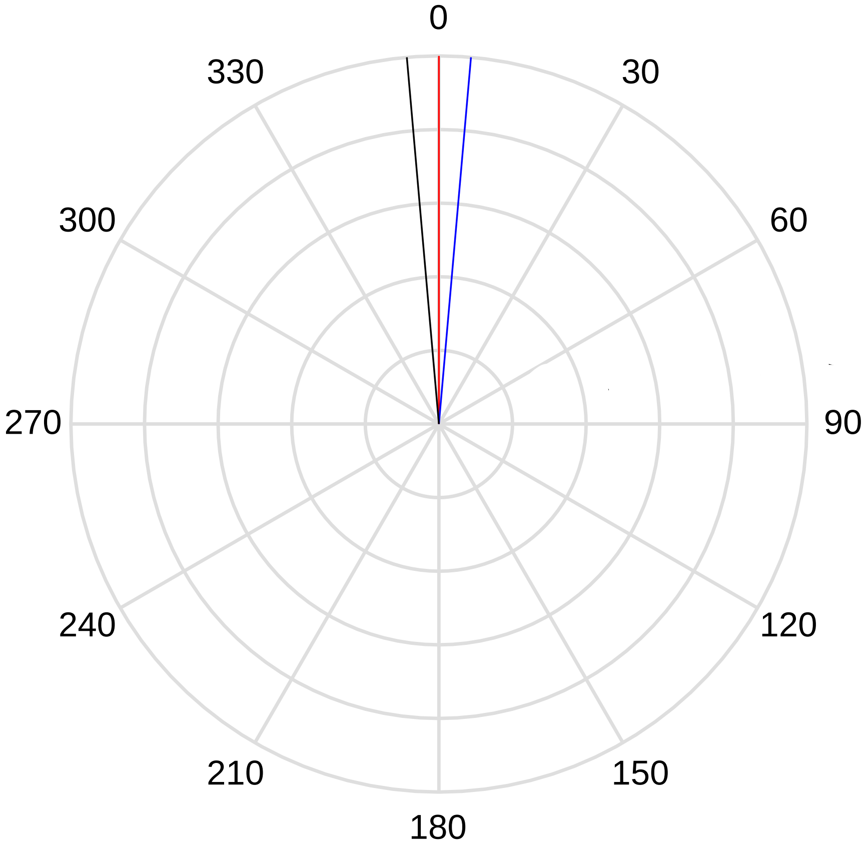


Figure 19: A polar plot to show the tilting of the antenna, both in simulation and in measurement.

In figure 19 the blue line shows an antenna that have been tilted with a negative direction while the black shows the tilting in a positive direction. The red shows the antenna without any tilting, at zero degrees.

This projects second goal was to try to turn a 3D simulation to fit a 2D measurement. This was done by comparing measured data with simulated data that have been tilted. In figure 20 simulated data at 22 dBm are tilted 5° in a positive direction and in negative direction. The simulated 22 dBm is matched with measured vector norm at 0dBm. The blue polar plot is the measured vector norm at 0 dBm, the red polar plot is simulated 22 dBm without tilt. The yellow polar plot is with negative 5° tilt and the purple is with positive 5° tilt. Both in figure 20 and figure 21 a similarity can be seen. At 180° the purple polar plot, positive tilt, is closer to the measured vector norm, the blue polar plot than the yellow polar plot, negative tilt. To be able to see the differences and similarities statistic methods are used, which can be seen in table 5. The values with tilt will be compared to the value without tilt. In both cases, the negative tilt resulted in higher values both in sum of squares and correlation estimation. The positive tilt resulted in lower values when correlation is calculated. Sum of squares results in one higher and one lower value. A lower value is desirable in sum of squares and correlation estimation, by continue tilting the simulation a match may be found.

Graph 22 shows calculation of sum of squares when the simulated data has been tilted in different angles. It has been tilted ±5°, ±3.75°, ±2.5° and ±1.25°. Sum of squares has been calculated and plotted together. The graph shows that the lowest value of sum of squares is given when the simulated is tilted 2.5° in a positive direction. When the measurements were made, the antenna was estimated to be at 0°, ie the antenna was looked at from an eye's view point. Had the antenna been precisely positioned at 0°, the graph had been shifted to the left so that the lowest sum of squares value had reached 0° and simulated 0° given the best match.

Table 5: Differences in statistical values

Measured	Simulated	Sum of squares	Correlation estimation
0 dBm	22 dBm	5403.1	0.9522
0 dBm	22 dBm tilted 5° positive	5411.6	0.9224
0 dBm	22 dBm tilted 5° negative	5510.5	0.9697
3 dBm	25 dBm	5580.6	0.9523
3 dBm	25 dBm tilted 5° positive	5576.5	0.9232
3 dBm	25 dBm tilted 5° negative	5705.4	0.9695

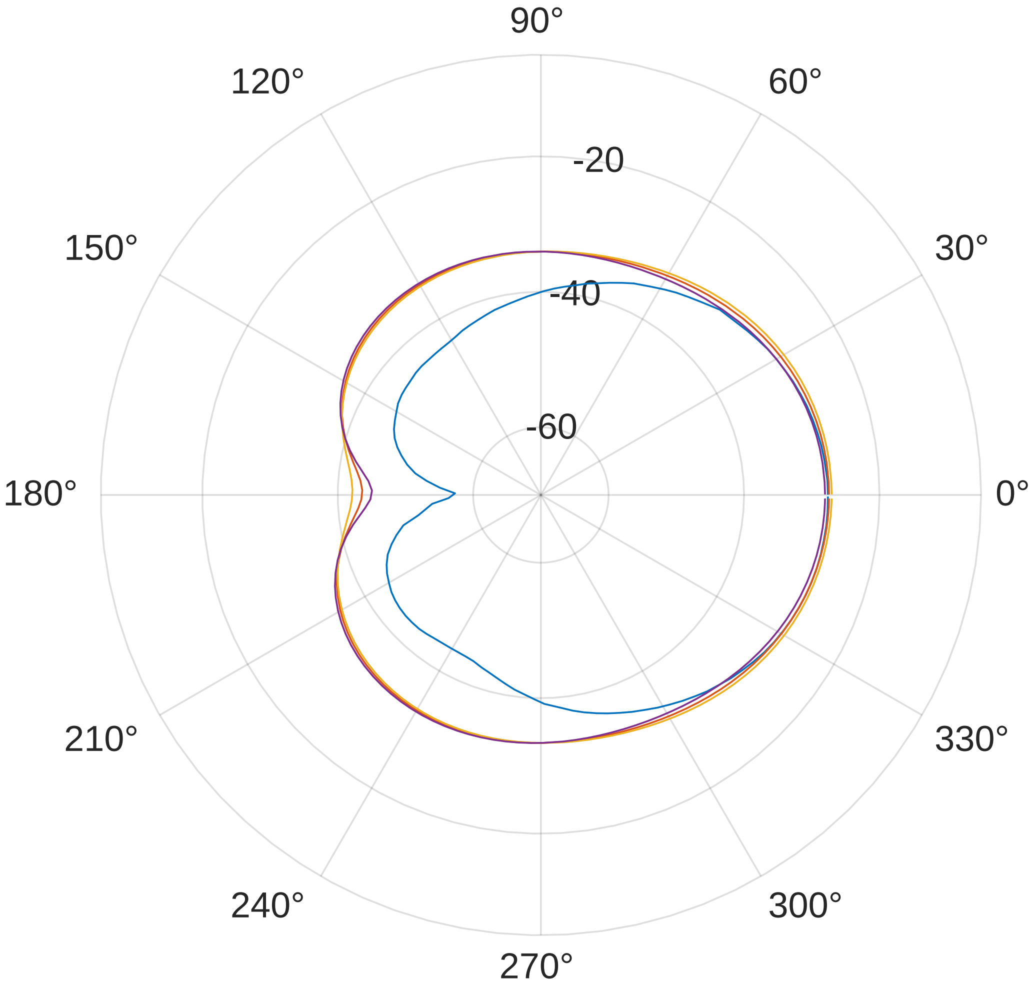


Figure 20: A 3D simulated 22 dBm polar plot compared to a 0 dBm measured data polar plot. The blue polar plot is the measured at 0dBm at 0 degrees. The red polar plot is the simulated at 22dBm at 0°. The yellow is the simulated at 22dBm with a negative tilt of 5°. The purple is the simulated at 22dBm with a positive tilt of 5°.

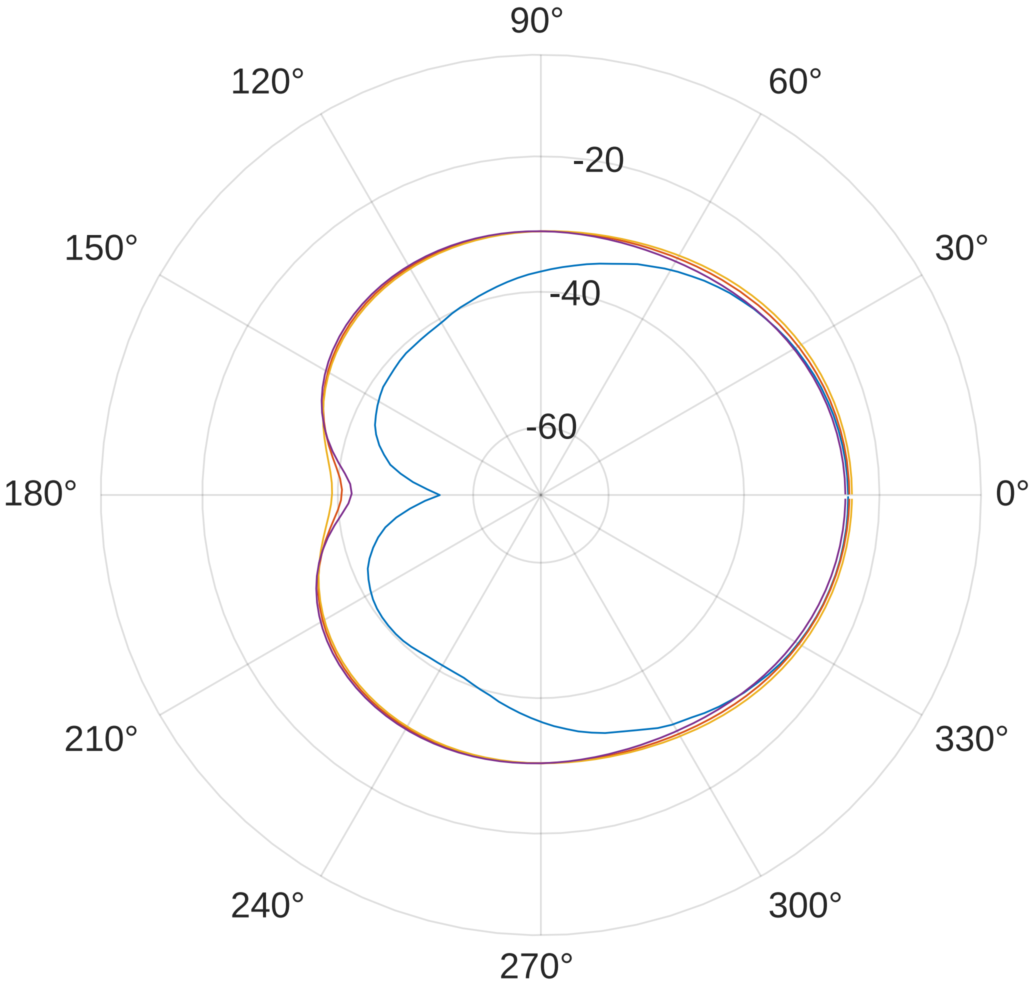


Figure 21: A 3D simulated 25 dBm polar plot compared to a 3 dBm measured data polar plot. The blue polar plot is the measured at 3dBm at 0 degrees. The red polar plot is the simulated at 25dBm at 0°. The yellow is the simulated at 25dBm with a negative tilt of 5°. The purple is the simulated at 25dBm with a positive tilt of 5°

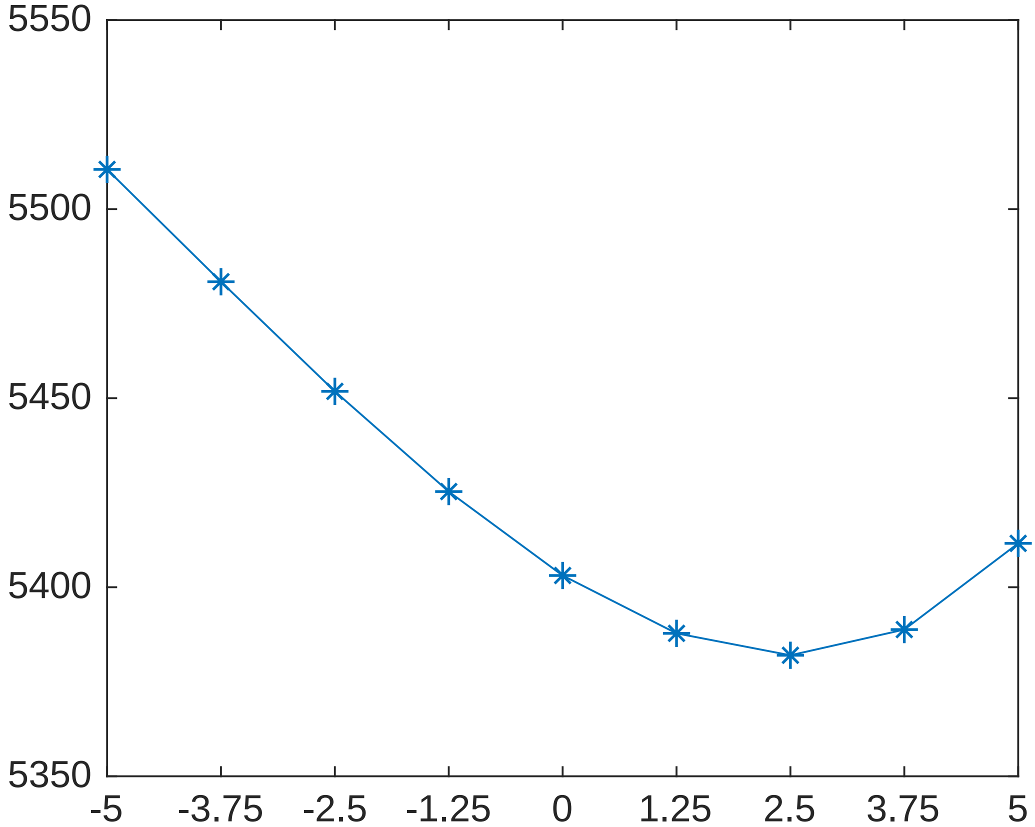


Figure 22: Sum of squares results when it was calculated with different tilted angles.

5 Discussion

When vector norm data where calculated from horizontal data and vertical data, it was noted that the matrices had different sizes and therefore interpolation of some values was required in order to get equal matrices. This gave results that were as close to the realistic values as possible.

The horizontal data had different angles, and different dBm values, when it was compared to the vertical data. The calculation and plotting of a vector norm, by using the data from both the horizontal and vertical data, can be done in three ways. The first is to use the row numbers. This is not such a scientific way since it only helps in short term. The use of this method is disadvantageous because the calculation of sum of squares, correlation and residual will provide incorrect values. Also the calculated vector norm needs angles to be able to compare it with the simulated data.

The second technique is to use angles that are close to one another and ignore those that do not fit in. A mismatch range is required for this to work. This is a bit scientific but some of the angles and dBm values are sorted out. Since the measurements are done in the 2.45 GHz range, the angles are least important as to when the 60 GHz range would be used. The advantage of this method is that sum of squares, correlation and residual can be calculated and provide more accurate results.

The third method is interpolation/rebin. This is roughly estimating angles and dBm values between two real ones in order to do comparisons between simulations and measurements, as well as plotting vector norm data. The downsize with this is that it's not accurate because a lot of data points are imaginary and therefore misleading. It is very hard to give a rough estimate range of acceptable values, if a lot of imaginary points have to be added. It is a very complex method and the least reliable if a quantitative method is to be drawn.

In this research, the second method is most desirable and therefore used because a lot of data points and angles exist. It enables the calculation of important statistical features that are required in order to try to quantitatively compare antenna measurements and simulations. Even though interpolation was done to some values to be able to match the sizes of the horizontal matrices to the vertical matrices, it was deemed most effective.

When comparing the simulated polar plots to the measured vector norm polar plots, it was noted that the dBm values differed by a large value. A 0 dBm simulated polar plot did not match a 0 dBm measured polar plot. Even though an anechoic chamber was used in measuring the data, signal path losses due to cables that are used in measuring had not been taken into account. This resulted in the difference in value.

When comparing 3D simulated data to 2D measured data, it was noted that the sign of the angle was also a determining factor when it came to the accuracy. See figure 20 and figure 21. Although it was not by much, by tilting the antenna downwards (negative angle), the 3D polar plot was further away. Tilting the antenna upwards (positive angle), caused the 3D polar plot to be closer to the measured 2D data. The positive values led to lower sum of squares and correlation as shown in table 5.

There was one polar plot figure 35 done without interpolated values, there every value is represented by a dot, which proved to be the most correct norm polar plot data. If it was drawn with a line, a gap would exist at 360°. The reason for not only using dots is because the differences between the simulated and measured values have to be easily seen. The slight change in line shape is hard to observe while using dots. By comparing this polar plot with the polar plot that have interpolated data and same dBm, no differences can be seen.

The theoretical directivity of a patch antenna is between 3.2-6.6. In dB, it's between 5-8 dB. The simulated patch antenna has a directivity of 6.6 dB which lies within this range. This is an acceptable patch antenna in regards to that comparison and thus provides accurate data for analysis. There is no standard when it comes to quantifying antenna measurements to antenna simulations. Due to this, different people have used various methods in trying to analyze the best way in doing this quantification. An example of this is stated in the previous work subsection, 1.4. It is therefore difficult to compare results between the various methods. The results achieved here are more quantitative than previous methods used since this research goes a step further and uses various statistical methods to show the accuracy of simulations to actual antenna measurements.

The sum of square values are high, see table 4. This is because the match between simulated and measured is not optimal. See examples in figure 18b. It can be seen that at zero degrees the match between them are desirable. However at 180 degrees it's not, already at around 60° the simulated has higher values. The way that the simulated and measured data is matched, it gives a large sum of squares. This is because the distance between the values between $60° - 300°$ increases and in some points the difference is around 10dBm. When these values are squared and later summed, it gives a large result. Values close to zero are desirable. However, in this study the mismatch gave a large number. When comparing measured data with simulated data, sum of squares decreases drastically when it comes to the data that have been tilted. This result might have been mainly due to the simulation adaptation that was done when trying trying to get the same resulting effect between antenna simulations and measurements that would have been straight forward. If the resulting effect might have been taken from a different position, it might have led to different results.

The correlation estimation, that can be seen in table 3, has values that are close to one. The high result indicates that the next value, from the graphs, are depended on the current one. The optimal would be if the value were closer to zero, that indicates that the next value do not depend on the current one.

The residual is an interesting way of seeing the difference. The optimal result would be if the residual lies at zero. By looking at figure 17 several trends are noticed. Between data point 0-15 and 110-126 almost every line has the same values. Another trend is that the, residual of measured 0dBm and simulated 22dBm, the residual of measured 3dBm and simulated 25dBm. Also the residual of measured 10dBm and simulated 32dBm, has a similar shape. Another trend is that the residual decreases drastically when the differ between two tilted is calculated. The residual gives an good perception of how they differ and an understanding of what could be changed. For instance, how would the sum of squares, correlation and residual change if the match between the simulated and measured were changed? Instead of finding a match at 0°, a match was searched for at 180°. Or if the match indicates that equal amount of simulated data would lie within the measured as outside. It all comes down to how the data is matched.

The above statistical tools helps in answering the first question in this report. From the graph 22, a deduction can be made of which kind of angles that give the lowest sum of squares if one looked at a similar graph. Thus, question two can easily be answered.

5.1 Impact on today's society

During the past few years companies used build and test methods to make antennas. Using simulations to optimize the process helps to save time, eradicate misuse of resources and help in keeping the environment clean in cases where antennas in the build and test methods were not compatible. It also helps to reduce costs which companies would have incurred. The money that would be saved due to being able to use simulations can be used to better simulation software and educating personnel on using simulation programs.

In addition to the impact that simulations have on the company, it also affects society in different ways. It also helps to reduce concern about possible health consequences from exposure to the RF fields produced by wireless technologies due to many build and test procedures.

This research will help ease communication between people with hearing problems and those without. It may give people with impaired hearing more confidence as they will not struggle to cope with people who speak fast and/or with low voices. Being able to receive the sound signals at the same time in both hearing aids will enable them to concentrate and not be disturbed by delayed sound signals. It will ease frustration and save time while communicating with one another.

6 Conclusions

If the signal losses and impedance matching when doing actual measurements had been taken into account when creating antenna simulations, the data gotten from the numerical calculations done by COMSOL might have been very similar (slight variation) to the ones gotten from the measurement process. A matching of a 0 dB antenna simulation might have been done to a 0 dB antenna measured data rather than the 22dB simulated versus 0 dB measured one. Sum of squares, correlation and residual are good tools to use when carrying out a data comparison. However, in this report, both sum of squares and correlation got high values. Since the simulated data had higher values at multiple points, which can be seen in several figures, e.g in figure 31b. The residual is a good tool to see the difference. The use of correlation, Sum of squares and residuals helped in identifying a quantitative way of comparing simulated data to measured data. This is because they depend on how the data is matched.

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7 Appendices

7.1 Polar plots from simulated data

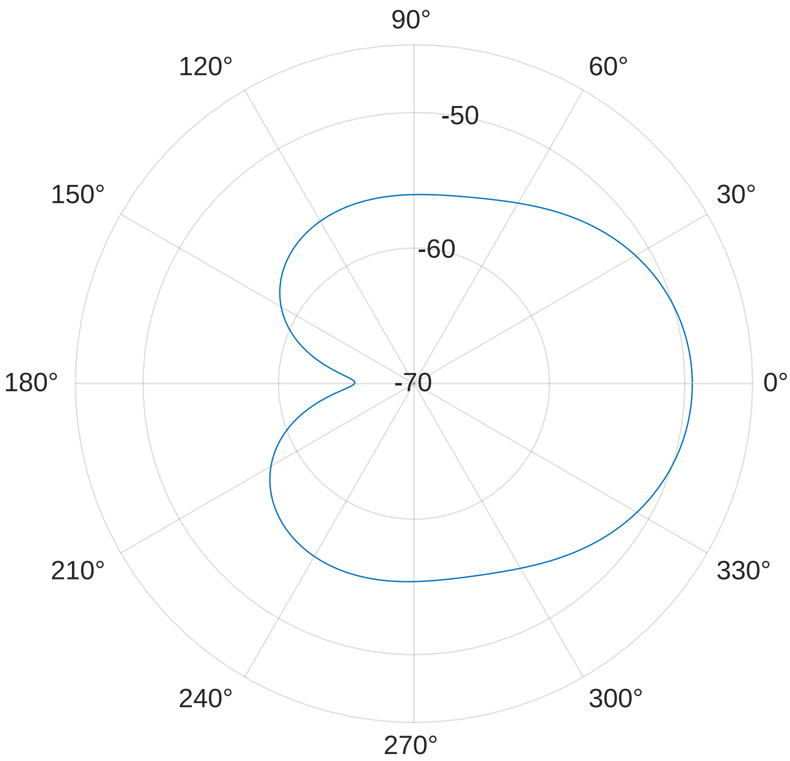


Figure 23: Simulated normalized polar plot data, 0dBm

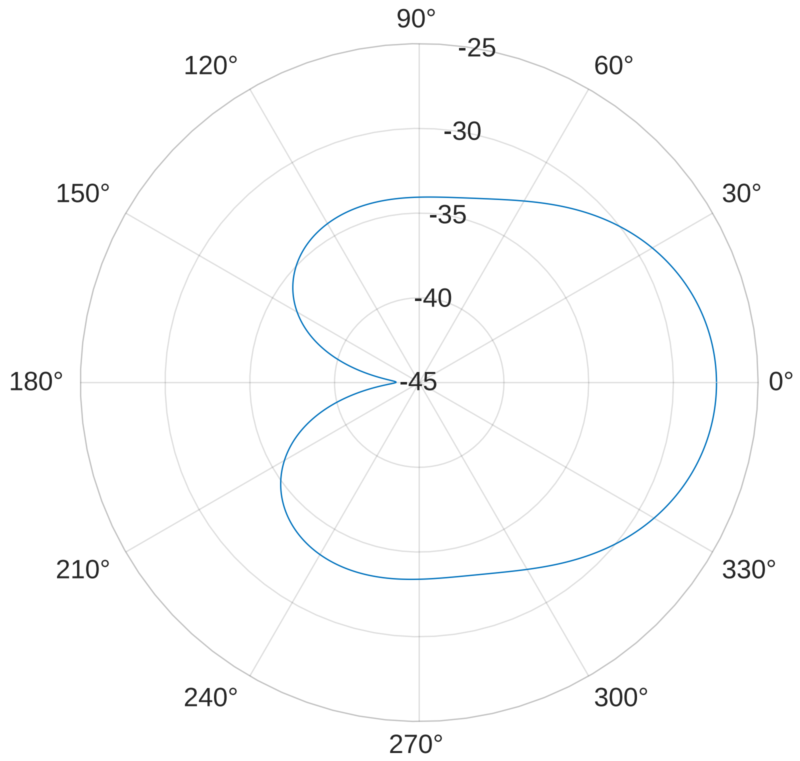


Figure 24: Simulated normalized polar plot data, 22dBm

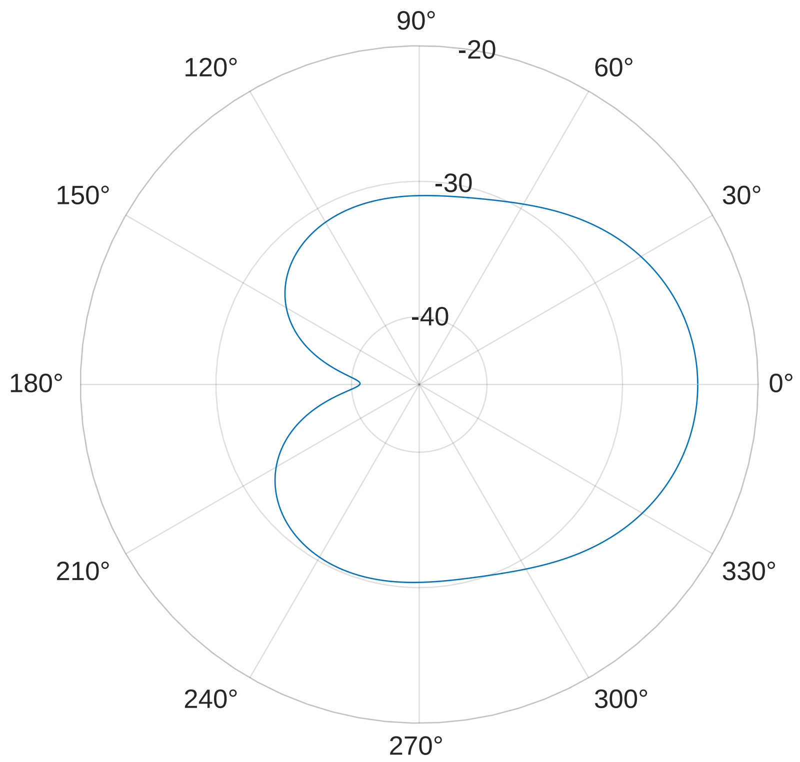
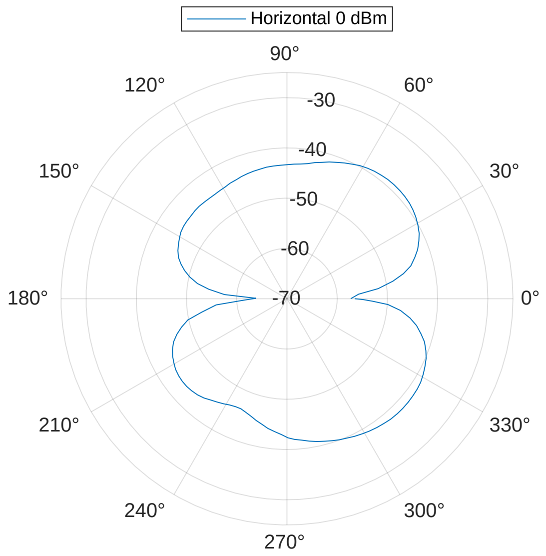
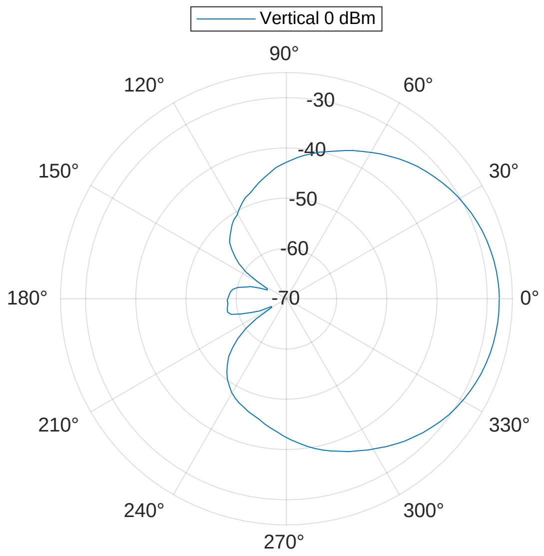


Figure 25: Simulated normalized polar plot data, 25dBm

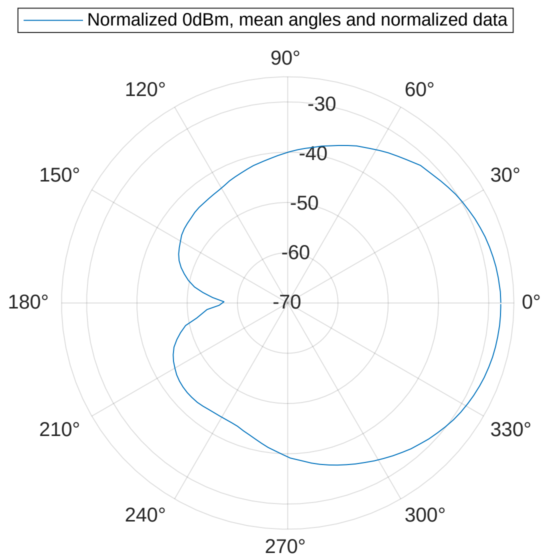
7.2 Polar plots from measured data



(a) 0dBm horizontal

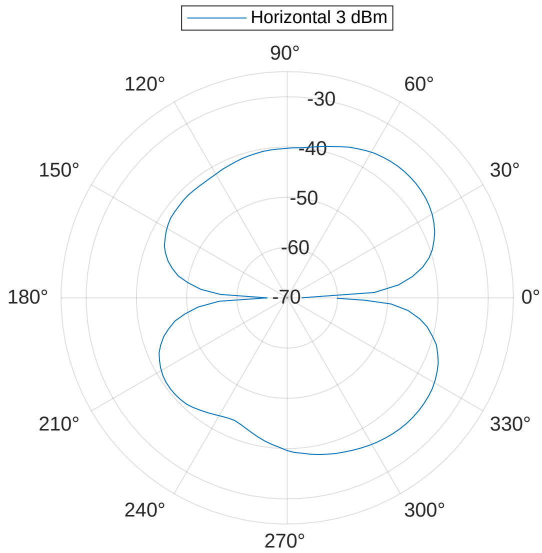


(b) 0dBm vertical

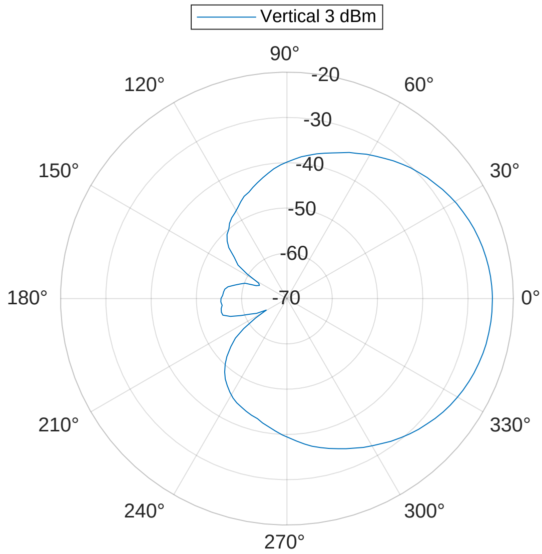


(c) 0dBm vector norm

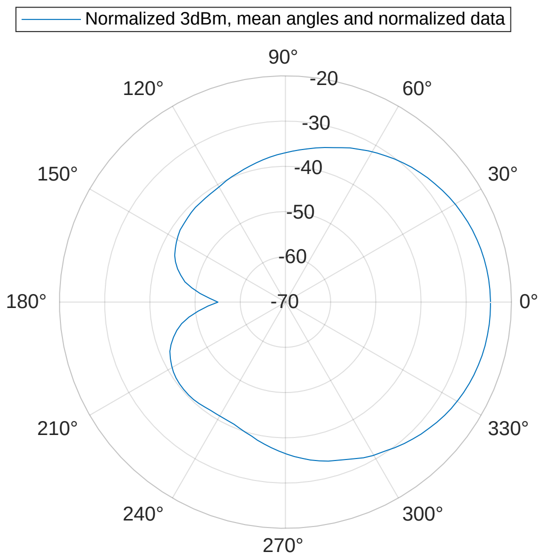
Figure 26: Graphs of measured data at 0dBm that has been plotted. a) is the horizontal radiation pattern and b) is the vertical radiation pattern. c) is the norm data with angles that are the mean of vertical and horizontal.



(a) 3dBm horizontal

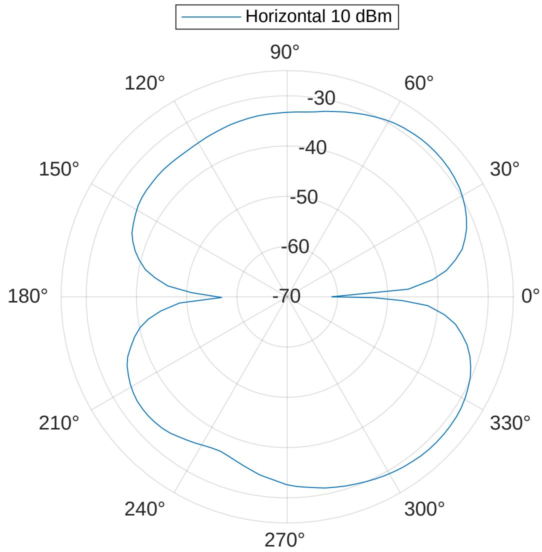


(b) 3dBm vertical

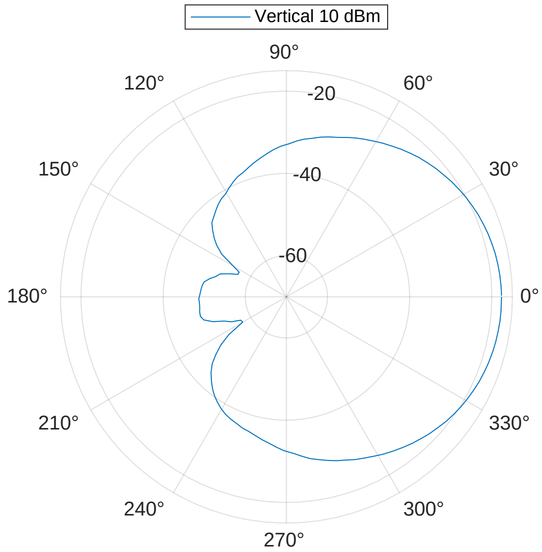


(c) 3dBm vector norm

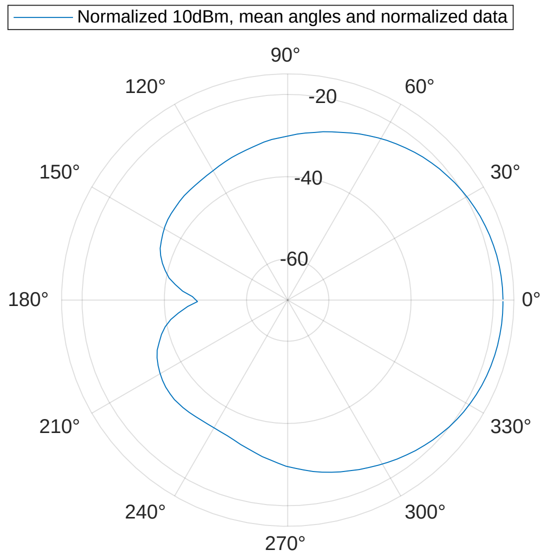
Figure 27: Graphs of measured data at 3dBm that has been plotted. a) is the horizontal radiation pattern and b) is the vertical radiation pattern. c) is the vector norm data with angles that are the mean of vertical and horizontal.



(a) 10dBm horizontal

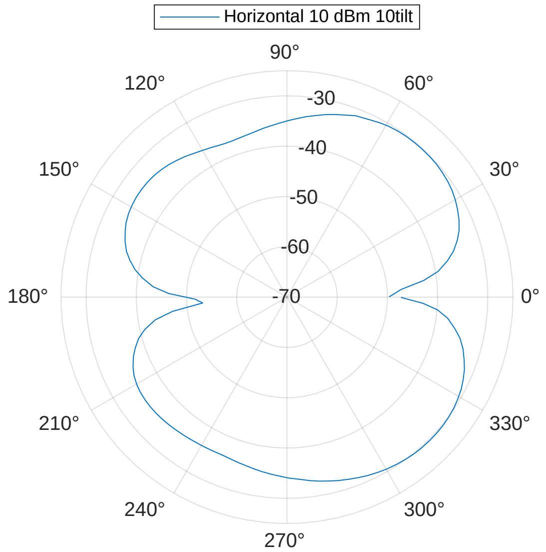


(b) 10dBm vertical

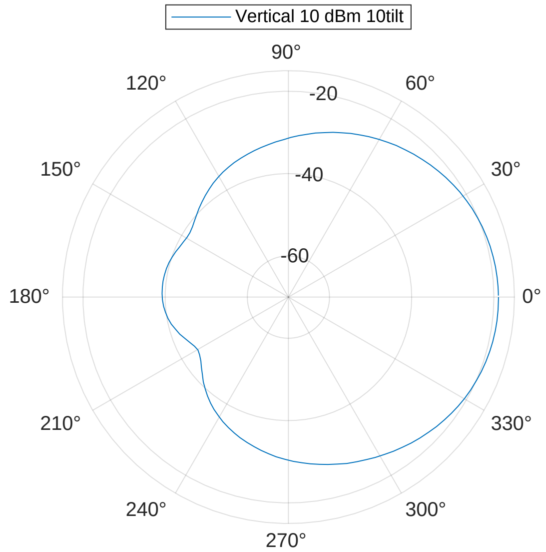


(c) 10dBm vector norm

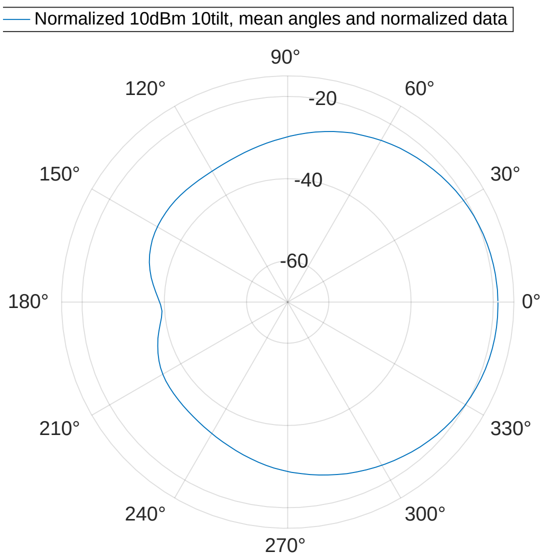
Figure 28: Graphs of measured data at 10dBm that has been plotted. a) is the horizontal radiation pattern and b) is the vertical radiation pattern. c) is the vector norm data with angles that are the mean of vertical and horizontal.



(a) 10dBm with 10 tilt horizontal

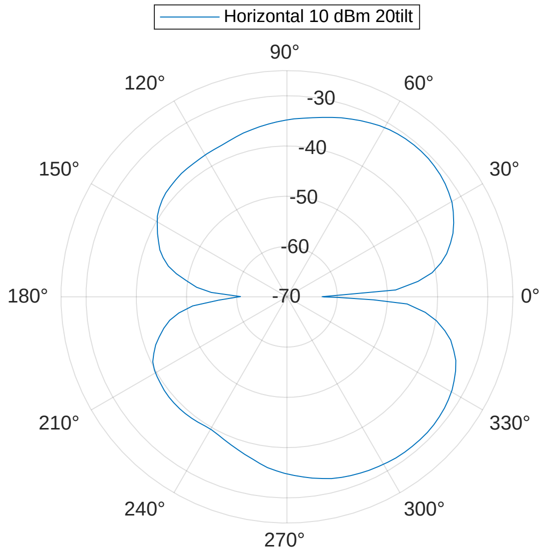


(b) 10dBm with 10 tilt vertical

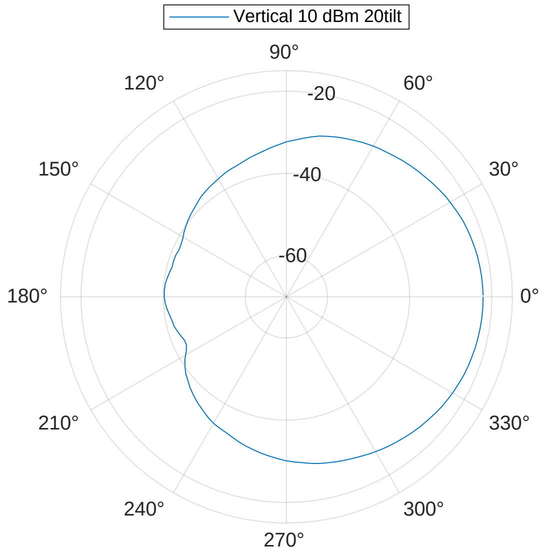


(c) 10dBm with 10 tilt vector norm

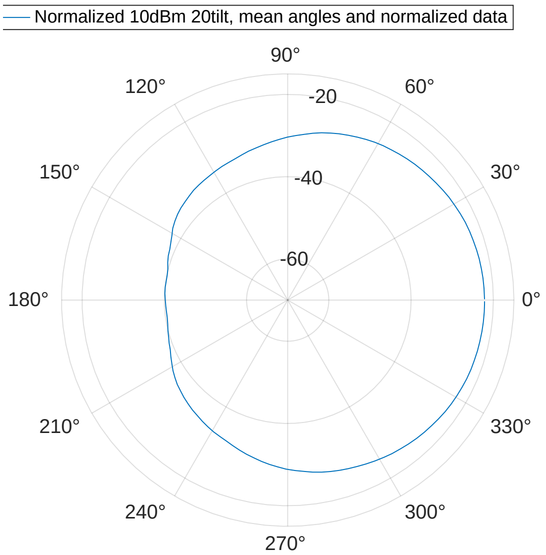
Figure 29: Graphs of measured data at 10dBm with 10tilt that has been plotted. a) is the horizontal radiation pattern and b) is the vertical radiation pattern. c) is the vector norm data with angles that are the mean of vertical and horizontal.



(a) 10dBm with 20 tilt horizontal



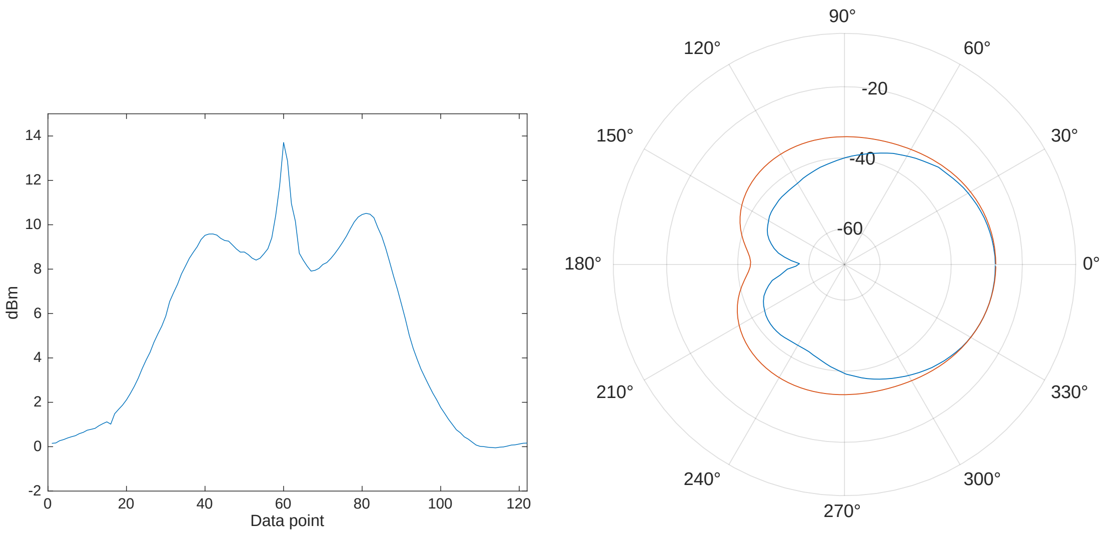
(b) 10dBm with 20 tilt vertical



(c) 10dBm with 20 tilt vector norm

Figure 30: Graphs of measured data at 10dBm with 20tilt that has been plotted. a) is the horizontal radiation pattern and b) is the vertical radiation pattern. c) is the vector norm data with angles that are the mean of vertical and horizontal.

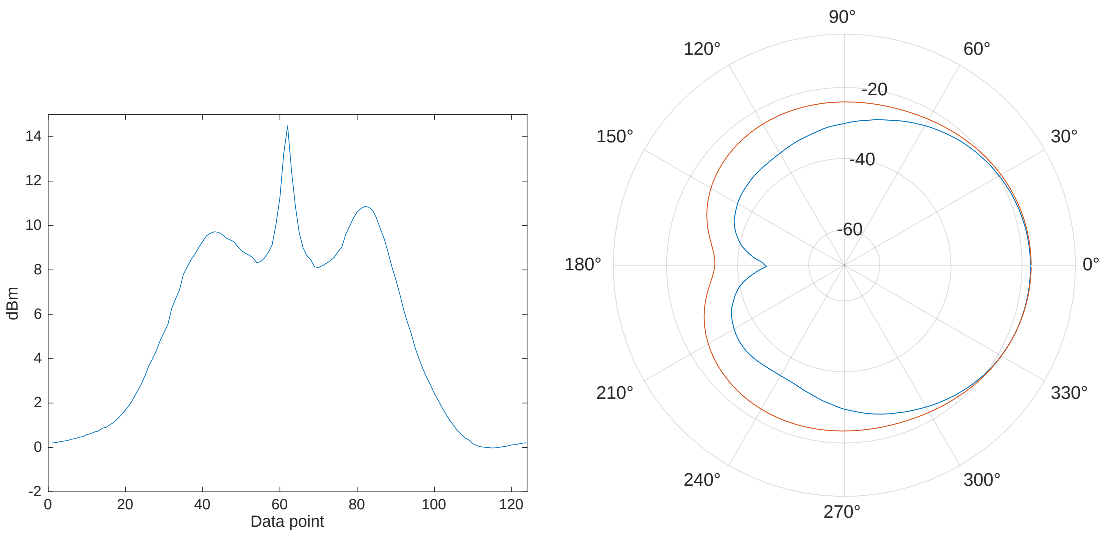
7.3 Differences in simulated data and measured data



(a) Residual of a 0dBm measured data and 22dBm simulated data

(b) The blue polar plot indicates a 0dBm measured vector norm polar plot and the red polar plot indicates a 22dBm simulated polar plot.

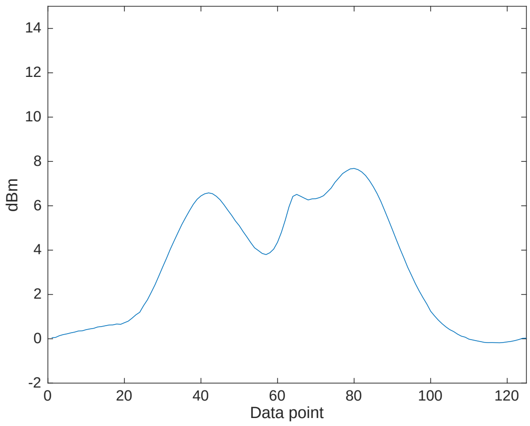
Figure 31: Differences between measured vector norm and simulated data.



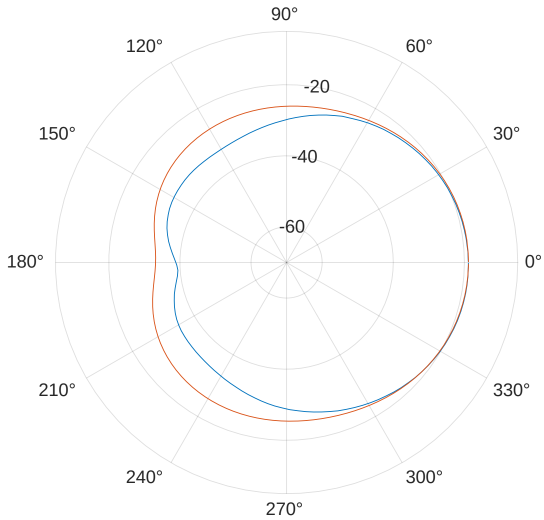
(a) Residual of a 10dBm measured data and 32dBm simulated data

(b) The blue polar plot indicates a 10dBm measured vector norm polar plot and the red polar plot indicates a 32dBm simulated polar plot.

Figure 32: Differences between measured vector norm and simulated data.

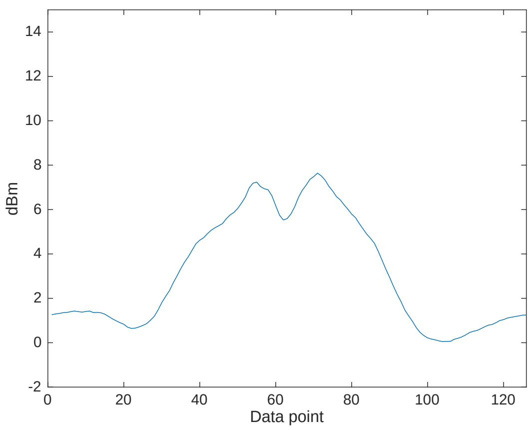


(a) Residual of a 10dBm 10tilt measured data and 30dBm 10tilt simulated data

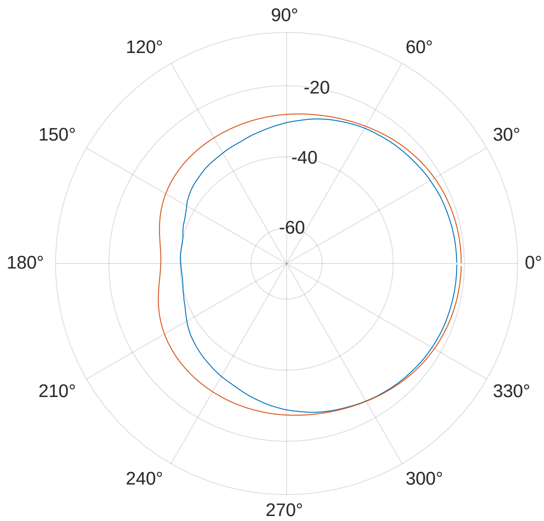


(b) The blue polar plot indicates a 10dBm 10tilt measured polar plot and the red polar plot indicates a 30dBm 10tilt simulated polar plot.

Figure 33: Differences between measured and simulated data.



(a) Residual of a 10dBm 20tilt measured data and 28dBm 20tilt simulated data



(b) The blue polar plot indicates a 10dBm 20tilt measured polar plot and the red polar plot indicates a 28dBm 20tilt simulated polar plot.

Figure 34: Differences between measured and simulated data.

7.4 Most accurate vector norm polar plot

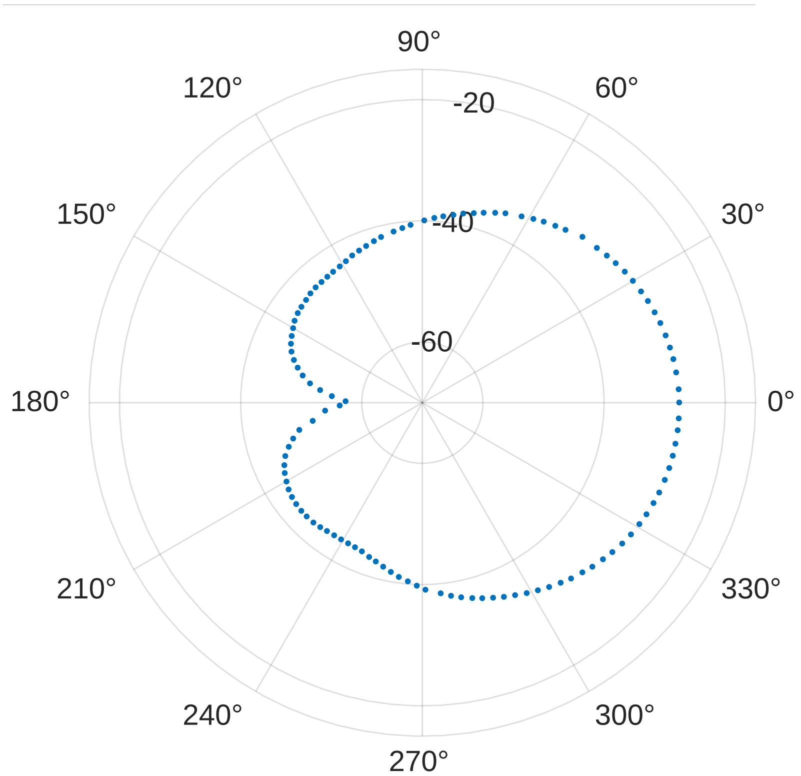


Figure 35: 0dBm vector norm without interpolation

George Kiarie, Electrical Engineer 180 credits

Elin Andersson, Computer Science and Engineering 300 credits

HALMSTAD UNIVERSITY

PO Box 823, SE-301 18 Halmstad
Phone: +35 46 16 71 00
E-mail: registrator@hh.se
www.hh.se