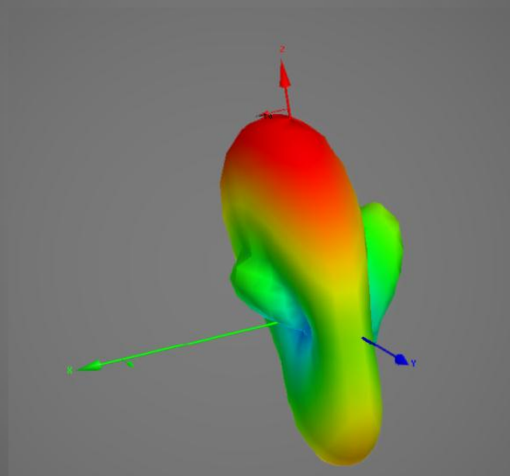


I3's Final Internship Study

Louis Parent

I am doing my I3's final internship study in the United States at the University of Kansas in Lawrence (Kansas 66044). I have been working in the Information and Telecommunication Technology Center (ITTC) laboratory of this University to make some research about antennas.

The University of Kansas
2335 Irving Hill Road

+1 (785) 864-4776

01/11/2011

Acknowledgement

The special thank goes to my helpful supervisor, Dr. Sarah Seguin. The supervision and support that she gave me truly helped the progression and smoothness of the internship program. The co-operation is much appreciated. She was my contact when I was in France and in the laboratory. Without her, I would never have been in this Laboratory.

All projects during the program would be nothing without the enthusiasm and imagination from the people who work in the lab. Besides, this internship program makes me realize the value of working together as a team and as a new experience in working environment, which challenges us every minute. Moreover, great appreciation goes to the rest of Lab's staff that helped me from time to time during the project. The whole program really brought us together to appreciate the true value of friendship and respect of each other.

Factsheet

Subject of the internship:
Help to write a paper "The Spectrum Attributes of Phased Array Antenna"

Theme:
Research, HFSS, MatLab

Company:
University of Kansas (KU), Information and Telecommunication Technology Center (ITTC) Department, Nichols Hall, Kansas, United-States

Place:
2335 Irving Hill Road • Lawrence, KS, 66044

Dates:
From the 1th of June, 2011 to the 31th of November, 2011

Objectives:
Help to write a conference paper one the subject "The Spectrum Attributes of Phased Array Antenna". Work with Matlab and HFSS to model antennas and find the spectrum.

Difficulties:
Research is never easy; you don't really know where you are going. For people who never did it, it could be difficult to find ways to go.

Framing:
Dr Sarah Seguin (seguin@ku.edu)

Results:
Most of the objectives have been achieved. But the paper was not done in the time. We are still working on it.

Fiche de Synthèse

Sujet du stage:
Aide à l'écriture d'un papier avec pour thème "The Spectrum Attributes of Phased Array Antenna"

Thème:
Recherche, HFSS, MatLab

Entreprise:
University of Kansas (KU), Centre de Technologie de l'Information et de la Télécomunication (ITTC), Nichols Hall, Kansas, Etats-Unis

Lieu:
2335 Irving Hill Road • Lawrence, KS, 66044

Date:
Du 1er Juin 2011 au 31 Novembre 2011

Objective:
Aide à l'écriture d'un papier de conference ayant pour thème "The Spectrum Attributes of Phased Array Antenna". Modélisation sur Matlab et via HFSS d'antenne afin d'en définir le spectre.

Difficultés:
La recherché n'est jamais une chose facile, on ne sait jamais réellement ou l'on va et comment on y va. Pour des personnes comme moi qui n'en avais jamais fait ce n'était pas une chose facile.

Encadrant:
Dr. Sarah Seguin (seguin@ku.edu)

Resultats:
La plupart des objectifs ont été atteint. Mais il nous a manqué de temps pour terminer le papier dans les dates. Nous sommes toujours en train de travailler dessus.

Summary

I. Figures Summary

II. Abstract

« The Spectrum Attributes of Phased Array Antenna »

Sarah Seguin

University of Kansas

Lawrence Cohen

Naval Research Laboratory

Phased array radars have been a reality for many years and in particular for radars used in long distance air search by the world's militaries and air traffic controllers. Recently, with the influx of wireless systems worldwide, such as WiMAX, there has been competition between radar and wireless in the band from 2.0-4.0 GHz (S Band). With the World Radio Conference 2012 approaching, consideration among the nations of the world has been on-going as to what degree the RSEC and ITU's spectral emission masks for radars in S band requires steeper role offs beyond the allowable 40 dB bandwidth. When considering phased array radar systems a question arises as to what might be the difference between a radar on a ship, for example, and a WiMAX base station on shore.

This paper discusses on-going research in radar spectrum engineering at NRL and the University of Kansas. A MATLAB and electromagnetic model of a simple eight element linear array operating at 3.5 GHz will be built. The element spacing will be a half of a wavelength. The model will be stimulated utilizing CW, pulse amplitude, and FMCW chirp waveforms. The spectral content of these emissions in the far field will be assessed at a variety of angles with respect to bore sight. These results will then be applied to the design of fictitious land based long range air traffic control radar. The emissions from this fictitious radar will be allowed to impinge on the antenna of a WiMAX base station operating at 3.5 GHz, at different angles relative to the radar antennas bore sight. Conclusion of base station degradation will be drawn with respect to the severity of interference to the base station and to what extent the change in spectral content in the emissions effects this degradation.

III. Introduction

I spent my six month internship at the University of Kansas KU in the ITTC (Information & Telecommunication Technology Center) building. This University is located in Lawrence, Kansas. It is known and recognized in the United States.

Address and phone number of the University:

The University of Kansas
Lawrence, KS 66045
(785) 864-2700
http://www.ku.edu/

I was welcomed by Dr. Sarah Seguin, she has a PhD and she work for the University as a searcher and a professor. She was my contact when I was in France.

My office is in the ITTC building localized on the West campus.

Address and phone number of the laboratory:

Information and Telecommunication
Technology Center (ITTC) Nichols Hall
The University of Kansas
2335 Irving Hill Road
Lawrence, KS 6604
(785) 864-4776
http://www.ittc.ku.edu/

The Information and Telecommunication Technology Center (ITTC) advances knowledge and creates innovative technologies in telecommunications, information systems, bioinformatics, and radar. We are one of the largest research centers at the University of Kansas, with our resources and state-of-the-art facilities supporting various multidisciplinary inquiries. ITTC-affiliated faculty members have served as federal program directors at NSF, DARPA, and NASA.

ITTC researchers are helping shape not only national policy but also the technology leaders of tomorrow. ITTC, the only KTEC Center of Excellence focused on the core technologies below, is committed to the continued growth and diversity of the State's economy. Under faculty guidance, our students conduct fundamental research and develop strategic solutions for Kansas companies and national industries.

During the six months of my internship, I worked as a researcher in this laboratory. What I researched was Antennas, and more specifically, Linear Array Antenna. The goal of those six months was to write a paper. To model my work, I used HFSS and Matlab. At the end of the day, we want everything to be working on Matlab, so after working on HFSS, I transferred my work on Matlab.

My report is composed in two parts. The first part is a presentation of the university and about what we are doing in my building along with some history. My second part is about my project, what I did, what I realized, what my objectives were and what were my results plus the problems I met.

IV. Presentation

You will find in this part: a presentation of the University, the lab where I have worked during these three months and a presentation of my internship project.

A. The University

1. History of the University of Kansas

The University of Kansas (KU) was founded February 20, 1863 and opened in 1866 as a public research university and the largest university in the state of Kansas. KU campuses are located in Lawrence, Wichita, Overland Park, and Kansas City, Kansas with the main campus located in Lawrence on Mount Oread, the highest point in Lawrence.

Today the university is known for its Engineering school, but also for schools of Allied Health, Architecture, Design, and Planning, Business, Education, Arts, Music, Journalism and Mass Communication, Law, Medicine, Nursing, Pharmacy, and Social Welfare. (The study of academic sociology originated at the University in 1890).

You can find all KU's information on the website of the university:

http://www.ku.edu/

2. Information and Telecommunication Technology Center ITTC

a) *Presentation of the office*

During my internship, I worked in this building, the ITTC Building. This building host based collaboration areas for many research projects at the Information Technology and Telecommunications Center.

- The ITTC Research Lab
- The ITTC Research Project
- The ITTC Reading Group
- The EECS Classes

I worked in the first area, The ITTC Research Lab. This area is named “The Computer Systems Design Laboratory (CSDL)”.

You can read on https://wiki.ittc.ku.edu/ittc/Main_Page:

> ***The Computer Systems Design Laboratory (CSDL) will improve the design of computing systems, ranging from small, embedded elements to large, and distributed computing environments. Research addresses all aspects of a system’s life cycle, including specification and synthesis. This includes attention to system verification, design, and implementation of development and implementation platforms for real-time and embedded computing.***
>
> ***The CSDL maintains some documentation on Software Tools that are used in the lab and also, as part of our lab research activities, we maintain a Reading Group where we read papers from the literature.***

I worked more precisely, and as you could read in my abstract (page 3), on the “The Spectrum Attributes of Phased Array Antenna“. My job was to model on HFSS and Matlab a Phased Array Antenna. Afterward, these results will be applied to the design of fictitious land based long range air traffic control radar. I will explain all of it in my second part.

I have my own office in this building and I work with some others PhDs and Masters Students in the “Radar Systems & Remote Sensing Lab”.

I work with the Dr. Sarah Seguin, she is an Assistant Professor and she specializes in Electromagnetic compatibility, electromagnetic interference, radar systems, signal integrity, antenna design, and electromagnetic modeling.

b) The building

The website of my building (I will call it “building” because it’s not a company, it is a building where you can find a lot of laboratories, and it is on the campus of the university) is:

http://www.ittc.ku.edu

You can find everything about it on this website. But I will make a short summary.

This center works to be a leader and a partner in the creation and commercialization of innovative technologies in telecommunications, information systems, bioinformatics, and radar.

To do that, they have six laboratories on the campus of the University of Kansas, and five of those are in Nichols Hall (Name of the ITTC building). So there are more than 45 faculty and staff researchers and more than 135 students who work there.

72% of ITTC’s founds are from the Federal grants (government), 17% from the State, 9% from the industry and the 2 percent are made by sponsors. So the annual budget is more than $4.2 million.

> ***Existing companies collaborate with ITTC for research and development, realizing that targeted research reduces costs and improves service to consumers. Fledgling companies, seeking to develop new technologies, draw on the faculty and staff. Technologies developed by ITTC foster industry growth and often provide the core for new companies.***

c) History: “Radar Systems & Remote Sensing Lab”.

At this time, the lab works with a lot of big companies and on a lot of projects.

You can find on this website all information about research projects in my area of work, “Radar Systems & Remote Sensing Lab”.

RSL was originally founded as the Remote Sensing Laboratory in 1964.

Sarah Seguin is the Assistant Professor who has helped me with her research expertise in “Electromagnetic compatibility, electromagnetic interference, radar systems, signal integrity, antenna design, and electromagnetic modeling”

http://www.ittc.ku.edu/research/rsl/history.html

RSL has been involved with the following space-borne radar programs: Skylab, Seasat, SIR-A, SIR-B, SIR-C, ERS-1, JERS-1, TRMM, and SeaWinds. RSL has participated in many large national and international programs for study of vegetation, oceans, sea ice, and glacial ice.

In 1998, RSL merged with the Telecommunication & Information Sciences Lab (TISL) to form the Information and Telecommunication Technology Center (ITTC) at KU. In 2005, RSL research formed the basis of the Center for the Remote Sensing of Ice Sheets (CReSIS), an NSF Science and Technology Center established to study the ice sheets in Greenland and Antarctica.

V. Project

A. Presentation of the Project

The abstract, page 12, explains the project I worked on. As research implies, you are working a lot on something, you have skills for it but you don't really know where you are going, what you will find and how much time everything will take. You are always learning new things and get to discover a lot. It's very interesting.

In this project, my goal was, step by step be able to model a phased array antenna at 3.5GHz and to ride a paper with my boss and my coworker.

Figure 3: Illustration of what can be a Phased array antenna

In this abstract, you have no choice about which Array you will have to use, it's obligatory an electromagnetic model of a simple eight element linear array. But we have the choice about which kind of antenna we can use. So we worked on different type of antennas.

1. What is a phased array?

http://en.wikipedia.org/wiki/Phased_array:

> ***In wave theory, a phased array is an array of antennas in which the relative phases of the respective signals feeding the antennas are varied in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions***

The goal is to product a directive pattern to obtain the desired radiation pattern. The radiation pattern can be called the near-field pattern or the Fresnel pattern.

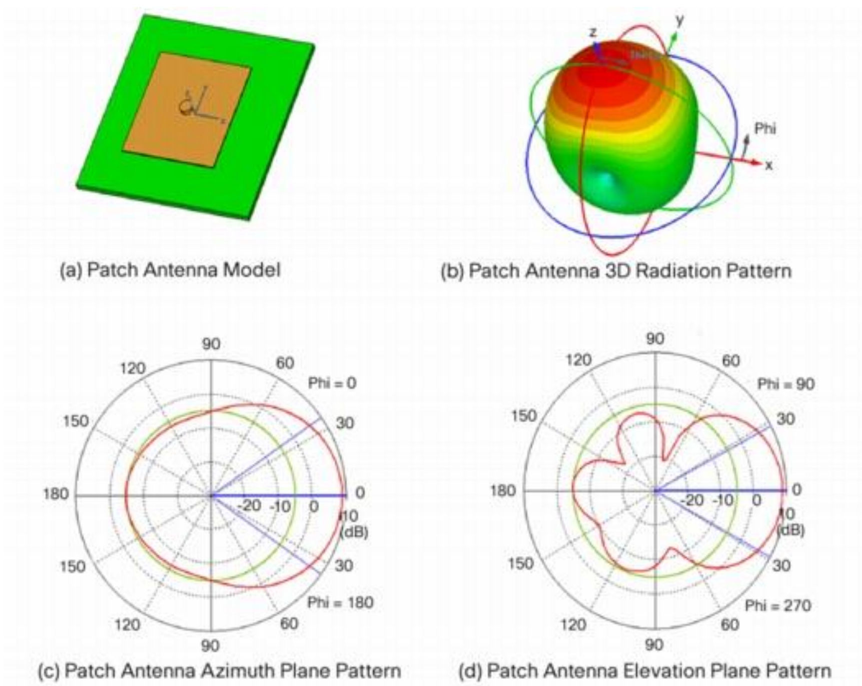


Figure 4: Example or radiations pattern for a simple patch antenna model

We just modeled a group of active antenna couple on the same source to produce the directive radiation pattern we want to. An example of an array antenna who everybody knows is the television antenna.

This kind of transmission was developed in 1905. It was used for the WWII for the radar system and later adapted for the radio astronomy. Afterward, they were developed at the University of Cambridge.

Here is an example of a Phased array antenna with only two elements.

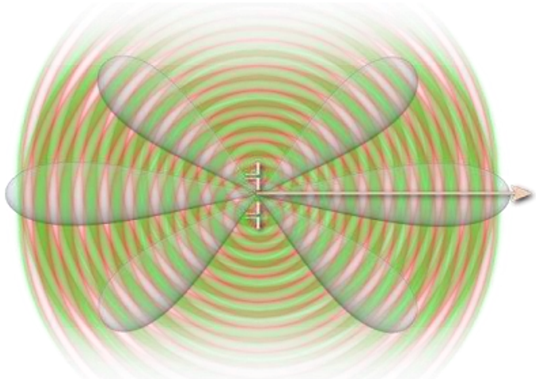


Figure 1: two antenna elements, fed with the same phase

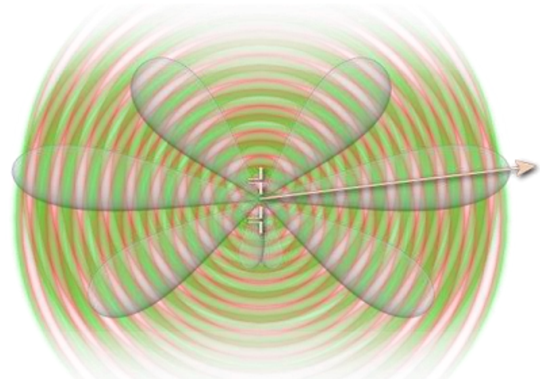


Figure 2: two antenna elements, fed with different phase shift

In Figure 1, both radiation elements are fed with the same phase. In the Figure 2, the signal is emitted by the lower radiating element with a phase shift of 10 degrees earlier than of the upper radiating element. Because of this the main direction of the emitted sum-signal it is moved upwards.

a) Different type of phased array

There are two different types of phased array, we can call them beamformers.

- Time domain beamformers

This type of phased array works on time-based operations. The goal is to make a delay with each incoming signal of array element and then add them together.

- Frequency domain beamformers

There are two types, the first one just separates the different frequency component present in the received signal into different frequency bins. Used for communication links. The second one makes use of so called Spatial Frequency. This one is simple, but not flexible because the different directions are fixed.

In our case, we are using the frequency domain beamformers.

b) In which areas do we use phased arrays antennas

Today, phased arrays antennas are used in 7 areas:

- **Broadcasting** (Radios Stations),

Figure 5: Broadcasting array antenna

- **Naval usage** (radar system for surface detection and tracking, air detection and tracking and missile uplink capabilities),

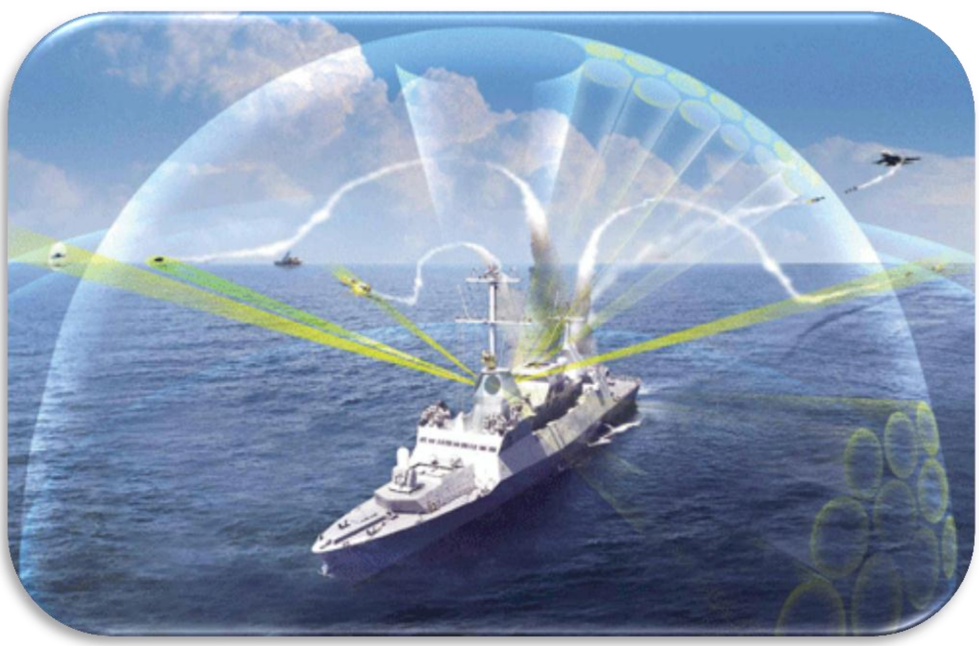


Figure 6: Naval Usage for phased array antenna

- **Spaceprobe communication** (used for a Mercury mission in March 2011 named spacecrafed),

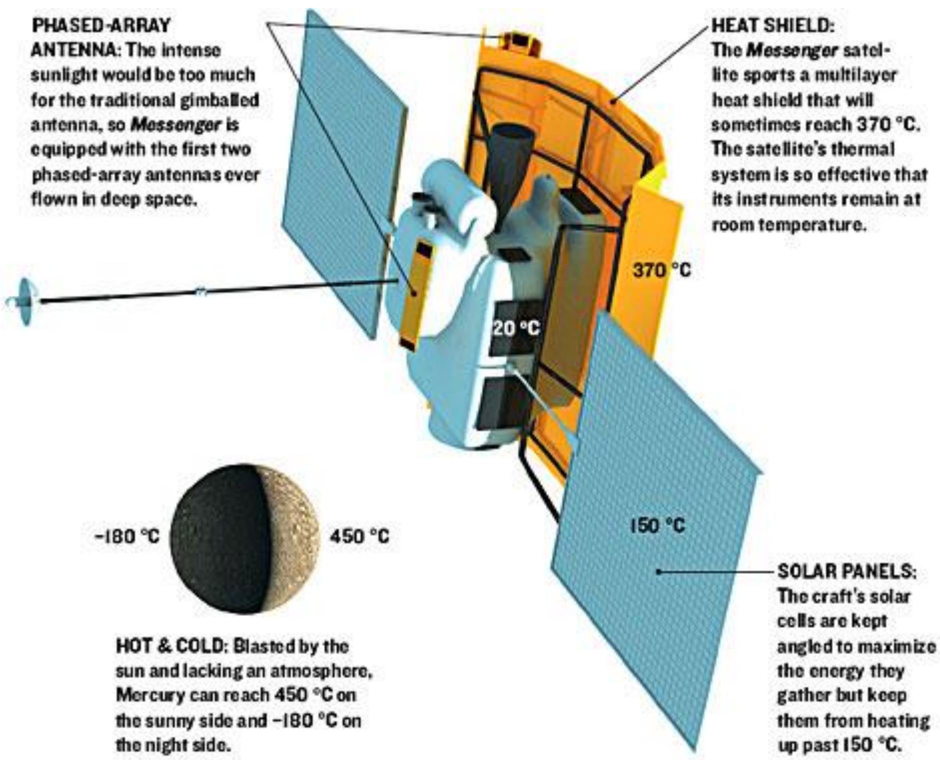


Figure 7: Space Probe.

- **Optics** (electromagnetic waves it also possible to construct optical phased arrays),

- **Radio Frequency Identification** (you can find it in RFID, they boost the reading capacity of UHF tags),

- **Human-Machine Interfaces** (with acoustics transducers to induce tactile feedback).

- **Weather research usage** (the US navy use it at the *National Severe Storm Laboratory* since 2003 for tornados in Oklahoma),

Figure 8: Phased Array Antenna Used in the weather station in Oklahoma

We assume that this technic will be used for a lot of other areas in the future. My work was based on the radar system for airplanes.

2. Linear array

As indicated in the abstract, I am working on a linear array. A single antenna has a limited radiation pattern. If we use several antennas working together, as an array, it is possible to improve the radiation according to some specification.

A linear array antenna consists of lines whose elements are fed about a common phase shifter. They have the advantage to be really simple to arrange. But there is one disadvantage; the ray reflection is only in a single plane possibility.

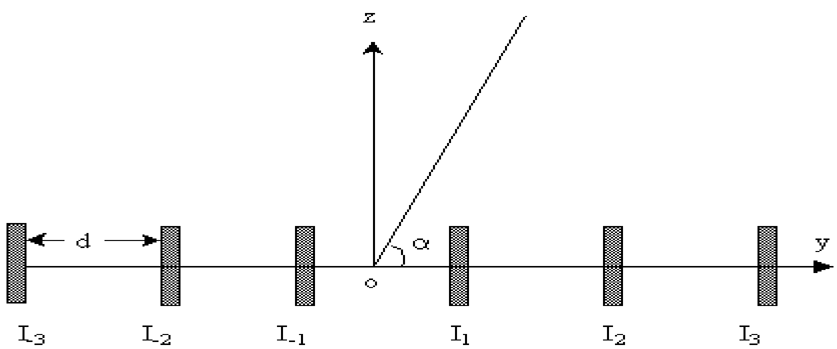


Figure 9: Linear array antenna

Distance between two elements: d
Number of array elements: N
Phase offset between elements: β

Here you can find a linear array antenna with six elements. A uniform linear array antenna has the entire array elements placed on the same axis. In this example, it's on the y axis. They are spacing by a distance d. We can use those equations for each current I_n elements. They only differ by a phase angle increment of β as given below:

$$I_n = Ie^{(j\left(n-\frac{1}{2}\right)\beta)}$$

$$I_n = Ie^{(-j\left(n-\frac{1}{2}\right)\beta)}$$

I is a referent current,
n = 1, 2, …., N/2
and N is the number of elements of our array.

If we assume that an element placed at the origin is the reference of the electric field $\overline{E_e}$, then every single element produce a field like this:

$$E_n = E_e\, e^{\left(j\left(n-\frac{1}{2}\right)W\right)}$$
$$E_n = E_e\, e^{-\left(j\left(n-\frac{1}{2}\right)W\right)}$$

With $W = \beta + kdcos(\alpha)$ k ϵ N

The total electric field is then:

$$\boxed{E_{total} = \sum_{n=1}^{N/2} E_n + \sum_{n=1}^{N/2} E_{-n} = E_e\, F}$$

F is the array factor, and you can find it by:

$$F = \frac{\sin(\frac{NW}{2})}{\sin(\frac{W}{2})}$$

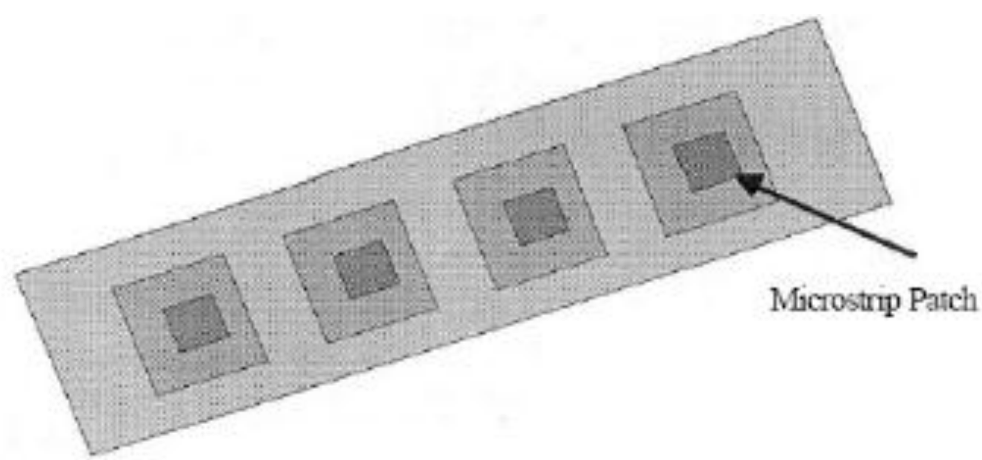


Figure 10: Linear array micro strip antenna

3. Which kind of antenna we should use?

We can use every single antenna with an array antenna. For our abstract, we choose to work on Patch antennas and on Slot antennas, which are two antennas that we already know. It's easier to support some results when you have an idea of what you should find.

I will make a presentation in the two next parts of those antennas.

a) Patch antenna

A Patch Antenna or Rectangular Micro Strip Antenna is a low-profile antenna that has a number of advantages over other antennas, which can be mounted on a flat surface. A patch antenna is lightweight, inexpensive, and easy to integrate with accompanying electronics. Moreover, it's easy to modify and customize one of them.

The Micro Strip patch antenna (Patch Antenna) is among the most common antenna type in use today. The better range to use them is between 1 and 6 GHz. They were invented during the 70's because they were very useful in term of performances. They are very used mostly for aircraft and spacecraft applications. More recently, they are used for GPS signal and other mass-producted products like cell phones and other wireless.

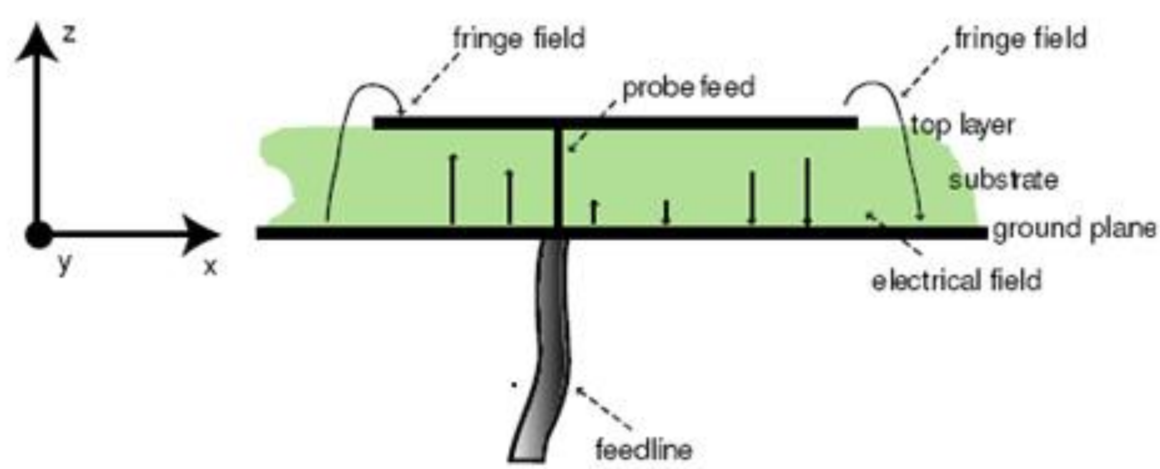


Figure 11: Representation of a Simple Basic Patch Antenna

- Advantages of a Patch Antenna

The Patch Antenna has the propriety to be two-dimensional. So an array can have a large aperture with corresponding high gain but having a low volume and weight.

You can fit different applications to manipulate the dielectric layer. Air dielectric has very low loss, making Micro Strip antennas interesting for wireless communication system where we want low weight and high gain. Moreover, it’s really easy to play with the wavelength. If the wavelength is smaller, the side of the antenna can be reduced. This one is used a lot in GPS antennas.

- Disadvantages

One disadvantage of those antennas is that with these dimensions, a patch can create higher-order modes that allow radiation, or reception of interference, at other frequencies. So to balance them, it is better to have some additional circuitry for the band pass filtering.

We will speak now about the Patch Array Antenna. This method is an array of several Patch antennas.

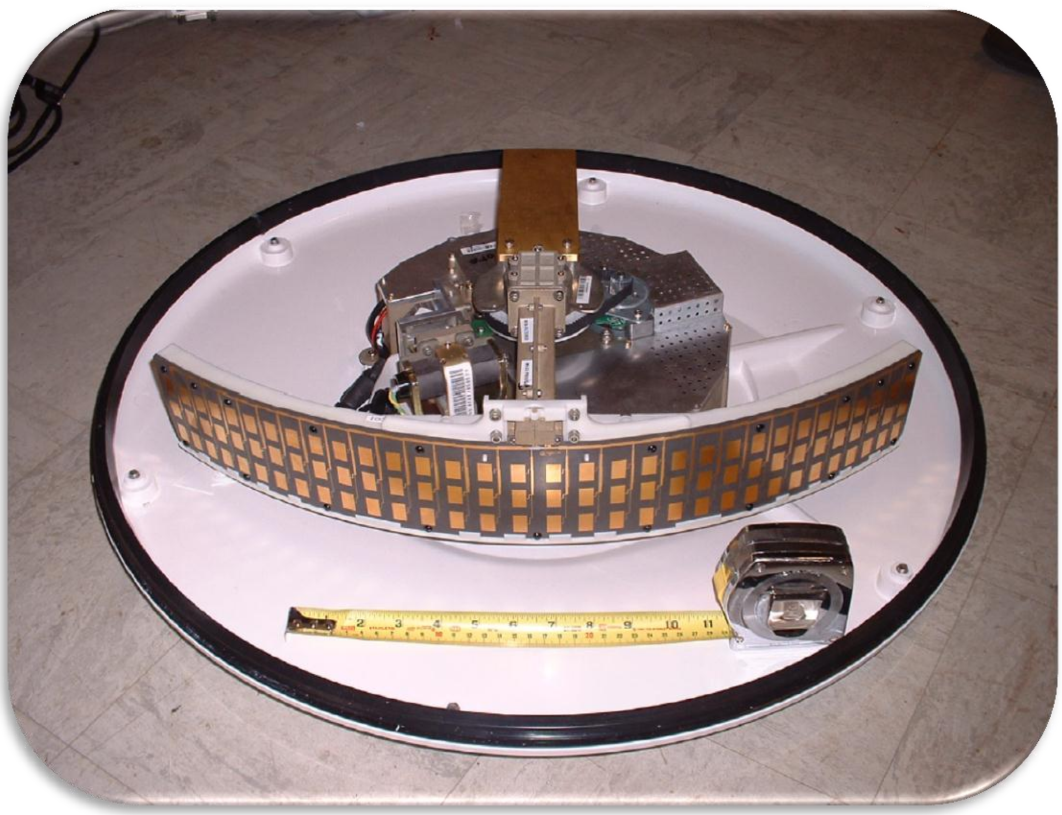


Figure 12: Patch Array Antenna

Patch Array Antenna proprieties are more interesting than a simple patch antenna. The gain is better, and it easier to work on the pattern. The directivity of a patch array antenna is better than for a simple one. You can see in those examples the difference between the pattern of a simple patch antenna and a patch array antenna is showed.

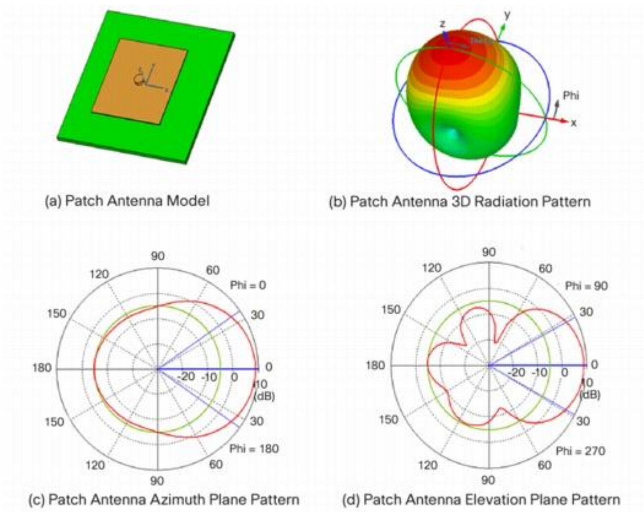
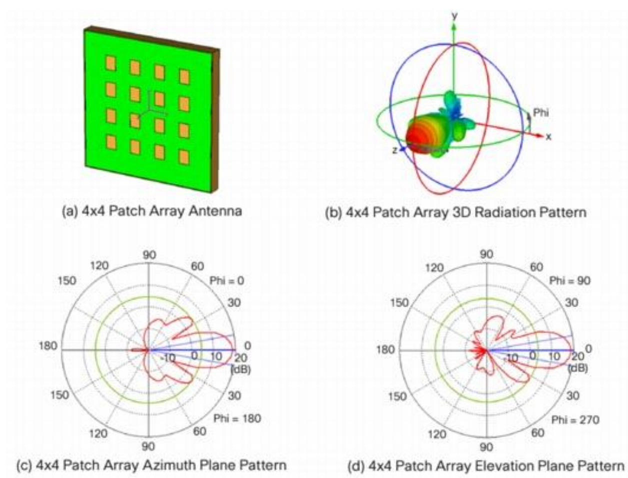


Figure 13: Simple Patch Antenna Patterns

Figure 14: Patch Array Antenna Patterns



In this example, we can clearly see than the pattern is totally different and that it is easy to obtain better results with an array antenna. In our case, we will work on and 8-linear patch array antennas. The directivity of the pattern is really improved by using a patch array antenna.

b) Slot antenna

A slot antenna consists of a metal surface, with a hole or slot cut, typically used between the frequency of 300 MHz and 24 GHz. The particularity of this antenna, and why it is popular, is because with this kind of antenna, it is easy to cut out of whatever surface they are to be mounted on, and they have radiation patterns that are roughly omnidirectional. With a linear polarization, it is easy to change the size of the slots, the shape and what is behind it (the cavity). It's easy to use to optimize the performance of the Antenna.

The Slot antenna has a lot of advantages. Those advantages are: the size of it, the simplicity of the design and the robustness.

They were invented in 1938 for the VHF television broadcasting for the horizontal polarization, the omnidirectional horizontal radiation pattern and a narrow vertical radiation pattern.

More often, the radio waves are provides by a waveguide, the slots in this waveguide compose our antenna.

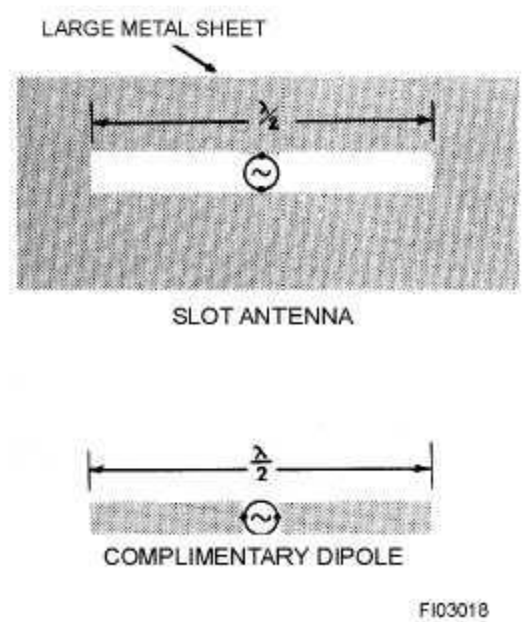


Figure 15: Simple Slot Antenna

A thin slot antenna in an infinite ground plan is the complement to a dipole in a free space. The slot has the same radiation pattern as a dipole with the same dimension than as the slot. But it is swapped, as we can see in the *figure 15.*

Work with this kind of antenna is easy because we are able to understand it very well. It's easy to calculate the pattern of a dipole, and the pattern of those antennas is the same one. There is just a rotation to do. Thus, a longitudinal slot in the broad wall of a waveguide radiates just like a dipole perpendicular to the slot.

The Slot Array Antenna is just several slots in the same piece of metal.

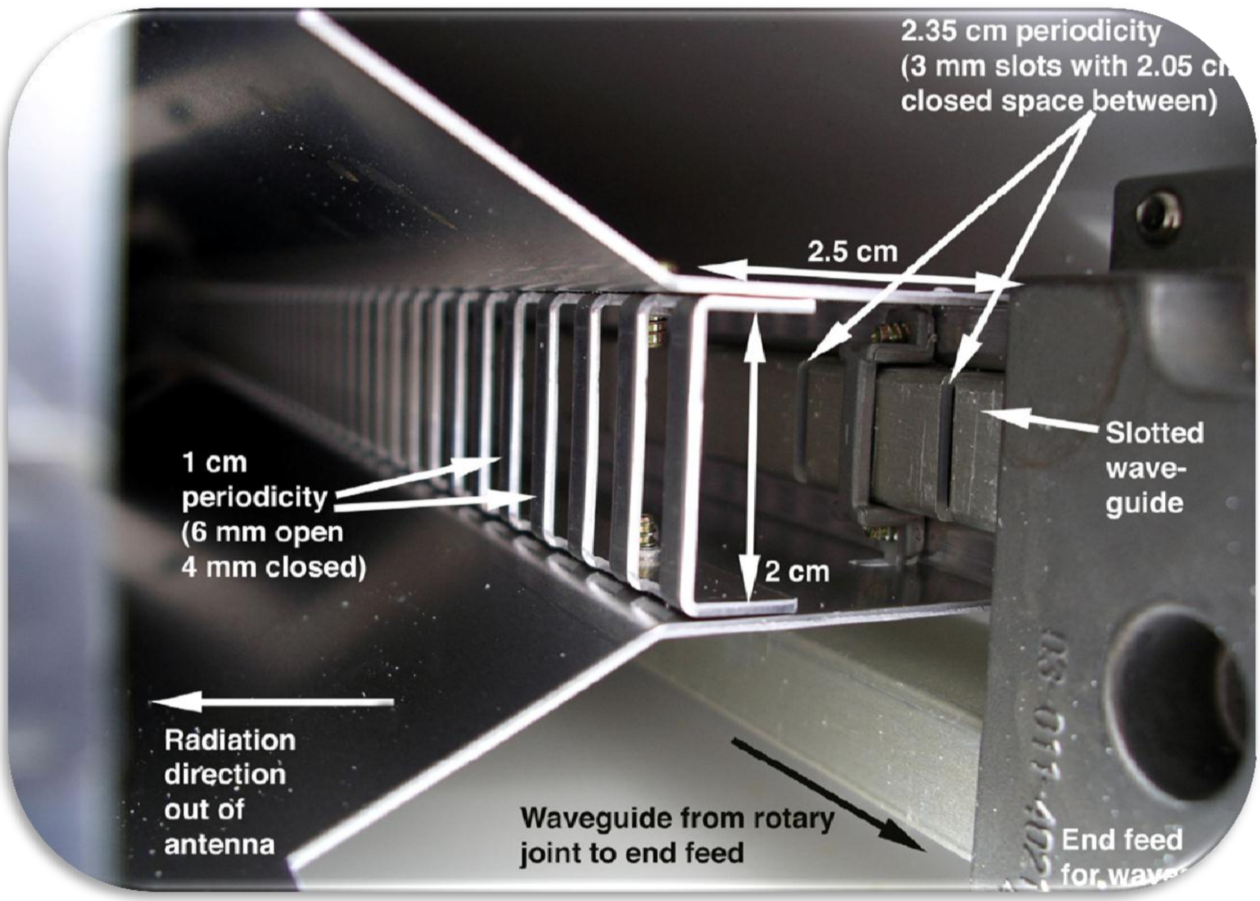


Figure 16: Slotted waveguide assembly with end of random removed

I studied about this type of antenna because they know more things about this one in my laboratory. They wanted to support the research on something they have understanding of. Through this, it is easier to tell if the results are good or not.

Moreover, study another antenna is always a must for the comparison.

You can find here below how realize a slot array antenna.

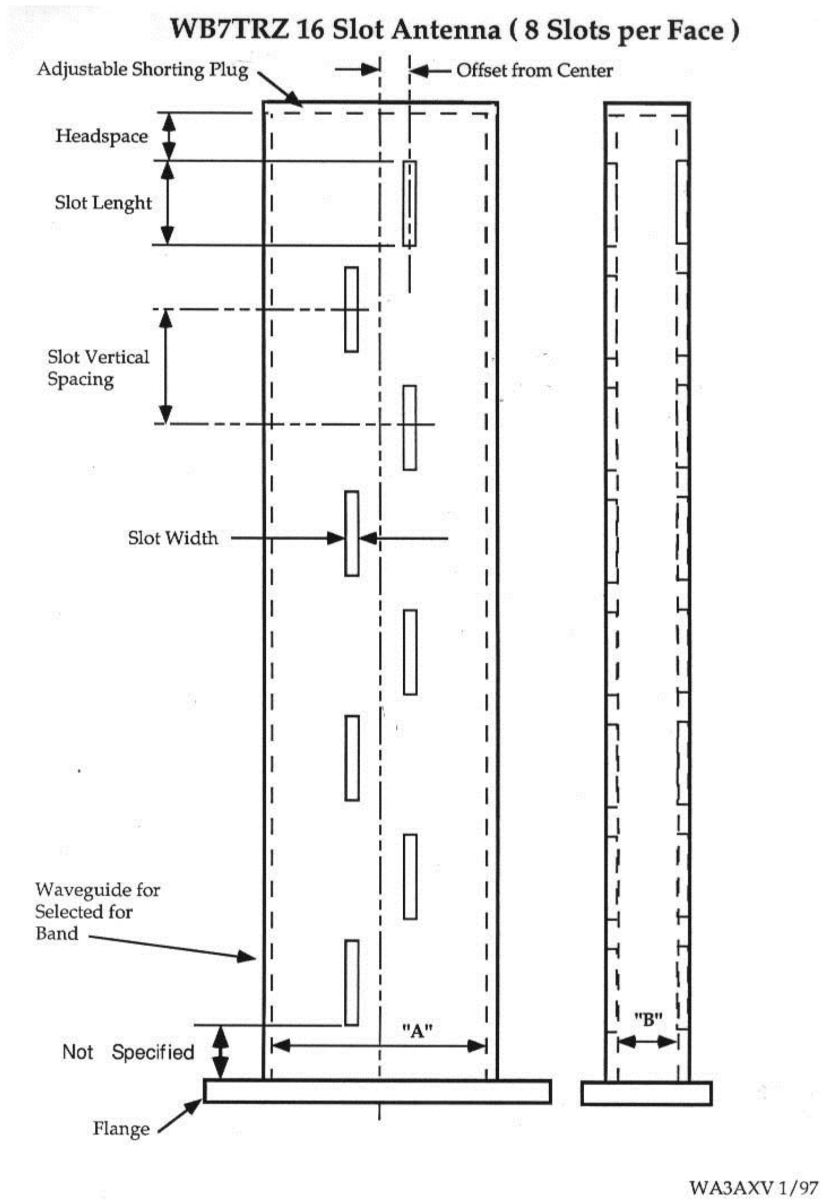


Figure 17: Front view of a waveguide slot antenna

This is an 8-linear element of a Slot Array Antenna (Waveguide Slot Antenna). The same kind of one we will use for our abstract.

You can find here the pattern of a simple and an array antenna using slots.

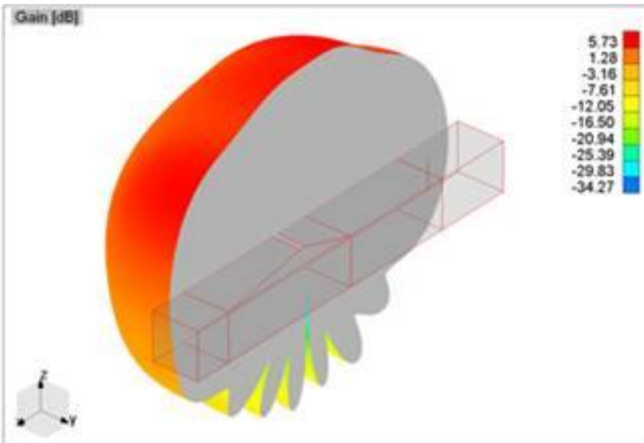
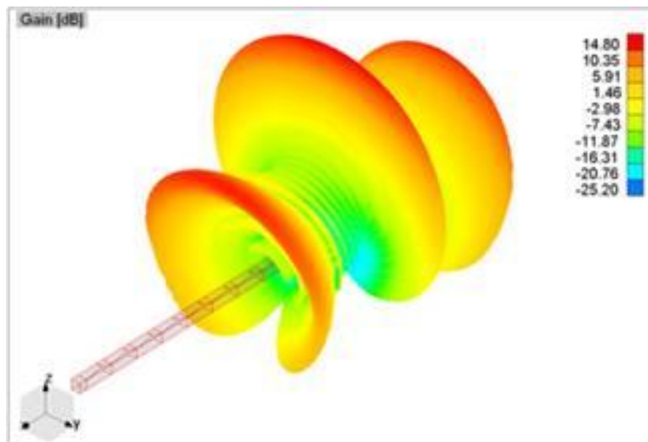


Figure 18: Simple Slot Antenna Pattern

Figure 19: Slot Array Antenna Pattern



Same ascertainment than with the patch antenna, we can easily say in those Figures than with an array, the directivity is really better, and the gain too.

B. Electromagnetic waves

I will in this part explain the waves used in this abstract and in our manipulations. We have chosen to use three different electromagnetic waves:

- The pulse amplitude,
- The continuous wave (CW),
- And the frequency modulated continuous wave.

Those waves are used in our case for radars experimentations.

1. The pulse amplitude

Pulse amplitude is just an impulsion during a lap of time.

So we don't send a continuous wave, we just send impulsions, based on the Doppler effect, it is possible to know the target's range.

The problem with this kind of wave is that the Pulse-Doppler (another name for pulse amplitude) can be too slow. The maximum time to scan the entire volume of the sky must be on the order of a dozen seconds or less for systems operating in that environment.

It's why we are also working with two others electromagnetic waves.

2. The continuous wave (CW)

As opposed to pulsed amplitudes, this wave is a continuous electromagnetic radiation. Radars were invented to determine the distance between to targets. In this case, the energy is continuous, so it is impossible to determine the target's range.

These kinds of radars, CW radars, are able to measure the instantaneous rate-of-range in the target's range. They do it by a direct measurement of the Doppler Shift of the return signal. The Doppler Shift is a change in the frequency of the electromagnetic wave caused by motion of the transmitter, target or both.

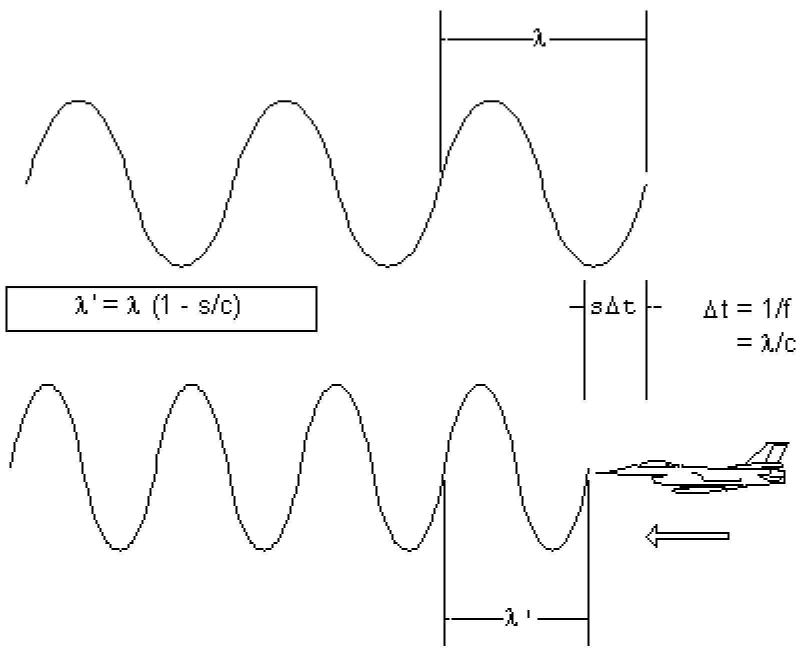


Figure 20: Doppler Shift

For an example, the police often use the CW radar to measure the speed of cars.

They are used in military applications. Continuous wave systems measure the instantaneous range rate, and maintain continuous contact with the target.

3. The frequency modulated continuous wave (FMCW)

http://www.fas.org/man/dod-101/navy/docs/es310/cwradar/cwradar.htm

> ***It is also possible to use a CW radar system to measure range instead of range rate by frequency modulation, the systematic variation of the transmitted frequency. What this does in effect is to put a unique "time stamp" on the transmitted wave at every instant. By measuring the frequency of the return signal, the time delay between transmission and reception can be measure and therefore the range determined as before. Of course, the amount of frequency modulation must be significantly greater than the expected Doppler shift or the results will be affected.***
>
> ***The simplest way to modulate the wave is to linearly increase the frequency. In other words, the transmitted frequency will change at a constant rate.***

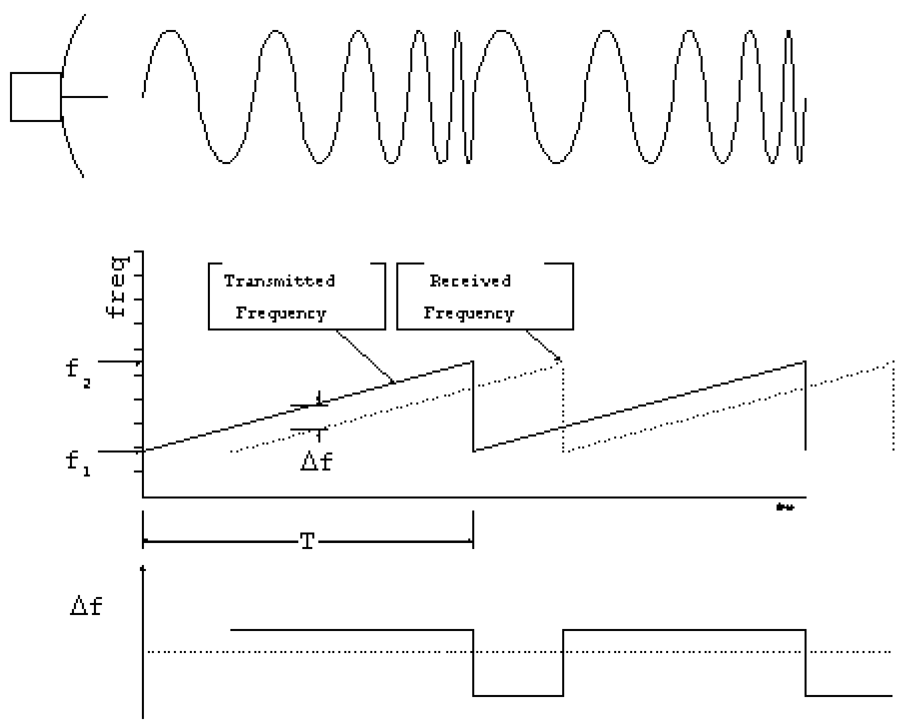


Figure 21: How calculate range by FMCW

They measure the instantaneous difference between the transmitted and the received frequency, Δf. It is Directly proportional to the time delay, Δt.

They are mostly used for radar altimeters or radar proximity fuses for warheads.

C. Conduct of research

1. Paper & Information, make inquiries

My entire project is based on research of information about what we already know, and what can be useful.

My weeks were pretty much spent the same:

- I had a meeting every single Tuesday with Sarah Seguin to speak about what I did, what I have to do, if I am going in a good way or if I have to change it, what should be my results, And to decide deadlines.
- Every single Friday, we have with my coworker (PhD Students and Master Students) plus Sarah Seguin, a Lab meeting. During this lab meeting, one of us, each turn, choose a paper and explain it to everybody. After that, we would speak about it and about what we are doing. It is a really good idea to open your mind to what the others are doing, and to find other opinion about your work. It is another way to learn and to find solutions.
- The rest of the week is the same, working in an office or in a library. Always on the campus because we have access to a lot of document and information.

Anyway, most of my time was spent learning about what was a “Phased Array Antenna”. So I looked for a lot of papers to read, I researched a lot in scientific books, and I tried to find solution and information.

I think it is the most important part of the work of a researcher. We always have to learn about everything, the world changes all the time.

To work on it, we are lucky. We have access on the campus to a lot of libraries with a lot of documents. Furthermore, on the internet, working or studying for the University, we have access to an on-line library where we can find a lot of papers. Those one are on the website www.lib.ku.edu and for us, EE people, we use the internet search engine “*IEEE Xplore*”. It is a very important data base. So the first part of my time was spent reading and research of information. I did this during six months to be able to move on with my research.

In a second time, we have to model antennas via Matlab. To do that sometime, I used HFSS, because it was easier to model antennas on HFSS and extract data afterward. This data will be read by a MatLab code I made.

I will treat in the next two parts how I made it on HFSS and MatLab.

Our entire project has to work on MatLab. I started to work on Matlab and to learn a few things I will need next. Sometimes, things were really easier via HFSS. It is why I used HFSS.

2. MatLab and HFSS

I worked on MatLab with the Phased Array System Toolbox. It took me a lot of time to understand how it works, and to be really able to use it.

http://www.mathworks.com/products/phased-array/

> ***Phased Array System Toolbox™ provides algorithms and tools for the design, simulation, and analysis of phased array signal processing systems. These capabilities are provided as MATLAB® functions and MATLAB System objects™. The system toolbox includes algorithms for waveform generation, beamforming, direction of arrival estimation, target detection, and space-time adaptive processing.***
>
> ***The system toolbox lets you build monostatic, bistatic, and multistatic architectures for a variety of array geometries. You can model these architectures on stationary or moving platforms. Array analysis and visualization tools help you evaluate spatial, spectral, and temporal performance. The system toolbox lets you model an end-to-end phased array system or use individual algorithms to process acquired data.***

I started to work with Patch Antennas. So my goal was to model the pattern of a simple patch antenna in a first time to finally work on a Phased array antenna and made some work on Matlab.

All or our experiments work on 3.5GHz.

a) Patch Antennas

(1) Simple Patch Antenna

In a first time I worked on patch antennas. To start, I modeled a simple patch antenna on HFSS.

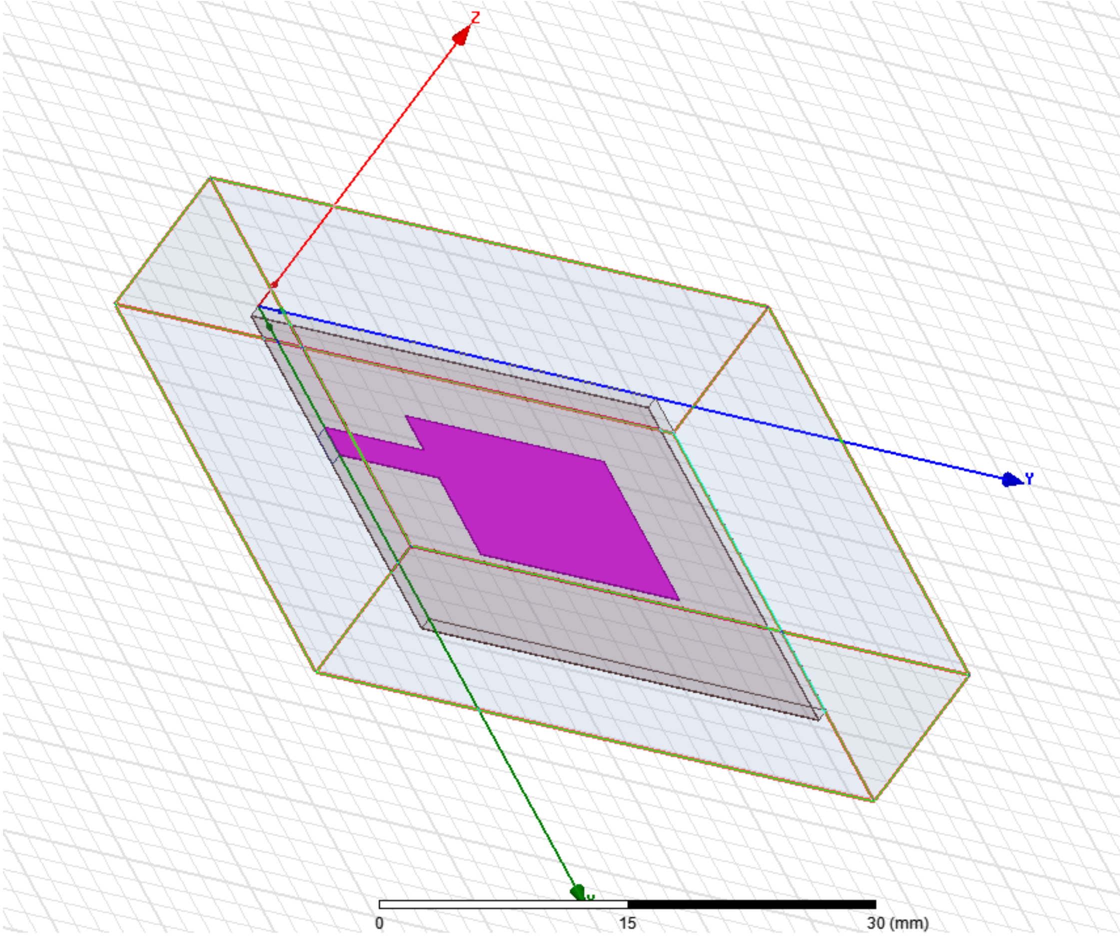


Figure 22: Simple Patch Antenna HFSS.

I simulated it with the data you can find in the abstract.

This antenna has these dimensions:

XSize: 12.45
YSize: 16
ZSize: 0.05
These dimensions were calculated in function of the wavelength.

I made the 3D pattern of the simple patch antenna.

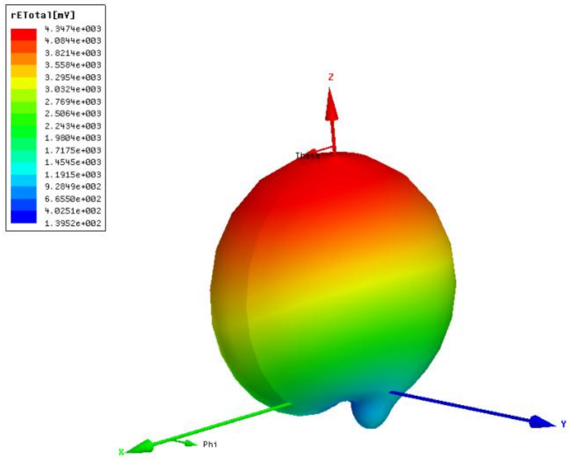


Figure 23: 3D Pattern of Simple Patch Antenna

In a second time I imported those results from HFSS in a .cvs file. It is an Excel file. And I made a code on MatLab able to read these.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                3DPlot
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure

RectangularPlot = importdata('SimplePatchPattern.csv')

% SimplePatchPattern.data;
%
% Rect = SimplePatchPattern.data;



Rect = xlsread('SimplePatchPattern.csv', 'A1:C216825');
PHI=Rect(:,1);
THETA=Rect(:,2);
R=Rect(:,3);


THETA = reshape(THETA,37,19);
PHI = reshape(PHI,37,19);
R = reshape(R,37,19);
[X,Y,Z] = sph2cart(pi/180*THETA,pi/180*PHI,R);



X(Y<=0) = -X(Y<=0)
X(X(:,1)<0) = -X(X(:,1)<0)
surfc(X,Y,Z)
```

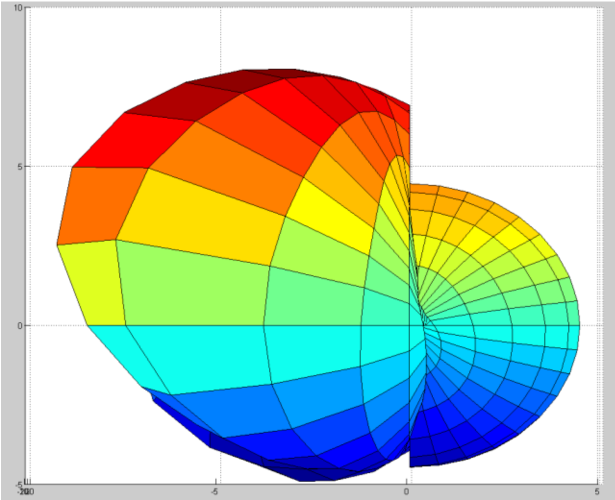


Figure 24: Simple Patch Antenna Matlab

Results are enough good to be used. So I did it with a Patch Array Antenna.

I modeled a patch array antenna on HFSS. With d=λ/2 between two antennas.

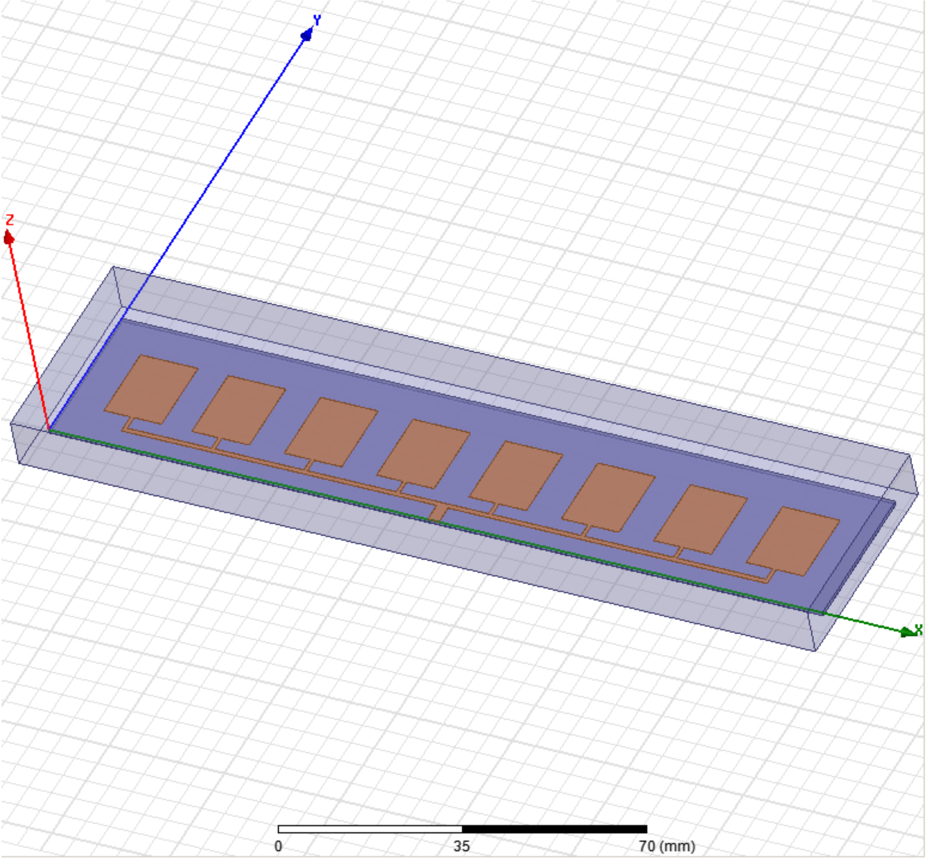


Figure 25: Madel of a Patch Array Antenna

This is an 8-Element linear Patch Antenna Array.

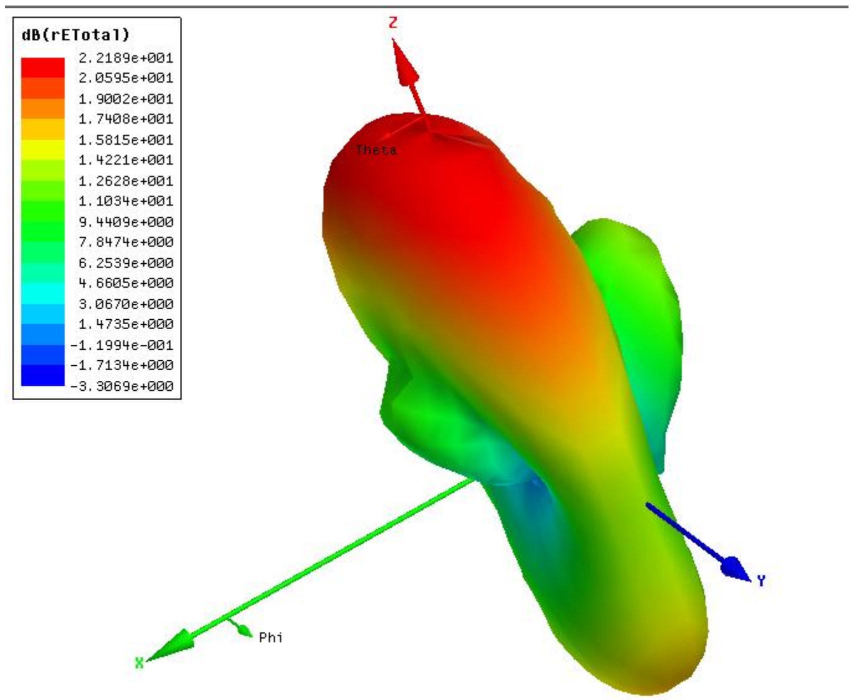


Figure 26: 3D Pattern Patch Array Antenna

I used the same Matlab code to read the .cvs file.

How I explained earlier, we can see that an array is really more directive than a simple antenna. And the gain is so much better with an array.

After these results, I tried work just on MatLab to model a Slot Array Antenna.

(2) Slot Antenna

I build a slot antenna on MatLab:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%                 Louis Parent      Slot Array Antenna
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Build the Antenna
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all
% Array Scratch

%Physical Constants
freq = 3.5e9;       %Operating Frequency
lambda = physconst('lightspeed')/freq;

%Waveguide Info
fc=physconst('lightspeed')/(2*0.8565*2.54/100);

freespace_beta = 2*pi./lambda;
beta_z = freespace_beta.*sqrt(1-(fc./freq).^2);
lambda_g = 2*pi./beta_z;
slot_spacing = 2.34e-2;     %2.34cm

%Array Object
helement = phased.IsotropicAntennaElement('FrequencyRange',[0.5e9 12e9]);
harray = phased.ULA(32,slot_spacing,'Element',helement);
```

This code model a Slot Array Antenna.

(3) Build a Radar Workflow Model

We want to represent on Matlab a real situation of transmission and reception of signal. To do it, I built a Radar Workflow Model. Define like this:

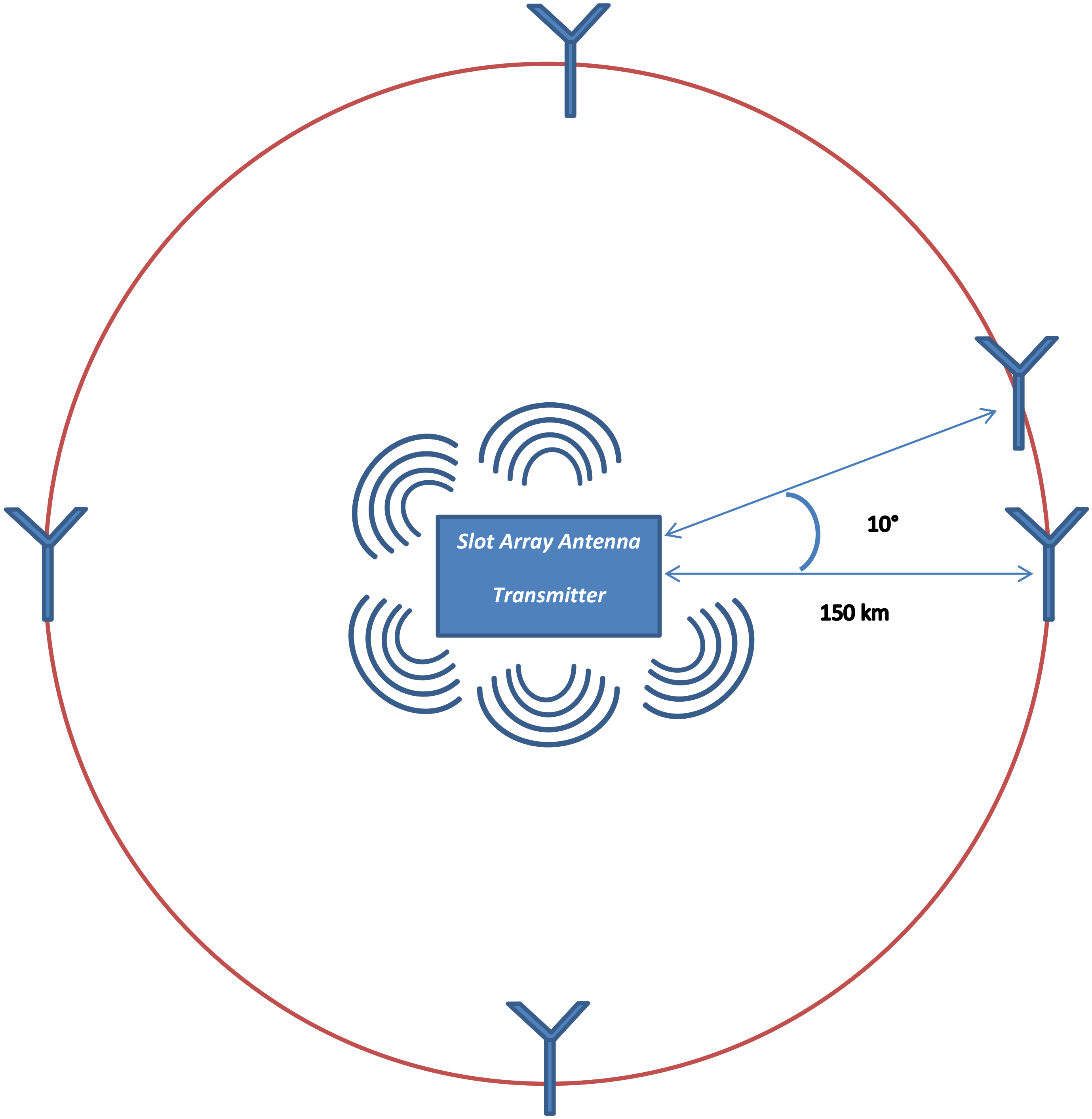


Figure 27: Model of the Radar Workflow.

We modeled it as represent on this figure. The Slot Array Antenna is the transmitter. And we placed at equal distance of this one (150km), an antenna receivers every 10°. A total of 35 Receivers antennas are modeled.

On our Matlab code, we will model just 17 of them, because the pattern is symmetric.

My Matlab code will be put in Annex. I will explain it here.

- Waveform

In this part of the code, I modeled the waveform that will be transmitted by our array antenna. There are three waveforms in the abstract. The pulse amplitude, the continuous waveform and the frequency modulated continuous wave.

You can see it the Linear FM Pulse Waveform and the Linear FM Spectrum.

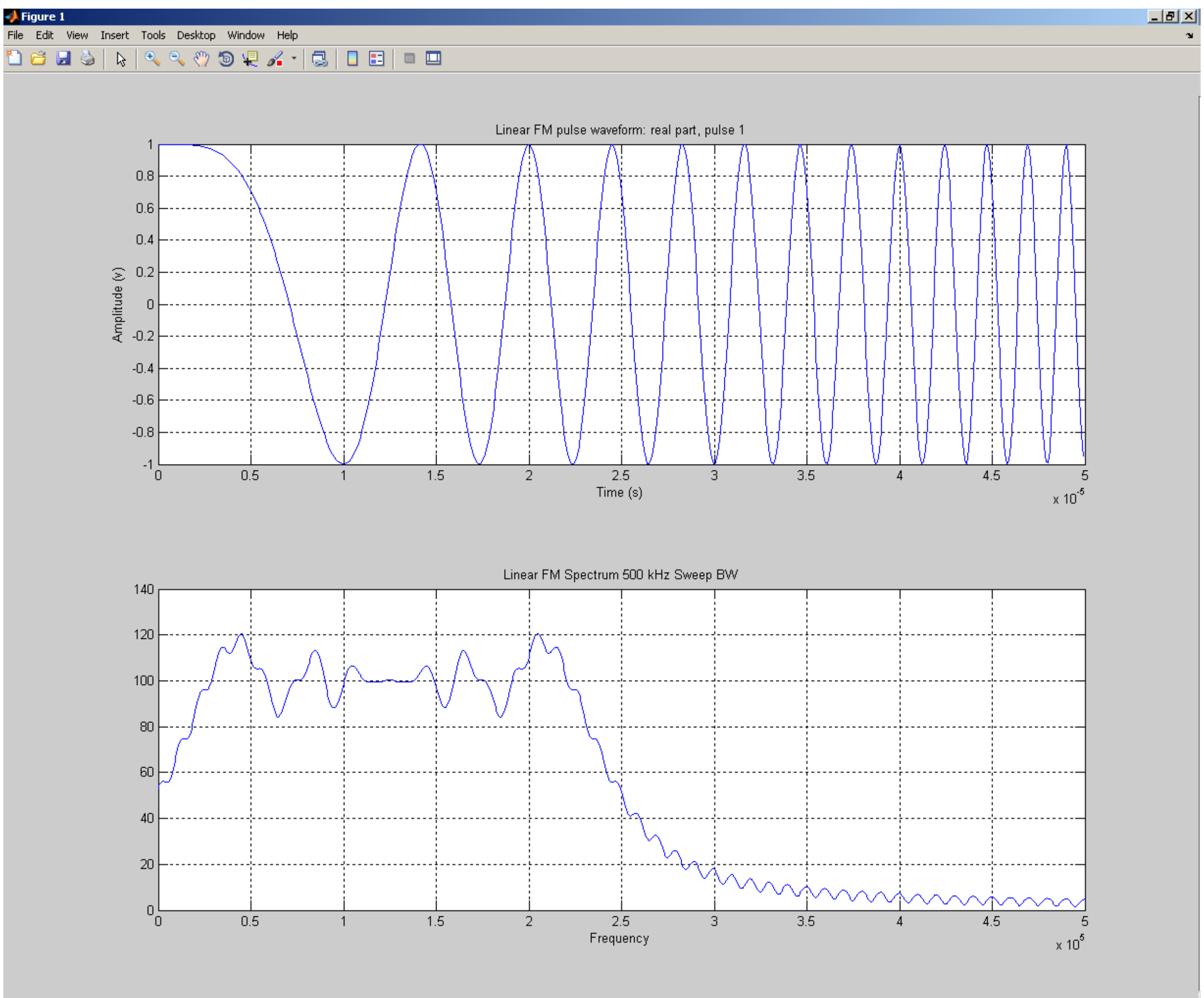


Figure 28: FMCW Waveform

- Antenna

In a second time, I code the slot antenna. I used the same code as earlier in the part "*Slot Antenna".*

Here the representation of the pattern of this Slot Array Antenna.

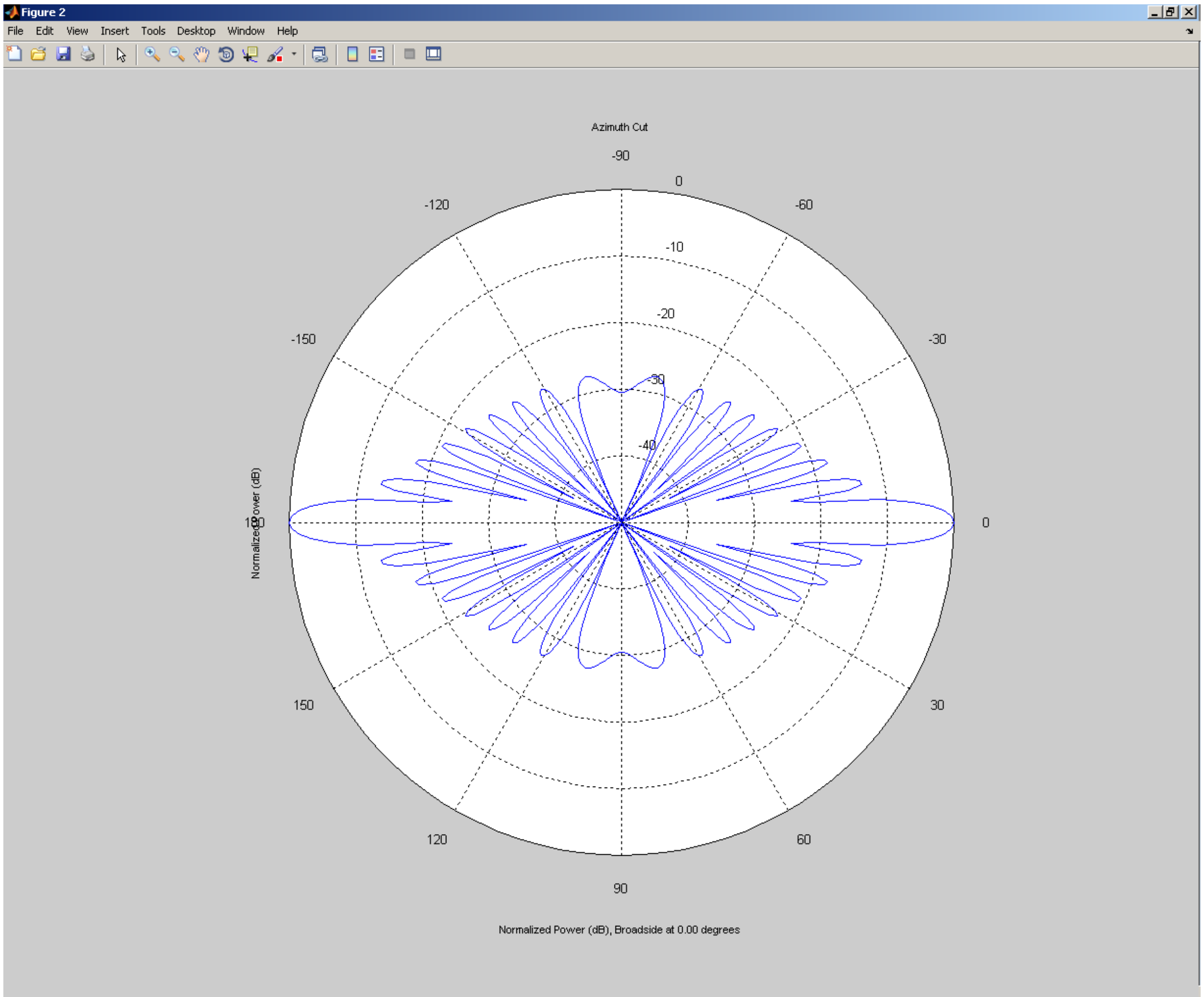


Figure 29: Slot Array Antenna 2D Pattern

- Target Model

The target has a nonfluctuation RCS of 0.5 square meters and the waveform incident on the target has a carrier frequency of 3.5GHz. The waveform reflecting off the target propagates at the speed of light.

- Antennas and Targets Platforms

In this part, we just place in the space all antennas. We define the target location and a velocity, here the transmitter is at the position [0,0,0] and it doesn't move. No one, of ours antennas move. And we define each single receiver with the initial position. As represented in this board:

Antenna #	x	y	z
0°	150.000	0	0
10°	147.721	26.047	0
20°	140.954	51.303	0
30°	129.904	75.000	0
40°	114.907	96.418	0
50°	96.418	114.907	0
60°	75.000	129.904	0
70°	51.303	140.954	0
80°	26.047	147.721	0
90°	0	150.000	0
100°	-26.047	147.721	0
110°	-51.303	140.954	0
120°	-75.000	129.904	0
130°	-96.418	114.907	0
140°	-114.907	96.418	0
150°	-129.904	75.000	0
160°	-140.954	51.303	0
170°	-147.721	26.047	0

- Modeling the Transmitter

In this part we just modeled the Transmitter. We determined the desired probability of detection, the maximum tolerable false-alarm probability, the number of pulses we want to send, and the required signal-to-noise ratio (SNR).

We want to determinate the required peak transmit power. For it, we assume that the transmitter gain has a 20 dB gain, the SNR is 5 dB and the target range is 150Km.

- Modeling Waveform Radiation and Collection

Use our element at the light speed for our operating frequency of 3.5GHz for the radiation, and we add the wave front which is a here a plane one.

- Modeling the Receiver

The gain of the receiver is 20 dB. We assume the noise at 2dB, the reference of temperature at 290°K.

- Modeling the Propagation Environment
- Implementing the Radar Model

In this part, we are generated for all our antennas the pulse, the propagation of the pulse to and from the target.

- Representation of the received signal

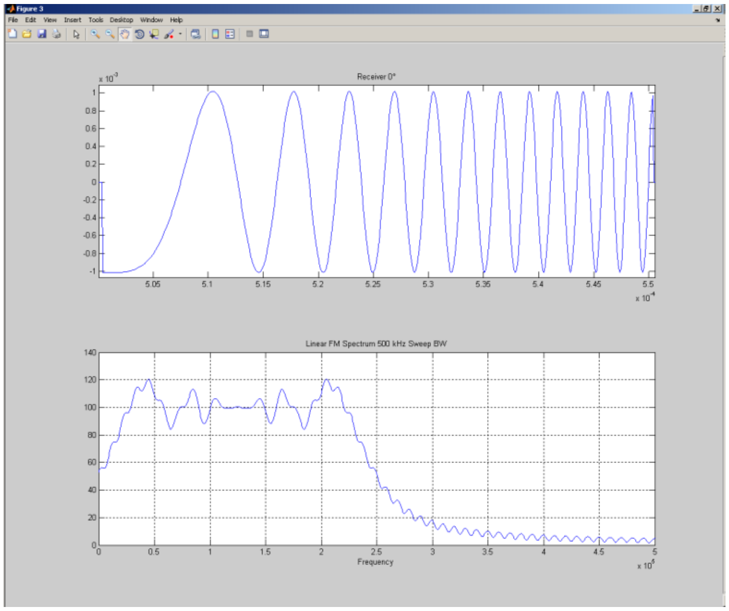


Figure 30: Received signal at the first receiver, 0°

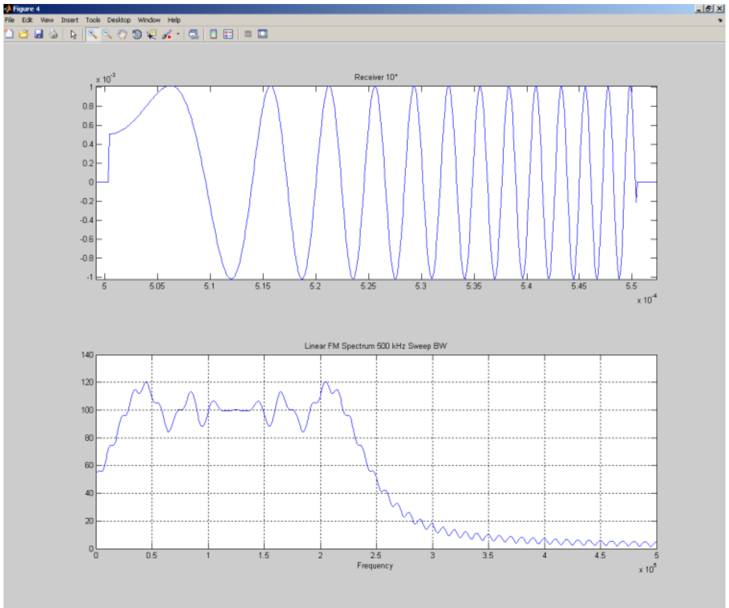


Figure 31: Received signal at the second receiver, 10°

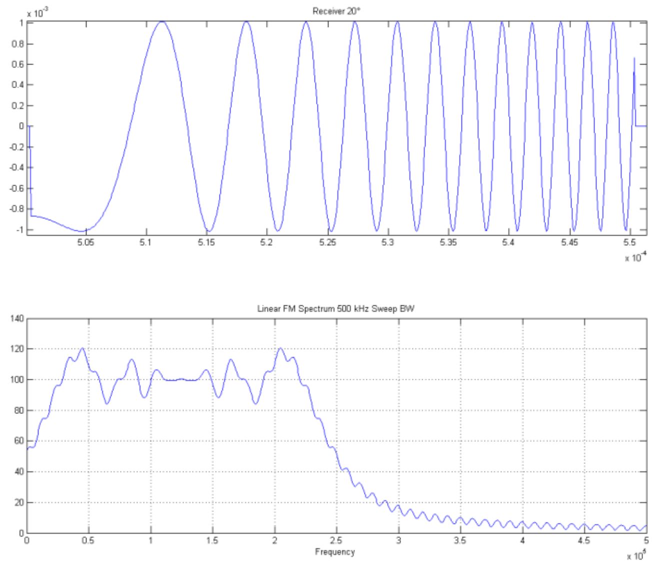


Figure 32: Received signal at the third receiver, 20°

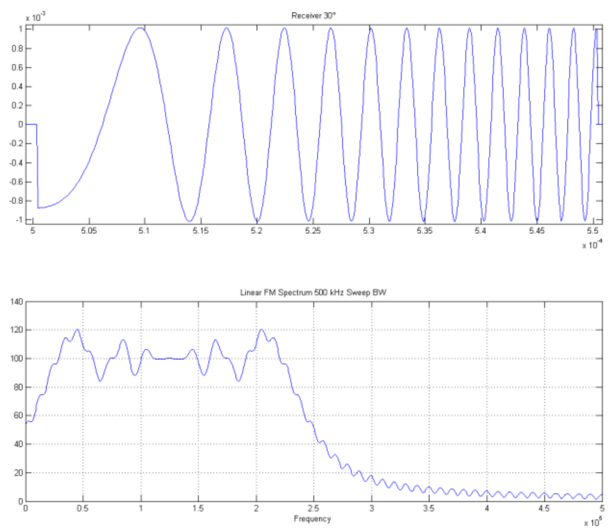


Figure 33 : Received signal at the forth receiver, 30°

I didn't put all of them, but we can see than the signal is always the same, but the phase changed, which what we wanted to note.

Those results show us the different reception of information in the space of an array antenna. When I finished this report, everything was not done. We still have some work to do for the paper. But it’s satisfying. We are able to represent in the space the reception in function of the pattern of an antenna.

VI. Conclusions

A. Work Conclusion

Working on this project was really interesting, and I obtained good results.

I modeled a radar workflow, and this one worked. I also modeled several types of antennas and patch antennas. The results I obtained show the signals received and transmitted by the radar workflow in the space. Every receivers got the signal emit by the transmitter with a different phase in function of the antenna used.

The paper was not finished when I finished my report. We need some more work on it to be able to write something good. For this reason, I don't have the final paper and results. I will get those before my presentation I hope. My next step will be to model the Spectrum.

B. Personal Conclusion

In conclusion of this report, I can tell that this internship was really interesting in a lot of ways.

Work experience in a foreign country is interesting; there is a time of adaptation. About the culture, the way of life, the language. Just for the dialect and for my English, it was a really good thing. It is also a really good experience of adaptation because when you arrive somewhere you don't know anything and everything is more complicated when you are not in your country, but in a way it is more interesting, because you discover a lot of new things. It is a good way to learn a lot about life, I think.

I could see that the work of a researcher is not an easy task, and that during my studies, I learned to learn. These six months were very interesting; I didn't know anything about research before I came here. So it was kind of complicated to know how that works. You always have to learn, always read about everything to be able to have all information to move on. The harder thing to know and learn is how to move on, and to what I have to move on to, and to be able to tell if the results are good or not.

I learned a lot about antennas and how conduct a project. But I don't think it was what I wanted to do in the future. I am more interested by field jobs and real team jobs.

It was a very good experience. I know that I want to learn all my life, and it is what our school teaches us during these 5 years.

VII. Glossary

Terms	Definition
CW	Continuous Wave
FMCW	The frequency modulated continuous wave
RCS	Radar cross section
SNR	Signal-to-noise ratio
RSEC	Radar Spectrum Engineering Critera
ITU	International Communication Union
WiMax	Worldwide Interoperability for Microwave Access
ITTC	Information & Telecommunication Technology Center
EECS	Electrical Engineering & Computer Sciences
WWII	World War two
UHF	Ultra High Frequency
GPS	Global Position System
VHF	Very high Frequency
HFSS	commercial finite element method solver for electromagnetic structures from Ansys Corporation
MatLab	« matrix laboratory », is a numerical computing environment and fourth-generation programming language, developed by MathWorks.

VIII. Sources

A. Papers

- *"60-GHz CPW-Fed Post-Supported Patch Antenna Using Micromachining Technology" • IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 15, NO. 10, OCTOBER 2005*
- *"Electromagnetic Theory of Reverberation Chambers"* by David A. Hill
- *"Phased Array Antenna Pattern Variation With Frequency and Implications for Radar Spectrum Measurement"* by Frank H. Sanders & Bradley J. Ramsey
- *"CHAPTER 4. MICROSTRIP PATCH ANTENNA DESIGN AND RESULTS"*
- "*The Basics of Patch Antennas"* by D. Orban and G.*J.K Moernaut*
- *"Design and Analysis of Slotted Waveguide Antenna Arrays"* by Phillip N. Richardson and Hung Yuet Yee

B. Books

- *"Advanced Engineering Electromagnetics"* by Constantine A. Balanis
- *"Antenna Theory third edition"* by Constantine A. Balanis

C. Websites

- Phased Array Antenna
- http://fr.wikipedia.org/wiki/Antenne_r%C3%A9seau_%C3%A0_commande_de_phase
- http://www.radartutorial.eu/06.antennas/an14.en.html
- Patch antenna
- http://en.wikipedia.org/wiki/Patch_antenna
- http://www.emtalk.com/mwt_mpa.htm
- Slot antenna
- http://www.antenna-theory.com/antennas/aperture/slot.php
- http://en.wikipedia.org/wiki/Slot_antenna
- http://packratvhf.com/Slot_Antenna/slot.html
- http://www.tpub.com/content/neets/14183/css/14183_163.htm
- Matlab
- http://www.mathworks.com/products/matlab/

IX. Annexes

Here you can find the Matlab code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%       Building The Basic Radar Workflow Model - Louis Parent
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


clear all
close all
clc

%% Waveform

fs = 1e7;
% hfmwav = phased.RectangularWaveform('OutputFormat','Pulses','SampleRate',fs,'PulseWidth',50e-
6,'PRF',1e4,'NumPulses',1);                % CW
hfmwav=phased.LinearFMWaveform('SweepBandwidth',5e5,'OutputFormat','Pulses','SampleRate',fs,'Pu
lseWidth',50e-6,'PRF',1e4,'NumPulses',1,'PRF',1000);
% % FMCW
wav=step(hfmwav); % Produce time domain samples for the waveform
% plot(hfmwav)

Wav_fft = fft(wav);
f_index = fs/2*linspace(0,1,length(wav));
figure(1)
subplot(2,1,1)
plot(hfmwav)
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on
```

%% Antenna

```
%hant = phased.IsotropicAntennaElement('FrequencyRange',[1e9 10e9])

% Array Scratch

%Physical Constants
freq = 3.5e9;       %Operating Frequency
lambda = physconst('lightspeed')/freq;

%Waveguide Info
fc=physconst('lightspeed')/(2*0.8565*2.54/100);

freespace_beta = 2*pi./lambda;
beta_z = freespace_beta.*sqrt(1-(fc./freq).^2);
lambda_g = 2*pi./beta_z;
slot_spacing = 2.34e-2;     %2.34cm

%Array Object
helement = phased.IsotropicAntennaElement('FrequencyRange',[0.5e9 12e9]);
harray = phased.ULA(32,slot_spacing,'Element',helement);

figure

plotResponse(harray,freq,physconst('lightspeed'),'Format','Polar')
```

%% Target Model

```
htgt=phased.RadarTarget('Model','Nonfluctuating','MeanRCS',0.5,'PropagationSpeed',physconst('lightsp
eed'),'OperatingFrequency',3.5e9)
```

%% Antenna and Target Platforms

```
    % Antenna location and velocity
htxplat = phased.Platform('InitialPosition',[0;0;0],'Velocity',[0;0;0],'OrientationAxes',[1 0 0;0 1 0;0 0 1])
    % Target location and velocity (put Receivers around the unique
    % Transmetter. same distance of the transmitter (150km) and 1
    % antenna every 10°)
htgtplat = phased.Platform('InitialPosition',[150000; 0000; 0],'Velocity',[0;0;0])
htgtplat10 = phased.Platform('InitialPosition',[147721; 26047; 0],'Velocity',[0;0;0])
htgtplat20 = phased.Platform('InitialPosition',[140954; 51303; 0],'Velocity',[0;0;0])
htgtplat30 = phased.Platform('InitialPosition',[129904; 75000; 0],'Velocity',[0;0;0])
htgtplat40 = phased.Platform('InitialPosition',[114907; 96418; 0],'Velocity',[0;0;0])
htgtplat50 = phased.Platform('InitialPosition',[96418; 114907; 0],'Velocity',[0;0;0])
htgtplat60 = phased.Platform('InitialPosition',[75000; 129904; 0],'Velocity',[0;0;0])
htgtplat70 = phased.Platform('InitialPosition',[51303; 140954; 0],'Velocity',[0;0;0])
htgtplat80 = phased.Platform('InitialPosition',[26047; 147721; 0],'Velocity',[0;0;0])
htgtplat90 = phased.Platform('InitialPosition',[000; 150000; 0],'Velocity',[0;0;0])
htgtplat100 = phased.Platform('InitialPosition',[-26047; 147721; 0],'Velocity',[0;0;0])
htgtplat110 = phased.Platform('InitialPosition',[-51303; 140954; 0],'Velocity',[0;0;0])
htgtplat120 = phased.Platform('InitialPosition',[-75000; 129904; 0],'Velocity',[0;0;0])
htgtplat130 = phased.Platform('InitialPosition',[-96418; 114907; 0],'Velocity',[0;0;0])
htgtplat140 = phased.Platform('InitialPosition',[-114907; 96418; 0],'Velocity',[0;0;0])
htgtplat150 = phased.Platform('InitialPosition',[-129904; 75000; 0],'Velocity',[0;0;0])
htgtplat160 = phased.Platform('InitialPosition',[-140954; 51303; 0],'Velocity',[0;0;0])
htgtplat170 = phased.Platform('InitialPosition',[-147721; 26047; 0],'Velocity',[0;0;0])
    % Use rangeangle to determine the range and angle between the antenna and the target.
[tgtrng,tgtang] = rangeangle(htgtplat.InitialPosition,htxplat.InitialPosition)
[tgtrng10,tgtang10] = rangeangle(htgtplat10.InitialPosition,htxplat.InitialPosition)
[tgtrng20,tgtang20] = rangeangle(htgtplat20.InitialPosition,htxplat.InitialPosition)
[tgtrng30,tgtang30] = rangeangle(htgtplat30.InitialPosition,htxplat.InitialPosition)
[tgtrng40,tgtang40] = rangeangle(htgtplat40.InitialPosition,htxplat.InitialPosition)
[tgtrng50,tgtang50] = rangeangle(htgtplat50.InitialPosition,htxplat.InitialPosition)
[tgtrng60,tgtang60] = rangeangle(htgtplat60.InitialPosition,htxplat.InitialPosition)
[tgtrng70,tgtang70] = rangeangle(htgtplat70.InitialPosition,htxplat.InitialPosition)
[tgtrng80,tgtang80] = rangeangle(htgtplat80.InitialPosition,htxplat.InitialPosition)
[tgtrng90,tgtang90] = rangeangle(htgtplat90.InitialPosition,htxplat.InitialPosition)
[tgtrng100,tgtang100] = rangeangle(htgtplat100.InitialPosition,htxplat.InitialPosition)
[tgtrng110,tgtang110] = rangeangle(htgtplat110.InitialPosition,htxplat.InitialPosition)
[tgtrng120,tgtang120] = rangeangle(htgtplat120.InitialPosition,htxplat.InitialPosition)
[tgtrng130,tgtang130] = rangeangle(htgtplat130.InitialPosition,htxplat.InitialPosition)
[tgtrng140,tgtang140] = rangeangle(htgtplat140.InitialPosition,htxplat.InitialPosition)
[tgtrng150,tgtang150] = rangeangle(htgtplat150.InitialPosition,htxplat.InitialPosition)
```

```
[tgtrng160,tgtang160] = rangeangle(htgtplat160.InitialPosition,htxplat.InitialPosition)
[tgtrng170,tgtang170] = rangeangle(htgtplat170.InitialPosition,htxplat.InitialPosition)
```

%% Modeling the Transmitter

```
Pd = 0.9;                  % desired probability of detection
Pfa = 1e-6;                % maximum tolerable false-alarm probability
numpulses = 10;            % nomber of pulses
SNR = albersheim(Pd,Pfa,10)    % required signal-to-noise ratio (SNR)


maxrange = 1.5e4;          % range up to 15kM
lambda = physconst('lightspeed')/3.5e9;       % Lambda
tau = hfmwav.PulseWidth;                 % Tau
Pt = radareqpow(lambda,maxrange,SNR,tau,'rcs',0.5,'Gain',20)      %required peak transmit power


htx=phased.Transmitter('PeakPower',50e3,'Gain',20,'LossFactor',0,'InUseOutputPort',true,'CoherentOnT
ransmit',true)
```

%% Modeling Waveform Radiation and Collection

```
hrad=phased.Radiator('Sensor',helement,'PropagationSpeed',physconst('lightspeed'),'OperatingFrequen
cy',3.5e9)
hcol=phased.Collector('Sensor',helement,'PropagationSpeed',physconst('lightspeed'),'Wavefront','Plane'
,'OperatingFrequency',3.5e9)
```

%% Modeling the Receiver

```
hrec=phased.ReceiverPreamp('Gain',20,'NoiseFigure',2,'ReferenceTemperature',290,'SampleRate',fs,'En
ableInputPort',true,'SeedSource','Property','Seed',1e3)
```

%% Modeling the Propagation Environment

```
hspace=phased.FreeSpace('PropagationSpeed',physconst('lightspeed'),'OperatingFrequency',3.5e9,'Two
WayPropagation',false,'SampleRate',fs)
```

%% Implementing the Basic Radar Model

```
    %% The following code prepares for the main simulation loop.
    % Time step between pulses
T = 1/hfmwav.PRF;
    % Get antenna position
txpos = htxplat.InitialPosition;
    % Allocate array for received echoes
rxsig = zeros(hfmwav.SampleRate*T,numpulses);
%
    %% You can execute the main simulation loop with the following code:

for n = 1:numpulses
    % Update the target position
 tgtpos = step(htgtplat,T);
 tgtpos10 = step(htgtplat10,T);
 tgtpos20 = step(htgtplat20,T);
 tgtpos30 = step(htgtplat30,T);
 tgtpos40 = step(htgtplat40,T);
 tgtpos50 = step(htgtplat50,T);
 tgtpos60 = step(htgtplat60,T);
 tgtpos70 = step(htgtplat70,T);
 tgtpos80 = step(htgtplat80,T);
 tgtpos90 = step(htgtplat90,T);
 tgtpos100 = step(htgtplat100,T);
 tgtpos110 = step(htgtplat110,T);
 tgtpos120 = step(htgtplat120,T);
 tgtpos130 = step(htgtplat130,T);
 tgtpos140 = step(htgtplat140,T);
 tgtpos150 = step(htgtplat150,T);
 tgtpos160 = step(htgtplat160,T);
 tgtpos170 = step(htgtplat170,T);
    % Get the range and angle to the target
 [tgtrng,tgtang] = rangeangle(tgtpos,txpos);
 [tgtrng10,tgtang10] = rangeangle(tgtpos10,txpos);
 [tgtrng20,tgtang20] = rangeangle(tgtpos20,txpos);
 [tgtrng30,tgtang30] = rangeangle(tgtpos30,txpos);
 [tgtrng40,tgtang40] = rangeangle(tgtpos40,txpos);
 [tgtrng50,tgtang50] = rangeangle(tgtpos50,txpos);
 [tgtrng60,tgtang60] = rangeangle(tgtpos60,txpos);
 [tgtrng70,tgtang70] = rangeangle(tgtpos70,txpos);
 [tgtrng80,tgtang80] = rangeangle(tgtpos80,txpos);
```

```
[tgtrng90,tgtang90] = rangeangle(tgtpos90,txpos);
[tgtrng100,tgtang100] = rangeangle(tgtpos100,txpos);
[tgtrng110,tgtang110] = rangeangle(tgtpos110,txpos);
[tgtrng120,tgtang120] = rangeangle(tgtpos120,txpos);
[tgtrng130,tgtang130] = rangeangle(tgtpos130,txpos);
[tgtrng140,tgtang140] = rangeangle(tgtpos140,txpos);
[tgtrng150,tgtang150] = rangeangle(tgtpos150,txpos);
[tgtrng160,tgtang160] = rangeangle(tgtpos160,txpos);
[tgtrng170,tgtang170] = rangeangle(tgtpos170,txpos);

    % Generate the pulse
sig = step(hfmwav);
    % Transmit the pulse. Output transmitter status
[sig,txstatus] = step(htx,sig);
    % Radiate the pulse toward the target
sig = step(hrad,sig,tgtang);
sig10 = step(hrad,sig,tgtang10);
sig20 = step(hrad,sig,tgtang20);
sig30 = step(hrad,sig,tgtang30);
sig40 = step(hrad,sig,tgtang40);
sig50 = step(hrad,sig,tgtang50);
sig60 = step(hrad,sig,tgtang60);
sig70 = step(hrad,sig,tgtang70);
sig80 = step(hrad,sig,tgtang80);
sig90 = step(hrad,sig,tgtang90);
sig100 = step(hrad,sig,tgtang100);
sig110 = step(hrad,sig,tgtang110);
sig120 = step(hrad,sig,tgtang120);
sig130 = step(hrad,sig,tgtang130);
sig140 = step(hrad,sig,tgtang140);
sig150 = step(hrad,sig,tgtang150);
sig160 = step(hrad,sig,tgtang160);
sig170 = step(hrad,sig,tgtang170);
    % Propagate the pulse to the target in free space
sig = step(hspace,sig,txpos,tgtpos);
sig10 = step(hspace,sig10,txpos,tgtpos10);
sig20 = step(hspace,sig20,txpos,tgtpos20);
sig30 = step(hspace,sig30,txpos,tgtpos30);
sig40 = step(hspace,sig40,txpos,tgtpos40);
sig50 = step(hspace,sig50,txpos,tgtpos50);
sig60 = step(hspace,sig60,txpos,tgtpos60);
sig70 = step(hspace,sig70,txpos,tgtpos70);
```

```
sig80 = step(hspace,sig80,txpos,tgtpos80);
sig90 = step(hspace,sig90,txpos,tgtpos90);
sig100 = step(hspace,sig100,txpos,tgtpos100);
sig110 = step(hspace,sig110,txpos,tgtpos110);
sig120 = step(hspace,sig120,txpos,tgtpos120);
sig130 = step(hspace,sig130,txpos,tgtpos130);
sig140 = step(hspace,sig140,txpos,tgtpos140);
sig150 = step(hspace,sig150,txpos,tgtpos150);
sig160 = step(hspace,sig160,txpos,tgtpos160);
sig170 = step(hspace,sig170,txpos,tgtpos170);
    % Collect the echo from the incident angle at the antenna
sig = step(hcol,sig,tgtang);
sig10 = step(hcol,sig10,tgtang10);
sig20 = step(hcol,sig20,tgtang20);
sig30 = step(hcol,sig30,tgtang30);
sig40 = step(hcol,sig40,tgtang40);
sig50 = step(hcol,sig50,tgtang50);
sig60 = step(hcol,sig60,tgtang60);
sig70 = step(hcol,sig70,tgtang70);
sig80 = step(hcol,sig80,tgtang80);
sig90 = step(hcol,sig90,tgtang90);
sig100 = step(hcol,sig100,tgtang100);
sig110 = step(hcol,sig110,tgtang110);
sig120 = step(hcol,sig120,tgtang120);
sig130 = step(hcol,sig130,tgtang130);
sig140 = step(hcol,sig140,tgtang140);
sig150 = step(hcol,sig150,tgtang150);
sig160 = step(hcol,sig160,tgtang160);
sig170 = step(hcol,sig160,tgtang160);
    % Receive the echo at the antenna when not transmitting
rxsig(:,n) = step(hrec,sig,~txstatus);
rxsig10(:,n) = step(hrec,sig10,~txstatus);
rxsig20(:,n) = step(hrec,sig20,~txstatus);
rxsig30(:,n) = step(hrec,sig30,~txstatus);
rxsig40(:,n) = step(hrec,sig40,~txstatus);
rxsig50(:,n) = step(hrec,sig50,~txstatus);
rxsig60(:,n) = step(hrec,sig60,~txstatus);
rxsig70(:,n) = step(hrec,sig70,~txstatus);
rxsig80(:,n) = step(hrec,sig80,~txstatus);
rxsig90(:,n) = step(hrec,sig90,~txstatus);
rxsig100(:,n) = step(hrec,sig100,~txstatus);
rxsig110(:,n) = step(hrec,sig110,~txstatus);
```

```
 rxsig120(:,n) = step(hrec,sig120,~txstatus);
 rxsig130(:,n) = step(hrec,sig130,~txstatus);
 rxsig140(:,n) = step(hrec,sig140,~txstatus);
 rxsig150(:,n) = step(hrec,sig150,~txstatus);
 rxsig160(:,n) = step(hrec,sig160,~txstatus);
 rxsig170(:,n) = step(hrec,sig170,~txstatus);
end

%% Representation of the received signal on each antenna

t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig(:,1)))
title('Receiver 0°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig10(:,1)))
title('Receiver 10°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on
```

```
t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig20(:,1)))
title('Receiver 20°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on



t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig30(:,1)))
title('Receiver 30°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig40(:,1)))
title('Receiver 40°')
subplot(2,1,2)
```

```
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig50(:,1)))
title('Receiver 50°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig60(:,1)))
title('Receiver 60°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
```

```
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig70(:,1)))
title('Receiver 70°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on



t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig80(:,1)))
title('Receiver 80°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on



t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig90(:,1)))
title('Receiver 90°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
```

```
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig100(:,1)))
title('Receiver 90°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on



t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig110(:,1)))
title('Receiver 90°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
```

```
figure
subplot(2,1,1)
plot(x,real(rxsig120(:,1)))
title('Receiver 90°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig130(:,1)))
title('Receiver 90°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig140(:,1)))
title('Receiver 90°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on
```

```
t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig150(:,1)))
title('Receiver 90°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig160(:,1)))
title('Receiver 90°')
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on


t = unigrid(0,1/hrec.SampleRate,T,'[)');
rangegates = (physconst('lightspeed')*t)/2;
x = linspace(0,T,10000);
ylim = get(gca,'YLim');
figure
subplot(2,1,1)
plot(x,real(rxsig170(:,1)))
title('Receiver 90°')
```

```
subplot(2,1,2)
plot(f_index,abs(Wav_fft))
xlim([0,5e5])
xlabel('Frequency')
title('Linear FM Spectrum 500 kHz Sweep BW')
grid on
```