GNSS PATCH ANTENNA MODELING PASSIVE GAIN OPTIMIZATION USING FEKO, DESIGN OF EXPERIMENTS AND P-TRANSFORM TECHNIQUE

by

GHOLAM D. AGHASHIRIN

A dissertation submitted in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY IN ELECTRICAL AND COMPUTER ENGINEERING

2021

Oakland University
Rochester, Michigan

Doctoral Advisory Committee:

Hoda S. Abdel-Aty-Zohdy, Ph.D., Chair
Mohamed A. Zohdy, Ph.D.
Maged Kafafy, Ph.D.
Adam Timmons Ph.D.
Darrell Schmidt, Ph.D.

For My Mother and Father

ABSTRACT

GNSS PATCH ANTENNA MODELING PASSIVE GAIN OPTIMIZATION USING FEKO, DESIGN OF EXPERIMENTS AND P-TRANSFORM TECHNIQUE

by

GHOLAM D. AGHASHIRIN

Adviser: Hoda S. Abdel-Aty-Zohdy, Ph.D.

The objective of this work was to design a compact new microstrip patch antenna for applications in support of Global Navigation Satellite System (GNSS), and automotive. My GNSS patch antenna was created and developed in this dissertation to serve and represent the critical component from the system level perspective for the next generation of Automotive Radio Head Units, Navigation Systems, and L3 systems HD maps in autonomous domain. Conducted literature review and published papers studied, however observed a **deficiency in the area of modeling, optimization of the design parameters, passive gain of rectangular patch antenna using FEKO, Design of Experiments, and P-Transform algorithm. Furthermore**, **there is no such antenna related to the Center Frequency of 1.555 [GHz] GNSS antenna, which has not been investigated.** The proposed work involved a modeling of New GNSS rectangular patch antenna. The design focus was on the operating frequency range of 1.500 [GHz] to 1.610 [GHz] and FEKO 3D Electromagnetic simulation software package from Altair [4] was used, Design of Experiments (DoE) [5], and as well as applying the P-Transform algorithm [6] optimization method on the presented dual band GNSS (GPS and GLONASS) patch antenna passive

gain. The proposed antenna designed to operate at both bands, GPS (L1=1.57542 [GHz]) and GLONASS (L1=1.602 [GHz]) signal. Moreover, the ground plane length (X1[mm]), ground plane width (X2[mm]), and the substrate dielectric constant design (X3[mm]) parameters were varied at each FEKO simulation run, in order to obtain the simulation of GNSS patch antenna passive gain output results for the purpose of the optimization study by using P-Transform technique within the MATLAB environment. The presented GNSS patch antenna 2D far field and/or average passive gain measurement of GPS and GLONASS at center frequency of 1.555 [GHz] was plotted and analyzed. The computation and analysis of passive gain involved at taking the delta/difference between elevation angle at 30 and 90 degrees from the average passive gain 2D graph and this step was conducted for 120 FEKO simulation iteration runs. For each FEKO simulation run the far field (average passive gain=Y [dBi]) was computed separately unique for that specific design parameters (X1 [mm], X2 [mm], X3 [mm]) and recorded in a lookup matrix table (.csv). This four columns lookup table was called out for the purposed of the P- Transform algorithm utilization and execution within the MATLAB environment.

PREFACE

The objective of this engineering research is to design, model, conduct analysis, simulate, and create a sample of runs (Lookup matrix) called the Design of Experiments. This process reduces the number of required simulation iteration test runs, determines the GNSS (GPS and GLONASS) patch antenna average passive gain, and utilizes the P-Transformation optimization methodology for the purpose of achieving robust and optimal Rectangular Microstrip GNSS patch antenna design parameters and passive gain. This work is divided into a number of chapters.

1. In chapter one an Introduction section is presented, which includes following topics:
2. Background research work information, applicability, advantages, antenna experimental measurements and problem statement in support of GNSS (GPS and GLONASS) patch antenna
3. Antenna definition, types, basic characteristics including radiation zones, transmit and receive site instrucmentations
4. Patch antenna structure configuration and design equations
5. Model of Design of Experiments method in general
6. P-Transformation objective function (passive gain) 2D cartesian plot

   A. Chapter two highlights the presented GNSS patch antenna design, modeling, and simulation material coupled with items below:

      1. FEKO model creation of the GNSS patch antenna
      2. GNSS patch antenna requirements specification design parameters

3. GNSS patch antenna meshing and dielectric loss tangent for porcelain substrate material parameters definition within the CADFEKO environment
4. GNSS patch antenna 2D and 3D model simulation and solution, far field/passive gain results within the CADFEKO and POSTFEKO space

B. Chapter three discusses the Design of Experiments (DoE) as an optimization methodology tool that can be utilized in an electromagnetic problem involving components and systems, such as passive patch antenna, Radio Frequency Identification (RFID) antenna, SAE L2 Advanced Driver Assistance Systems (ADAS) and L3 Automated Driving (AD) Systems. Design of Experiments mathematical model equations in terms of antenna input parameters and output response relationship are summarized here and furthermore, Design of Experiments advantages are outlined and covered in this chapter

C. In chapter four I elaborated on the P-Transformation technique, analysis details, where the algorithm implementation steps are described, which can be used to find the global minimum of an objective function. The FEKO simulation runs, steps involved in the GNSS (GPS and GLONASS) patch antenna passive gain optimization steps and the P-transformation method block diagram flowchart representation walkthrough details are provided here

D. In chapter five, I present our conclusion and future research work related to the GNSS patch antenna passive gain optimization problem solution for the following:

1. Automotive patch antenna component and OEM vehicle level system requirements specification
2. Core Verification and Validation testing location sites, which can be conducted in an Anechoic Chamber and/or an Antenna Range for the purpose of conducting a domestic and non-domestic OEMs and non-OEMs component and vehicle level antenna assessment and solution needs

ACKNOWLEDGMENTS

I would like to thank Professor Hoda S. Abdel-Aty-Zohdy for providing me with the advice and guidance to complete this work. I would also like to thank Professor Mohamed A. Zohdy and engineer Dr. Maged Kafafy for introducing me to the P-Transform technique. I would like to thank Professor Adam Timmons and Professor Darrell Schmidt for providing me with additional guidance. Lastly, I would like to thank all my committee members for agreeing to be on my dissertation committee.

Gholam D. Aghashirin

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

GPS	Global Positioning System (United States)
GLONASS	Global Navigation Satellite System (Began in Russian)
GNSS	Global Navigation Satellite System
ODD	Operational Design Domain (Of the Automated Driving System)
HD	High Definition (Maps)
DoE	Design of Experiments
RFID	Radio Frequency Identification
ADAS	Advanced Driver Assistance Systems
AD	Automated Driving
CDMA	Code Division Multiple Access
FEKO	"Feldberechnung für körper mit beliebiger oberfläche" (German), which indicates "field calculations involving bodies of arbitrary shape". FEKO stands for “Federation of English Karate Organization”
RHCP	Right Hand Circularly Polarized
TEM	Transverse Electromagnetic
FAA	Federal Aviation Administration
LAAS	Local Area Augmentation System
WAAS	Wide Area Augmentation System
NAVIC	Navigation with Indian Constellation
QZSS	Quasi-Zenith Satellite System
dGPS	Differential Global Positioning System

E	Electric Field Vector
H	Magnetic Field Vector
Tx	Transmit
Rx	Receive
AUT	Antenna Under Test
GNP	An Antenna Ground Plane
VNA	Vector Network Analyzer
OTA	Over-The-Air
E2E	End 2 End
SDARS	Satellite Digital Audio Radio Service
DC	Direct Configuration

LIST OF PUBLICATION FROM THIS WORK

1). Journal Paper

a) Journal Paper: "MODELING AND DESIGNED OF A MONOPOLE ANTENNA THAT OPERATE AT 3.3 [GHz] FOR FUTURE 5G sub 6 [GHz]," by Gholzam D. Aghashirin, Maged Kafafy, Hoda Abdel-Aty-Zohdy, Mohamed Zohdy, and Adam Timmons; International Journal of Engineering and Advanced Technology (IJEAT), ISSN:2249-8958, Vol.-10, Issue-5, pp.338-346, June 2021

b) Journal Paper: "EVALUATION OF (GPS/GLONASS) PATCH VERSUS RF GPS (L1) PATCH ANTENNA PERFORMANCE PARAMETER," by Gholam Aghashirin, Hoda S. Abdel-Aty-Zohdy, Mohamed A. Zohdy, Darrell Schmidt, and Adam Timmons; Journal of Computer Science, Engineering and Applications (IJCSEA), DOI: 10.5121/ijcsea.2020.10401, Vol.10, No.4, pp.1-17, August 2020

2). Conference Paper

a) A Conference Paper Title: "GNSS PATCH ANTENNA DESIGN PARAMETER OPTIMIZATION USING FEKO, DESIGN OF EXPERIMENTS & P-TRANSFORM TECHNIQUE," by Gholam D Aghashirin, Maged Kafafy, Hoda S. Abdel-Aty-Zohdy, Mohamed A. Zohdy, and Adam Timmons; International Conference on Advances in Electrical, Computing, Communications, and Sustainable (IEEE ICAECT 2021), Shri Shankaracharya Group of Institutions, SSTC, Bhilai, Chhattisgarh, India, pp.707-715, February 2021.

b) Conference Paper: “COMPARISON OF GNSS PATCH VERSUS GPS LI PATCH ANTENNA PERFORMANCE CHARACTERISTIC,” by Gholam Aghashirin, Hoda S. Abdel Aty-Zohdy, Mohamed A. Zohdy, Darrell Schmidt, and AdamTimmons; International Conference on Advanced Information Technologies and Applications (ICAITA 2020), 2020: ISBN: 978-1-92593-23-7, (CS & IT), Volume 10: Number 09, pp.1-12, July 2020

CHAPTER ONE

INTRODUCTION AND ENGINEERING RESEARCH WORK

1.1 Background

GNSS (GPS and GLONASS) patch antennas have a lot of applications, they are used across multiple areas of scientific and engineering disciplines, and they play a significant role in wireless communication systems or code-division multiple access (CDMA) systems, such as the Global Positioning System (GPS), in automobiles involving Radio Head Units, Navigation Systems, ADAS L2 and Automated Driving L3 systems, precise positioning, and mobile phones. Table 1.1, Table 1.2 and Figure 1.1 below illustrate further relevant applicability and applications, advantages, and a common example of our GNSS patch antenna. Because of its low profile and effective cost, it is considered a better antenna solution choice in a wide variety of applications. We investigated and presented our patch antenna geometry and structure design. Model creation and passive gain results were obtained from FEKO tools followed by the usage and implementation of the P-Transform method within the MATLAB software package, in order to optimize the proposed GNSS patch antenna design parameters, such as the Ground plane length, Ground plane width, and the Dielectric Constant of the substrate material as well as the Passive Gain. Next, analysis and evaluation were performed on the generated Passive Gains so that a conclusion could be drawn on the antenna solution.

Chichinadze [8] has shown that the optimization problems can be solved by using an objective function and this can be demonstrated by using the generic algorithm such as the Ψ -Transformation method. While on the other hand, Kafafy [6] has proposed the improved

P-Transformation algorithm, which can be utilized to solve global optimization problems and its application can be extended to cover both probabilistic and deterministic problems. Furthermore, [6] demonstrated that their improved P-Transformation is an efficient technique for global optimization algorithm as a universal heuristic optimization methodology. Moreover, Zohdy [10] covered a new robust and optimal global non-sequential search technique for an optimization in n-dimensions by using a stochastic approach. Adamczyk [9] presented the P-Transformation algorithm as an efficient method in finding the global maximum of an objective function. Nguyen [28] highlighted that microstrip patch antennas are used in a lot of applications because of their low profiles, light weight, and low cost. The patch antenna ground plane is one of the most significant parts of the antenna because if effects many of antenna characteristics, such as Gain, Bandwidth, and Radiation Pattern.

1.1.2 Applicability and Advantages of GNSS (GPS and GLONASS) Patch Antenna

Table 1.1GNSS patch antenna applicability matrix

	Applicability
GNSS (GPS and GLONASS) Patch Antenna	End-product printed circuit board and on top of a GPS receiver
	GLONASS and SDARS
	Automotive space (audio and telematics and HD onboard maps)
	Space and communication systems (aircraft, spacecraft, satellite communication systems, and internet of space)
	X-band (radar: weather monitoring, air traffic control and wireless computer network)
	L-band (1 [GHz] to 2 [GHz])-GPS units, satellite navigation and phones, amateur radio, digital audio/video/multimedia broadcasting, and astronomy)
	Digital television, RFID, and mobile handheld devices
	Flexible wearable watches and electronic systems (wearable cameras and medical devices)

Figure 1.1: Picture of patch antenna common illustration [128]

Table 1.2 GPS patch antenna advantages matrix

	Advantages
GPS Patch Antenna	Wide band operation over the GPS system Automotive production and quality approved Allows best in class Right Hand Circularly Polarized (RHCP) in support of GPS signals and ‘in order to be compatible with the Propagated GPS Signals’ [134] GPS Patch has excellent ability in mitigating, reducing or even eliminating common error such as multi-Path signal/effects in ground system facility, such as a Local Area Augmentation System (LAAS) GPS Patch provides good signal to noise (S/N) carrier ratio in relation to other types of antennas targeting GPS Per [134], ‘Patch Antennas offer small, low profile, easy to mount PCB Solutions; for systems requiring a flat of Compact Antenna’ According to [134], GPS Patch ‘include narrow bandwidth and high gain, to further improve system Performance’ GPS Patch allows for extremely high Desire and Undesired (D/U) ratio of up to 35 degrees in elevation angle GPS Patch is easy to fabricate, low cost, less size, and easy to feed coaxial cable According [1], ‘These antennas are low-profile, conformable to planar and nonplanar surfaces, simple and inexpensive to manufacture using modern printed-circuited technology, mechanically robust when mounted on rigid surfaces

1.2 Antenna Experimental Measurements

The Global Positioning System (GPS) is a worldwide passive radio navigation system that consists of three segments, namely the Space Component, User Component, and Control Segment. The GPS architecture has been developed, managed, and maintained by USA Air Force /Department of Defense. I conducted experimental measurements at the OU RF local lab to show the need for robust and optimum Patch Antenna design. The GPS passive antenna characteristics, sensitivity, and tolerances have not been studied and/or investigated intensively in the empirical literature. In addition to the characteristics and performance parameters measurements in the presence of

background noise, simulation studies were performed to evaluate the advantages, reduction in size, low/competitive cost, fewer components, better response to RF signals, and undesired sources that are received from external interference/multipath, as well as the stability of the proposed GPS passive antenna. The simulation studies were all conducted using the FEKO simulation software package.

The antenna experimental measurements were performed on the GPS passive antenna that operates at frequency range of 15724 [MHz] to 15784 [MHz] with Voltage Standing Wave Ratio (VSWR) 1.5:1. The presented GPS passive antenna has a very simple, low profile, single passive element structure and design, along with a directionally optimized radiation pattern, Right Hand Circularly Polarized (RHCP), which makes it very suitable for automotive applications. This single element GPS passive antenna had the following mechanical dimensions/sizes: Length of l= 1.694 in (43.03 [mm]), width of w=1.3 in ([33.02 [mm]), height of h= 0.552 in (14.02 [mm]). The GPS passive antenna under evaluation and study had a gain of 7.5 [dBi] with excellent stability on the GPS system. The characteristics of the patch antenna was experimentally measured and evaluated by performing a directional change and position of the test GPS passive antenna at various heights, horizontal distances, elevation rotation angles, and different polarizations between the transmitted and received GPS passive antenna. A very good agreement between the measured device characteristics verses the standard manufacturer specified parameters and data sheets was observed.

1.3 GPS Passive Antenna Test and Measurements

Transmit and Receive Test Instrumentations Used in the Antenna Measurements

The OU RF lab was used to setup the test equipment and conduct the engineering measurements. The antenna measurement equipment/setup used for recording the receiving power included the following:

1. Antenna OU RF lab room
2. Two insulator cardboard box items
3. Vector signal generator 9 [kHz]-3 [GHz]
4. Signal/spectrum analyzer 10[Hz]-13.6 [GHz]
5. Two GPS passive antennas with 4 feet of RF cable length with an N male termination

I set up the parameters necessary for the test and measurement. Parameters such as start, center, and stop frequency were coupled with a corresponding signal amplitude of the Agilent Technologies EXG Vector Signal Generator on the transmitting end and EXA Signal Analyzer.

Transmit and Receive Antenna Power Measurement Procedure

A vector function generator was used to generate the test signals at three different frequencies, namely start frequency (fstart=1.5724 [GHz]), center frequency (fcenter=1.5754 [GHz]), and stop frequency (fstop=1.5784 [GHz]), coupled with various RF signal amplitudes ranging from 1 [mV] to 100 [mV] in steps of 10 [mV] increments, and a patch passive antenna was utilized to launch and produce test signals into free space in the straight propagation path forward to receive the patch passive antenna. The space between the transmitted and received GPS passive antenna was set to 5*lambda=100 [cm] apart from each other. The Agilent Technologies EXA Signal Analyzer was used to perform the received signal power measurements at different antenna position/rotation angles. The steps are outline below:

1. Mount the transmit and receive GPS passive antennas on to insulating boxes with no obstructing objects between them
2. Connect the transmitting antenna N male termination from the RF cable end to the RF output port of Agilent Technologies EXG Vector Function Generator plus set the RF sinusoidal waveform frequency coupled with its corresponding signal amplitude
3. Next, connect the receive test antenna N male termination to the RF input port of Agilent Technologies EXA Signal Analyzer
4. Activate the power measurements on the Signal Analyzer
5. Set the desired frequency of interest on the Spectrum Analyzer that needs to be tuned
6. Perform the received power measurement by first placing the receive GPS passive antenna at the flat (0 degrees) position and then repeat this procedure for other antenna orientations, such as 45 degrees, perpendicular (90 degrees) and lastly 180 degrees

To be more specific, the radiated RF Electromagnetic energy and/or power from the transmit GPS passive antenna was successfully captured and the observation/the receive signal value by the received antenna was simply recorded

.

Figure 1.2: Photograph of transmit and receive mode instrumentation hardware antenna characteristic measurement setup

GPS Passive Patch Antenna

- Flat Position (0 degrees)

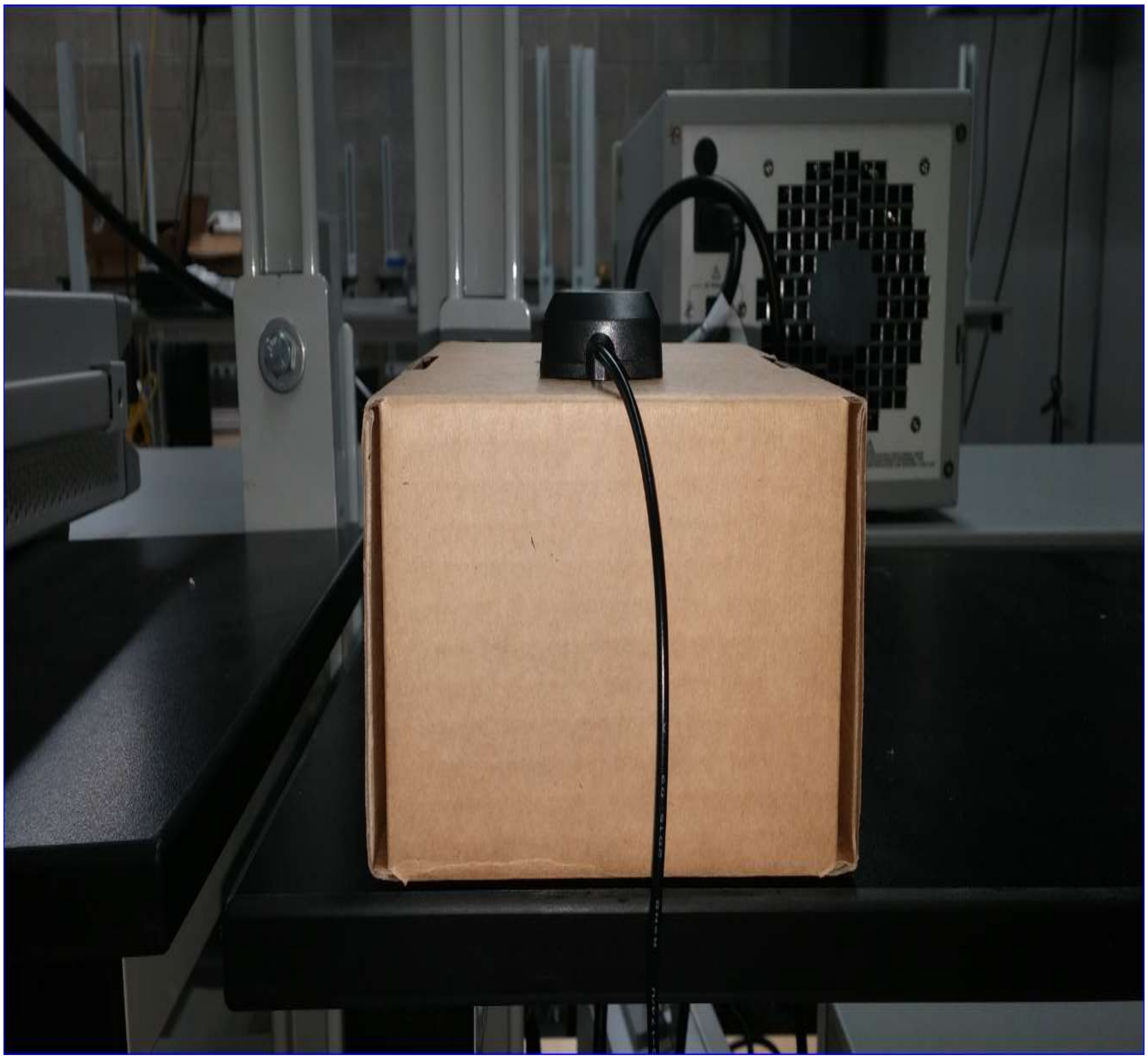


Figure 1.3: GPS patch antenna set up position flat view

- Elevate (45 degrees)

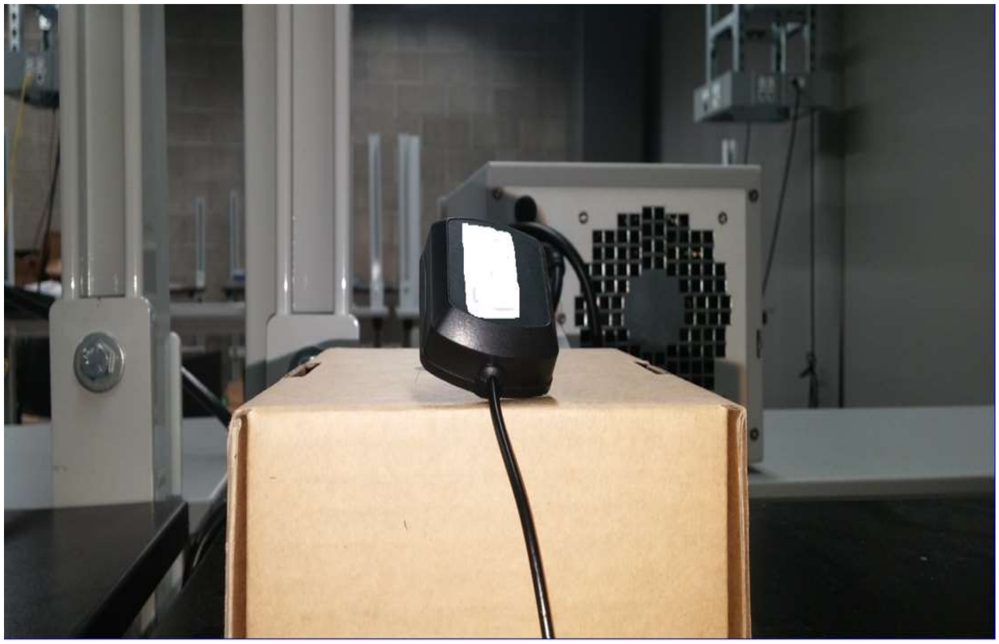


Figure 1.4: GPS patch antenna set up position 45 degrees view

- Elevate (90 degrees)

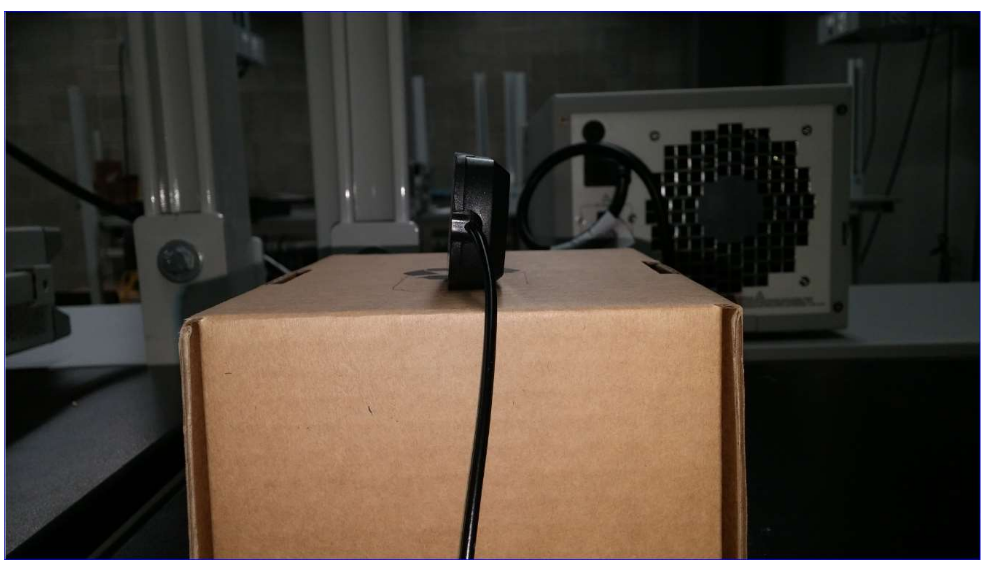


Figure 1.5: GPS patch antenna set up position 90 degrees view

- Elevate (180 degrees)

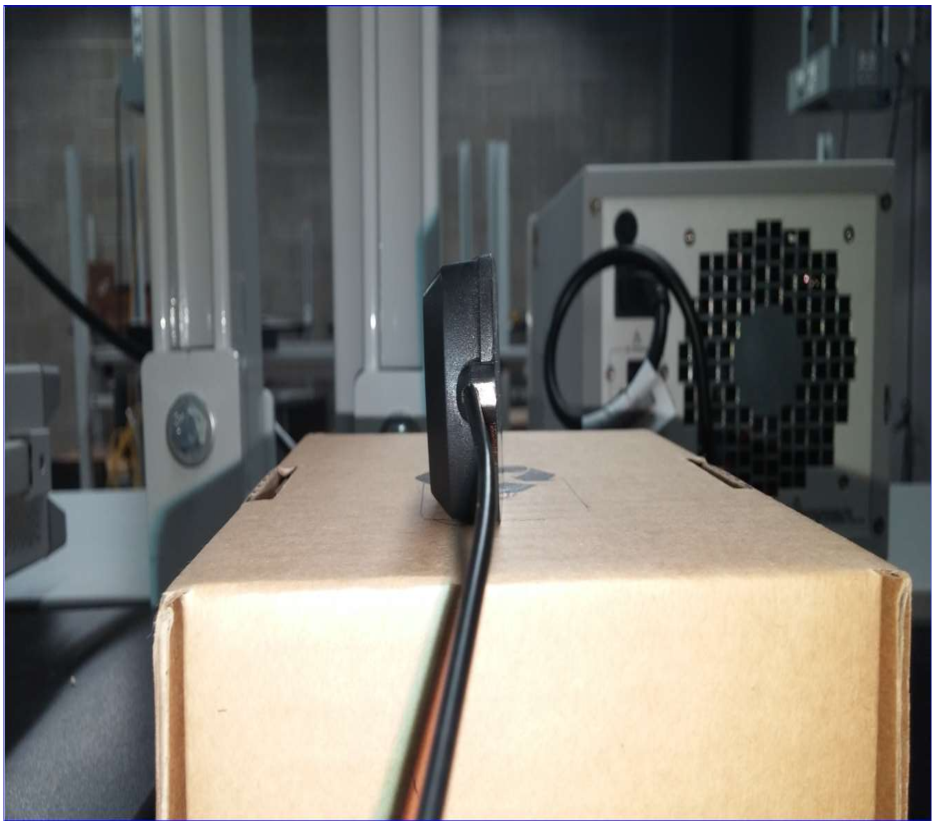


Figure 1.6: GPS patch antenna set up position 180 degrees view

Table 1.3 GPS passive patch antenna receive power preliminary measurements data matrix results

Received Signal Power [dBm] at Various Antenna Position							
Receiver Antenna	**Transmit RF Signal Amplitude [mv]**	**Center Frequency [MHz]**	**Spacing Distance between Transmit and Received Antenna [cm]**	**Flat (0 degrees)**	**Elevate (45 degrees)**	**Perpendicular (90 degrees)**	**Rotate/Flip (180 degrees)**
	1			-76	-73	-75	-77
	10			-72	-74	-71	-75
GPS Passive Patch	20	1575.4	100	-70	-71	-75	-76
	30			-68	-71	-69	-73
	40			-62	-67	-68	-72
	50			-60	-66	-59	-64
	60			-59	-65	-55	-63
	70			-57	-65	-55	-64
	80			-59	-64	-58	-60
	90			-60	-63	-58	-61
	100			-58	-60	-54	-58

Figure 1.7: Photograph of generated RF sinusoidal wave at the RF output port of Agilent Technologies EXG Vector Function Generator 9 [kHz]-3 [GHz], signal center frequency =1.5754 [GHz], and signal amplitude= 100 [mV]

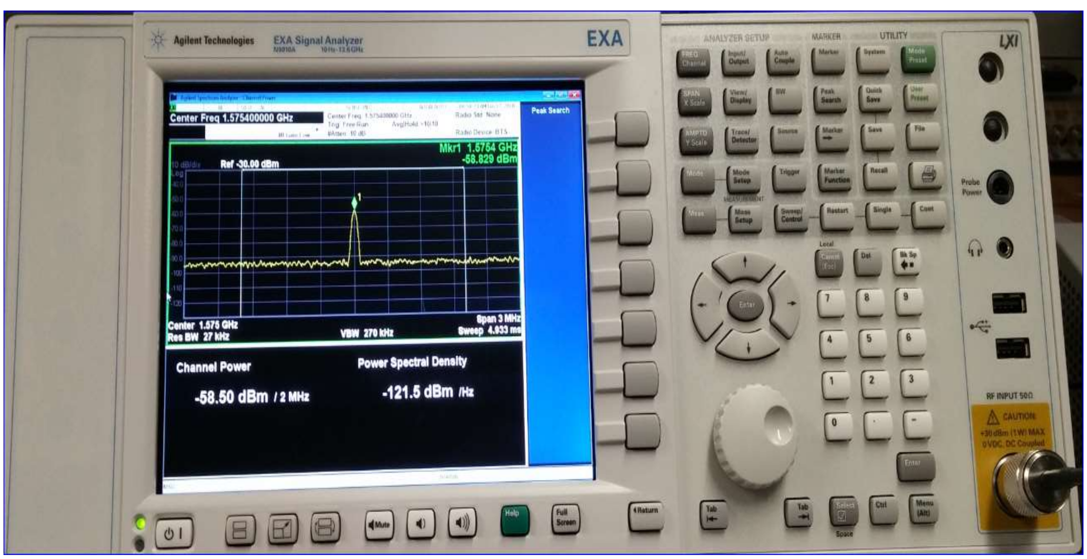


Figure 1.8: Photograph of received signal power at the RF input port of Agilent Technologies EXA Signal Analyzer 10 [Hz]-13.6 [GHz]

1.4 Question-Problem Statement

How to obtain optimized **Design Parameters** and **Passive Gain** in a NEW **Rectangular** GNSS (GPS and GLONASS) Patch Antenna?

1.5 Dissertation Architecture Overview and Engineering Tools

In this research work, our GNSS (GPS & GLONASS) patch antenna with a Resonate Frequency of 1.500 [GHz] and a Lambda (λ) equal to 193 [mm] is investigated, designed, modelled, simulated, and explored using FEKO.

The focuses in Chapter 1 are each of the following topics:

1. Background
2. Applicability and Advantages of GNSS (GPS and GLONASS) Patch Antenna
3. Antenna Experimental Measurements
4. GPS Passive Antenna Test and Measurements
5. Question-Problem Statement
6. Dissertation Architecture Overview and Engineering Tools
7. GNSS (GPS and GLONASS) Satellite Constellation
8. Antenna and Their Types
9. Antenna Definition
10. Antenna Types
11. Basic Antenna Characteristics, Analysis Planes & Radiation Zones
12. Basic Antenna Characteristics
13. Antenna Analysis Plane
14. Antenna Radiation Zones
15. Antenna Experimental Measurements

16. Transmitter Site Instrumentations
17. Receiver Site Equipment
18. Block Diagram Representation of Transmit and Receive Site of Basic Parameter of Antenna Measurements
19. Basic Performance Parameters of Antenna Measurements
20. GPS Passive Patch Antenna Received Signal Power Experimental Measurements Results
21. Patch Antenna Geometry and Design Equations
22. GNSS Patch Antenna Research Focus
23. Model of Design of Experiments Method in General
24. P-Transform, Objective Function 2D Plot

Chapter 2 demonstrates:

1. FEKO Model Creation of the GNSS Patch Antenna
2. GNSS Patch Antenna Design Parameters
3. Meshing and Simulation Parameters within FEKO
4. GNSS Patch Antenna 3D Model within FEKO
5. FEKO Simulated Far Field of GNSS Patch Antenna

Chapter 3 presents the:

1. Design of Experiments Advantages
2. Design of Experiments Mathematical Model Equation

Chapter 4 is devoted to:

1. P-Transform Analysis Details
2. P-Transform Algorithm Implementation Steps

3. FEKO Simulation Combination Run and P-Transform Results in the Experiment
4. P-Transform Technique Optimization Process and Block Diagram Representation

In Chapter 5, conclusions are drawn for our proposed GNSS patch antenna Design Parameters and Passive Gain optimization antenna solution and future research work has been covered.

1.6 GNSS (GPS and GLONASS) Satellite Constellation

Global satellite systems consist of each of the following constellations:

1. Global Positioning System (GPS), which is developed and managed by the United States government. It is mainly made of 33 satellites in 6 orbital planes at a height of 20,180 [km]. GPS constellation systems provides navigation signals, L1, L2, and L5. GPS satellite systems broadcast navigation signals and frequency, L1 centered at 1.575 [GHz], L2 centered at 1.227 [GHz], each with an initial signal bandwidth of 20 [MHz] and it can be expended up to 24 [MHz], and L5 band centered at 1.176 [GHz] with a bandwidth of 20 [MHz]. Some of GPS systems applications include transportations, shipping, railways, aviation, Satellite Based Augmentation System (SBAS), Federal Aviation administration (FAA) Local Area Augmentation System (LASS), and Wide Area Augmentation System (WAAS) where 3-dimensional positioning, and precision navigation is necessary and vital
2. Galileo and Russia GLONASS Satellites Constellation Systems developed by Europe
3. BeiDou (Compass) is a Chinese Satellite Navigation System that provides limited coverage in terms of navigation services to China and some neighboring countries
4. NAVIC stands for Navigation with Indian Constellation, and it was developed by India and supplies a regional satellite coverage

5. QZSS is an abbreviation for Quasi Zenith Satellite System was developed by Japanese government, and it provides a regional satellite system coverage

a. In Wireless Communication Systems (Analog, Digital, Computer and Optical) or Code Division Multiple Access (CDMA), such as Global Position System and GLONASS satellite constellation requires antennas for launching or receiving GPS signals with a frequency centered at L1 (1.57542 [GHz]) and GLONASS signals with a frequency centered at L1 (1.602 [GHz]) in free space. It is deemed necessary to utilize an antenna component that allows optimum coverage and constant gain over its service area while at the same time suppressing undesired electromagnetic wave fronts, multipath signals, or interfering signals impinging on its input terminals.

GPS signals are Right Hand Circularly Polarize (RHCP) and they are arriving at an antenna on earth from GPS constellation satellite system is a planar Transverse Electromagnetic (TEM) wave, which means that the Electric and Magnetic field vectors are everywhere perpendicular to each other and orthogonal to the direction of wave propagation. The incoming GPS and GLONASS signals into the GNSS input antenna terminals is a composite signal that consists of two components:

1. Direct signals from GNSS satellite system
2. Multipath signals that originate from ground plane, reflective surfaces, buildings, and solid structures; it is a combination of data from more than a single propagation path that distorts the signal characteristics

The desired GNSS (GPS and GLONASS) in free space propagates at the speed of light, c= 3*10^8 [m/sec] and when this wave encounters and comes in contact with a boundary, such as the surface of the Earth, a fraction of the electromagnetic wave intensity will be reflected. This reflected wave is accounted for by the reflection coefficient, which is a complex quantity and is a function of the constitutive parameters of the media, such as relative permittivity (εr), relative permeability (μr), and conductivity (Ʊ).

Figure 1.9 illustrates the above scenario and phenomena for a single multipath signal that is entering an antenna input terminal at a negative angle of incidence in relation to the antenna horizon and a GPS direct desired signal that reaches the antenna terminal at a positive angle of incidence.

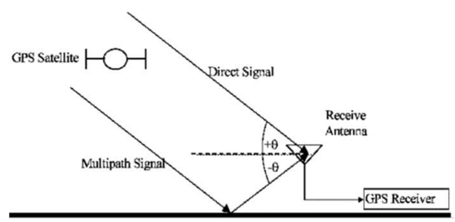


Figure 1.9: Ground multipath scenario model [51]

The Global Positioning System mainly consist of three segments:

1. GPS Space Segment
2. GPS Control Segment
3. GPS User Segment

Figure 1.10, Figure 1.11, and Figure 1.12 indicate the GPS, GLONASS space segment representation of satellites constellation, and GPS control segment locations and facilities.

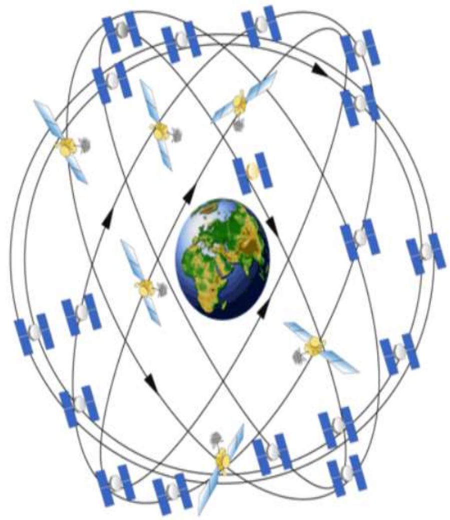


Figure 1.10: GPS constellation satellites [52]

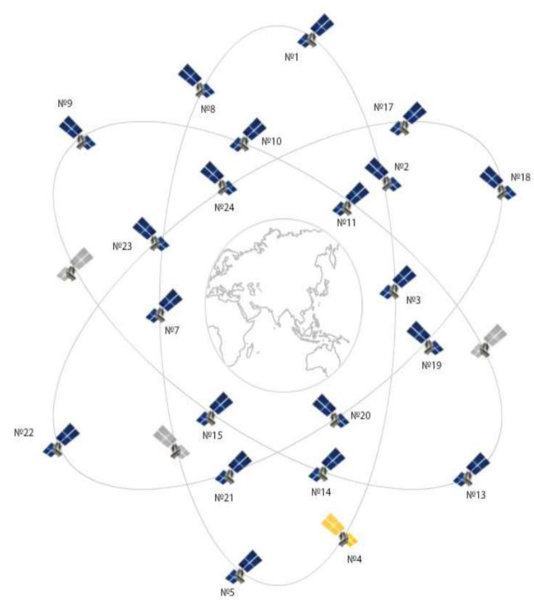


Figure 1.11: GLONASS constellation satellites [53]

The Control Segment of the GPS system is a worldwide network of ground earth-based stations at various locations and facilities that locks and tracks to the GPS satellites, monitors their transmissions, conducts analysis, and send data to the constellations.

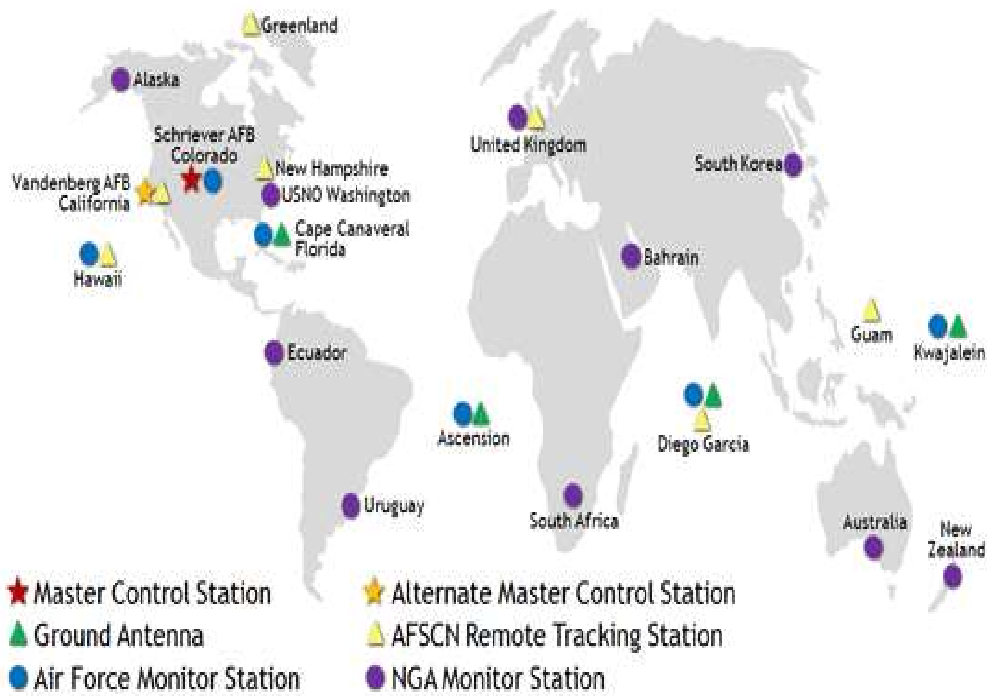


Figure 1.12: GPS control segment locations and facilities [56]

The GPS User Segment is made up of a GPS combo antenna and receiver assembly instrumentation, which receives the GPS signals, and it uses the received GPS data in order to compute 3-dimensional position and time information related to a hand hold GPS receiver device, a vehicle, ship, and airplane on earth. Figure 1.13 below shows user segment of the GPS system.

Figure 1.13: GPS user segment locations and facilities [57]

1.7 Antennas and Their Types

The definition of an antenna is described in section 1.8 and antenna types are covered in section 1.9.

1.8 Antenna Definition

An antenna is “a usually metallic device (as a rod or wire) for radiating or receiving radio waves.” [1], and/or the transition module/structure that launches an Electromagnetic field into free space or unbounded medium from a cable or transmission lines. An antenna component may be used in matching wave impedances, in order to mitigate the undesired reflection. An antenna can be used in the transmitting or receiving mode, more precisely it may be utilized to transmit and/or receive an Electromagnetic wave. Moreover, an antenna may be seen as a transducer component between a guided channel wave traveling in a transmission line and an Electromagnetic wave moving with

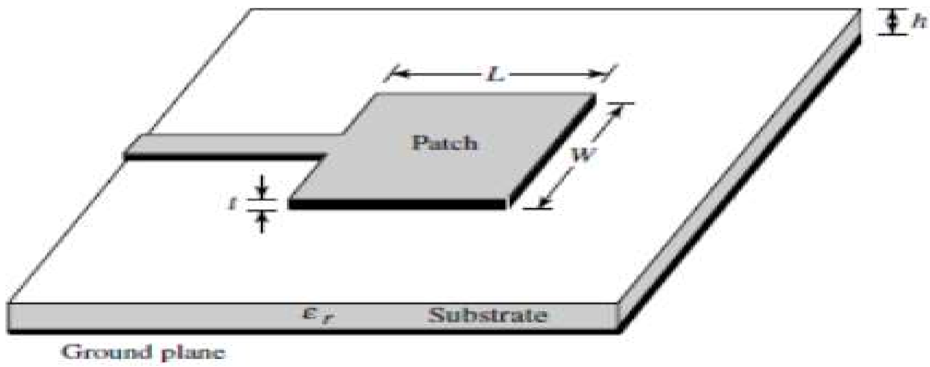


Figure 1.14: Schematic representation of rectangular patch antenna [58]

a speed of light in a free space. Figure 1.14 above indicates a configuration of a rectangular microstrip patch antenna.

1.9 Antenna Types

Typical antennas come in various sizes and types. Types of antennas are wire, aperture, array, lens, and parabolic dish reflector. Outlined below are some examples of the wire, aperture, array, parabolic dis reflector, and lens antenna:

1) Wire antennas configurations are dipole, loop, helix. Figure 1.15 below shows a wire dipole antenna geometry.

Figure 1.15: Wire dipole antenna [58]

2) Aperture antennas are pyramidal horn, conical horn, rectangular waveguide. Figure 1.16 below indicates a pyramidal horn antenna configuration.

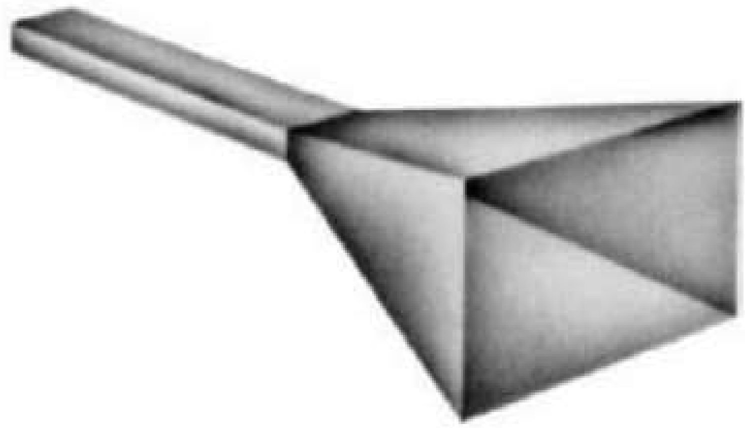


Figure 1.16: Horn antenna [58]

3) Array antennas are Yagi-Uda array and aperture array (see Figure 1.17).

Figure 1.17: Array antenna [59]

4) Lens antennas, such as parabolic dish reflector and convex plane (see Figure 1.18).

Figure 1.18: Parabolic dish reflector antenna [60]

1.10 Basic Antenna Characteristics, Analysis Planes, and Radiation Zones

The basic antenna performance parameters and/or characteristics are highlighted in section 1.11, antenna coordinate system and planes are elaborated in section 1.12, and antenna radiation regions are expressed in section 1.13.

1.11 Basic Antenna Characteristics

Antenna's various fundamental parameters are:

1. Gain
2. Radiation Pattern
3. Radiation Efficiency

4. Directivity

5. Impedance

6. Bandwidth

7. Polarization

8. Surface Electric Current or Current in the surrounding structure

1.12 Antenna Analysis Plane

An antenna's mathematical analysis is carried out in perpendicular spherical coordinate system, and it is the most appropriate coordinate system when the directionality, pattern (E plane pattern and H plane pattern), lobes (major and minor) are assessed and viewed in each of the following angles and planes:

1. Elevation angle and plane

2. Azimuth angle and plane

1.13 Antenna Radiation Zones

They are three regions enclosing an antenna according to Balanis [1] and those zones are listed below:

1. Reactive near field

2. Radiating near field

3. Far field

From a practical viewpoint, the environment surrounding an antenna is the most desirable to perform an analysis. This includes calculating E field and/or H field at a distance a point from a source of radiation/an antenna is in the Far field space, where the electric field and magnetic field components are orthogonal to each other and to the direction of the electromagnetic wave propagation. In other words, the E and H field components are transverse in this Far field region.

1.14 Antenna Experimental Measurements

From a system and component point of view, antenna experimental measurements can be performed in a small laboratory and/or at an antenna range in either an outdoor or indoor facility. The verification, validation testing, and assessment of antennas at a component and system vehicle level can be performed in antenna range. An antenna's basic performance parameters such as the polarization, directivity, beam, linear average gain, standard deviation, and sensitivity of an antenna characteristics to an environment can be conducted at an antenna range.

An antenna range where an antenna experimental measurement is carried out is mainly made up of two components:

1. The transmit space
2. The receive space

In order to successfully conduct an antenna experimental measurement at in an antenna range and/or a small laboratory environment in a transmit (Tx) and receive (Rx) mode configuration setup, various types of hardware and an antenna measurement software package running on a local machine such as a laptop or desktop need to be utilized. Outlined below in subsections 1.15 and 1.16 are the transmit and receive site equipment and tool items at a small laboratory in a university environment.

1.15 Transmitter Site Instrumentations

1. A Signal or function generator
2. Transmit source antenna

3. Rest of equipment such as RF cables, connectors, RF power amplifier, and oscilloscope

1.16 Receiver Site Equipment

1. An Antenna Under Test (AUT)/Receiving Antenna
2. A computer that is preloaded with an antenna measurement software
3. A vector network analyzer or spectrum analyzer (calibrated)
4. A Positioner mechanism along with its control units
5. An Antenna Ground Plane (GNP), circular or square sheet (Approximately 1 [m] or smaller)
6. Power supply
7. Bias-Tee
8. RF cables and connectors (calibrated)

The Antenna Under Test or Test Receiving Antenna needs to be a certain separation distance (20 [ft] or 10 [ft] for a small laboratory site) from the Source Transmit Antenna.

Figure 1.19: Shows a Pictorial Representation of Transmit and Receive site at Oakland University small RF laboratory space

.

1.17 Block Diagram Representation of Transmit and Receive Site of Basic Parameters of Antenna Measurements

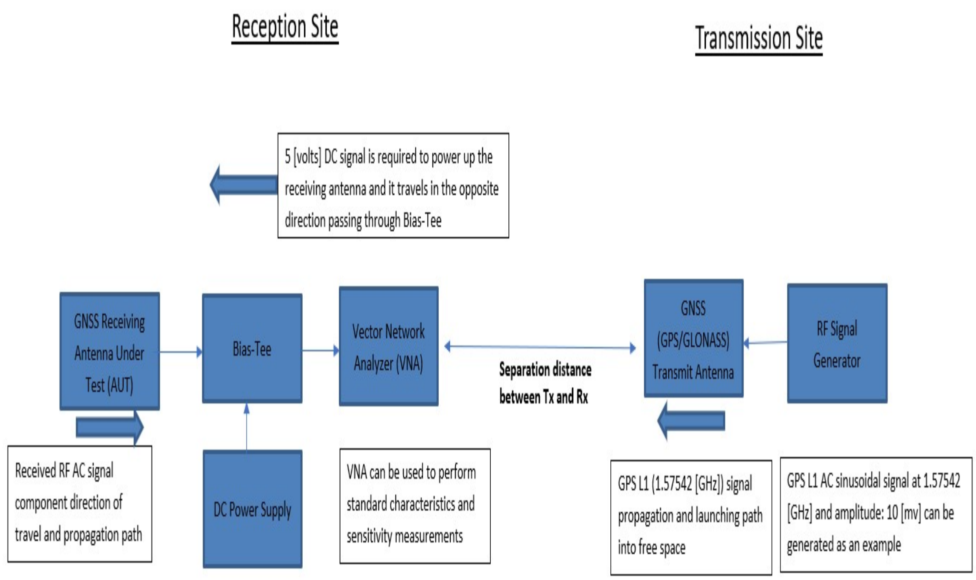


Figure 1.20: Block diagram of transmit (Tx) and receive (Rx) configuration

The RF signal oscillator or sinusoidal function generator produces a GPS L1 sine waveform at 1.57542 [GHz] frequency and corresponding magnitude of 10 [mv]. This signal gets injected into the input port of the transmitting antenna for the purpose of broadcasting the desired Electromagnetic field into free space.

The receiving GPS signal gets channel as a pass-through waveform without any signal processing or modification impose on it. This desire signal gets routed into the Bias-Tee and next it travels into a Vector Network Analyzer for the purpose of basic performance parameters and characteristics of an antenna measurements.

Figure1.20 indicates a block diagram representation of the reception site and transmission site, and this configuration can be used to perform the received signal power level or power density crossing at the receiving antenna input terminal and antenna passive gain measurement at a small laboratory environment.

1.18 Basic Performance Parameters of Antenna Measurements

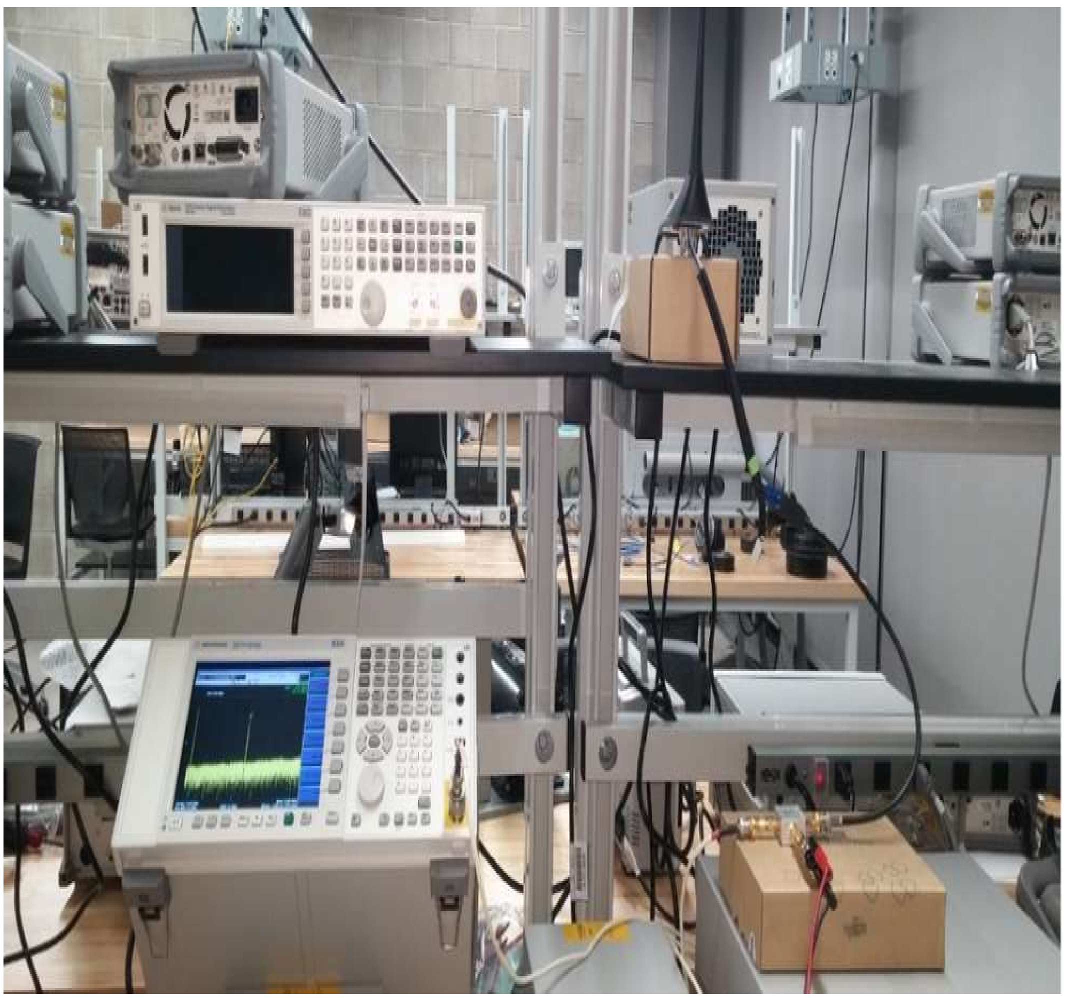


Figure 1.21: Indicates an image representation of a fundamental antenna component performance parameter measurements on the receiver site

1.19 GPS Passive Patch Antenna Received Signal Power Experimental Measurements Results

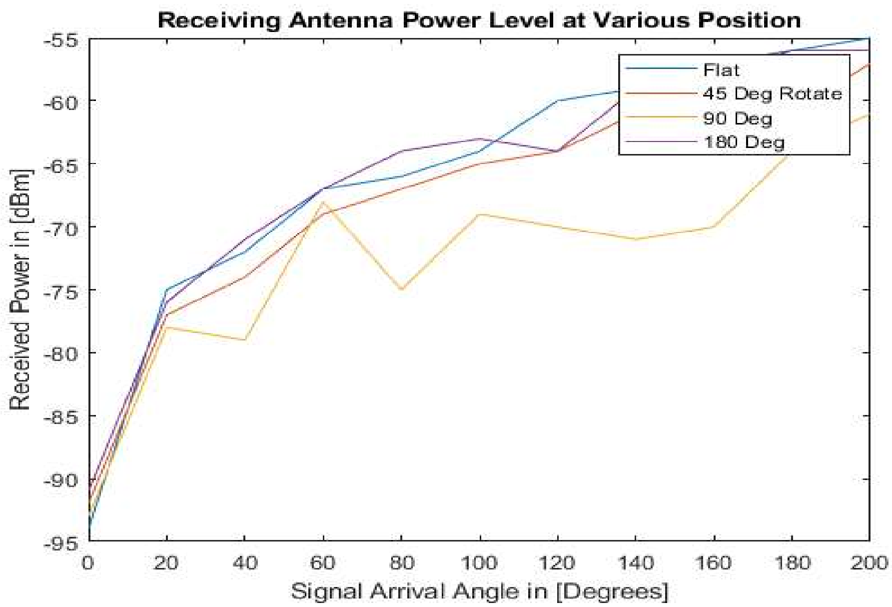


Figure 1.22: Shows a measured received power level of the passive GPS patch antenna at various elevated antenna position for the start frequency: 1.5724 [GHz]

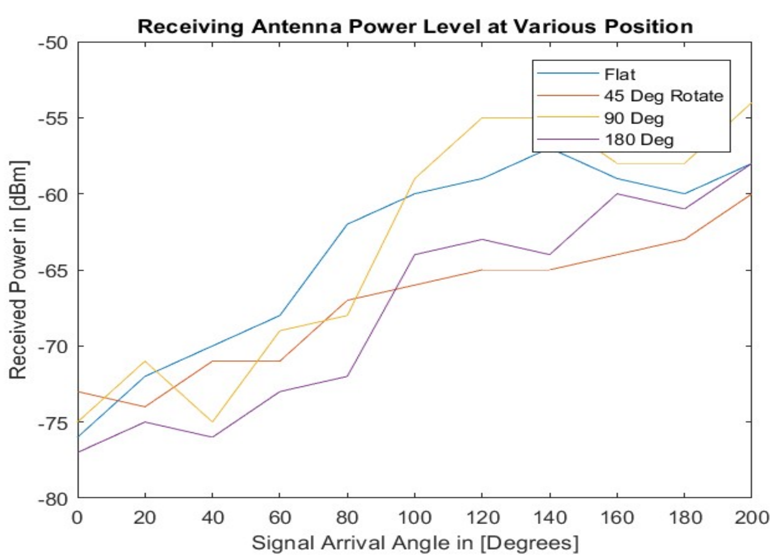


Figure 1.23: Indicates a measured received power level of the passive GPS patch antenna at various elevated antenna position for the center frequency: 1.5754 [GHz]

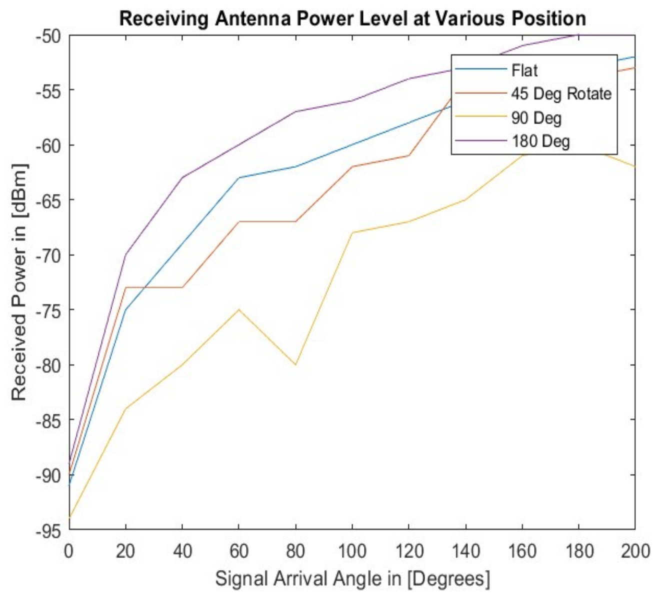


Figure 1.24: Indicates a measured received power level of the passive GPS patch antenna at various elevated antenna position for the stop frequency: 1.5784 [GHz]

1.20 Patch Antenna Geometry and Design Equations

In certain applications, such as automotive and non-automotive spaces, antenna size, performance, profile, weight, and price are deemed necessary and essential. To meet these requirement specifications, a patch antenna may be selected. Microstrip patch antennas consist of each of the following:

1) A radiating metallic patch element
2) A dielectric substrate with a specific dielectric constant or relative permittivity
3) A ground plane that is placed at the bottom of a substrate

Figure 1.25 below shows the patch antenna basic structure model in general, where we have a rectangular metallic patch that is placed over a dielectric substrate material with a specific relative permittivity. The bottom of the "Cuboid" [4] substrate is a conducting base sheet that acts as a conducting ground plane.

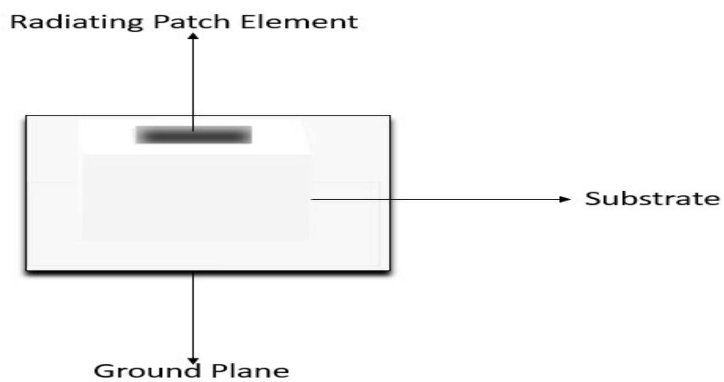


Figure 1.25: Microstrip patch antenna geometry

Per Balanis [1], a simplified rectangular patch antenna equation from below can be used to design microstrip antennas for a given dielectric constant of the substrate material (Relative Permittivity = Epsilon r = Ɛr), the Resonant Frequency (fr), and the Substrate Height (h).

Equation (1) Determine the Patch Width W:

$$Patch\,Width = W = \frac{V0\sqrt{2/(\varepsilon r + 1)}}{2fr}\ (cm\ or\ inches) \quad [1]$$

$Where\ V0 = The\ velocity\ of\ light\ in\ free - space\ (Constant\ value)$

$fr = The\ Resonant\ Frequency\ (in\ Hz)$

$\mathcal{E}r$ = The Dielectric Constant of the Substrate Material and/or Relative Permittivity of material

Equation (2) Determine the Patch Length L:

$$Patch\ Length = L = \frac{1}{2fr\sqrt{\mathcal{E}\mathrm{reff})}\sqrt{\mu 0\mathcal{E}0)}} - 2\Delta L \quad (cm\ or\ inches) \quad [1]$$

$$Where\ \Delta L\ = The\ extended\ incremental\ length\ of\ the\ Patch$$

$$= (h)(0.412)\frac{(\mathcal{E}\mathrm{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\mathcal{E}\mathrm{reff} - 0.258)(\frac{W}{h} + 0.8)}$$

$$\mathcal{E}\mathrm{reff} = \text{The effective dielectric constant} = \frac{\mathcal{E}r + 1}{2} + \frac{\mathcal{E}r - 1}{2}\left(1\ + 12\ \frac{h}{W}\right)^{-1/2}$$

$h = The\ height\ of\ the\ substrate\ material\ in\ cm\ or\ inches$

$W\ = The\ Patch\ Width$

$\mathcal{E}r$ = The Dielectric Constant of the Substrate Material and/or Relative Permittivity of material

$\mu 0$ = The Permeability of free space $= 4\pi 10^{-7}\ [\frac{henry}{metre}]$

$\mathcal{E}0$ = The Permittivity of free space $= (8.854)(10^{-12})\ \ [\frac{farads}{metre}]$

Equation (1) and Equation (2) allow for the calculation of a rectangular microstrip antenna actual patch length and width that would be a practical design for patch antennas.

The shape of the radiating patch element antenna can be rectangular, as depicted in Figure 1.25.

1.21 GNSS Patch Antenna Research Focus

Below is a list of the major areas of emphasis of this research work involving the simulation of a GNSS (GPS & GLONASS) microstrip patch antenna using Altair FEKO software package, and the optimization of a rectangular patch antenna, including the Design Parameters and Passive Gain:

1. We investigated by Modeling a new GNSS (GPS/GLONASS) and then changed the GNSS patch Design Parameters, namely Ground plane length (x1[mm]), Ground plane width (x2[mm]), and Substrate dielectric constant (x3[mm]) values for each FEKO simulation iteration ran within the CADFEKO space to obtain a 2D plot of the Patch Antenna Passive Gain (x4[dBi]), from the POSTFEKO page
2. We applied the Design of Experiments (DoE) for simplification to reduce the number of required simulation test runs and therefore improve the proposed antenna design cycle
3. We utilized the P-Transform technique in a MATLAB environment from MathWorks for optimization of the Patch Antenna Design Parameters and Passive Gain

1.22 Model of Design of Experiments Method in General

Figure 1.26 below shows the general model of Design of Experiments (DoE). Equation 1 indicates a design parameter as an input versus output response for an antenna, where

y hat = The predicted value of an output response variable

xi = The input factors and design parameters of an antenna

K = The design parameter in the summation symbol

βi = The coefficient proportional to the main effect, where the main effect represents the degree of a parameter individual influence on an output response variable,

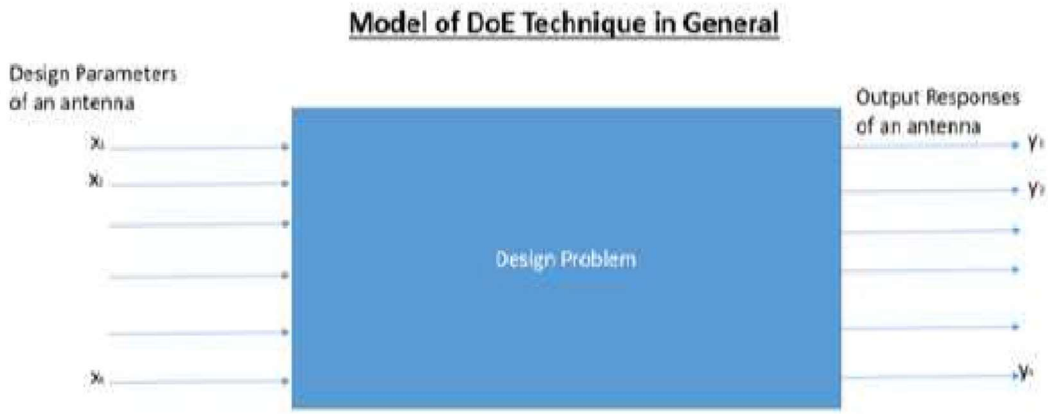
βij = The coefficient proportional to the two-factor interaction of the main effect.

To be direct, βi and βij are the unknown coefficients proportional to the main effect.

Here we are looking at the 2^k full factorial design, where 120 simulation combination runs were conducted in the experiment and the simulation operating frequency was set to 1.555 [GHz]. In our study, the value of k = 7, which resulted in 2^7 = 128, ~120 simulation runs. For each FEKO simulation run we varied three input factor design parameters, namely ground plane length, ground plane width, and dielectric constant of substrate material. We sought the antenna average and/or passive gain for each simulation run from the POSTFEKO environment.

1.23 P-Transform Objective Function 2D Plot

We defined and set our true objective function to be equal 1/passive gain. For each of the FEKO simulation runs, the new patch antenna average gain was obtained and then we conducted a mathematical inverse operation on our output passive gain parameter, which in turn provided us with the true objective function.



$$\hat{y} = \beta_0 + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k-1}\sum_{j=i+1}^{k}\beta_{ij}x_i x_j + \sum_{i=1}^{k-2}\sum_{j=i+1}^{k-1}\sum_{l=j+1}^{k}\beta_{ijl}x_i x_j x_j + \cdots + \beta_{ij\cdots k}x_i x_j \cdots x_k,$$

2^K full factorial design mathematically model equation 1, Reference [5]

Figure 1.26: Design of Experiments input, design problem and output response model

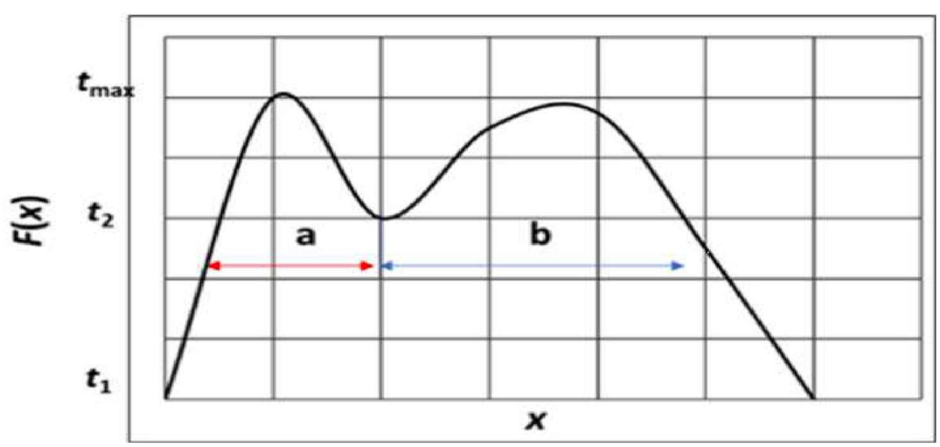


Figure 1.27: Type 1 – Continuous objective function rectangular graph [6]

CHAPTER TWO

GNSS PATCH ANTENNA DESIGN, MODELING, AND SIMULATION

2.1 FEKO Model Creation of the GNSS Patch Antenna

The proposed new GNSS (GPS and GLONASS) patch antenna was designed, modeled, and simulated using the FEKO simulation software package. The FEKO is an electromagnetic field simulator, and it can be used to design, model, and analyze simple and basic to large and complex antenna structures. FEKO is a commercial software tool chain based on the Method of Moments. A student version of FEKO was used to design, model, and conduct the simulation runs in this work. The desired GNSS metallic patch antenna was positioned on a substrate material with varying relative permittivity or dielectric constant values, ranging from 5.1 [mm] to 5.9 [mm]. While conducting the FEKO simulation run, the conducting rectangular ground plane mechanical length and width dimensions, and as well its substrate dielectric constant, were varied during each simulation run. The entire GNSS antenna model was constructed within the "CADFEKO" environment [4]. The steps outlined below highlight the FEKO geometry generation of the GNSS (GPS and GLONASS) patch antenna within the "CADFEKO" [4], and the antenna results were obtained from the "POSTFEKO" [4] environment:

1. We selected and set the antenna model unit to millimeters [mm]
2. Next, we declared the design parameters or variables, such as the operating frequency, ground plane length, ground plane width, substrate length, substrate width, patch length, patch width, etc., that define the antenna geometry and substrate material

3. Third, a “Rectangular” [4] ground plane surface geometry, with its corresponding media type selected to be a Metallic, was created
4. We added a “Cuboid” [4] solid substrate material with an initial setting of 5.1 [mm] for its dielectric constant, and it was placed on top of the conducting rectangular ground plane that was created in step 3
5. We generated the “Metallic” [4] patch element on top of the porcelain Substrate
6. Then, we created the feed pin by using the “Line” [4] curve function to excite or energize the GNSS patch antenna
7. Next, we added a wire port at the start of the Line location followed by a source of excitation, such as a voltage source was placed at this port
8. In step 8, we requested the “Far fields” [4] solution from under the “Configuration” [4] tab
9. We used the “Union” [4] function to group each component or elements of the overall GNSS patch antenna geometry together
10. Then, we set the operation and/or simulation frequency
11. We ran the “Create mesh” [4] function followed by the “CEM validate” [4] feature, in order to perform the “Meshing” [4] and “Computational electromagnetic validation” [4]
12. We conducted and executed the “Feko solver” [4] function and after the simulation is finished, next run and launch the “POSTFEKO” [4] post-processing program
13. Finally, the “POSTFEKO” [4] environment was used to plot the 2D Average Gain and/or Far fields and view the Passive Gain or Objective Function results

Due to the limited capabilities of the FEKO LITE (i.e., the Student Version of FEKO), one may need to use the full version, or nonacademic variant of the FEKO software package in their simulation studies to reduce uncertainty, utilize the errors bar, and ultimately enhance the mathematical calculation capabilities of the desired model meshing.

2.2 GNSS Patch Antenna Design Parameters

Table 2.1 indicates the design, modeling, and simulation of the GNSS (GPS and GLONASS) patch antenna geometry model creation initial numeric parameter values.

Table 2.1 Model creation initial parameter values of GNSS patch antenna

Parameter	Value
Feed Length	21 [mm]
Operating Frequency	1.555 [GHz]
Ground plane length	10[mm]
Ground plane width	10 [mm]
Patch Length	39 [mm]
Patch Width	52 [mm]
Dielectric Substrate Length	$-64 + 2.0e^{-3}$ [mm]
Dielectric Substrate Width	$-76 + 2.0e^{-3}$ [mm]
Substrate Thickness	4.0 [mm]
Substrate dielectric constant	5.1 [mm]

2.3 Meshing and Simulation Parameters within FEKO

Table 2.2 shows FEKO meshing and loss tangent parameter values.

Table 2.2 FEKO mesh and loss tangent parameters for GNSS patch antenna

GNSS Antenna	Parameter	Value
GNSS Patch Antenna	Mesh-Wire Segment Radius	0.9 [mm]
Operating at 1.555 [GHz]	Dielectric Loss Tangent for Porcelain Material	$2.0e^{-14}$ [mm]

2.4 GNSS Patch Antenna 3D Model within FEKO

The plot in Figure 2.1 shows the Top View of the GNSS (GPS and GLONASS) patch antenna structure. The long orange rectangle indicates the ground plane, the yellow square denotes the substrate with dielectric constant value of 5.1 [mm], and the green rectangle shows the patch element.

Figure 2.1, and Figure 2.2, indicate the Top View and Cross Section View within the "CADFEKO" [4] space. Figure 2.3 captures the Cross Section View of the GNSS patch antenna within the "POSTFEKO" [4] environment. Figure 2.1 shows our GNSS patch antenna geometry model in the "CADFEKO" [4] space. Figure 2.2 Depicts our GNSS patch antenna model in the "CADFEKO" [4] space. Figure 2.3 Depicts our GNSS patch antenna model in the "POSTFEKO" [4] page.

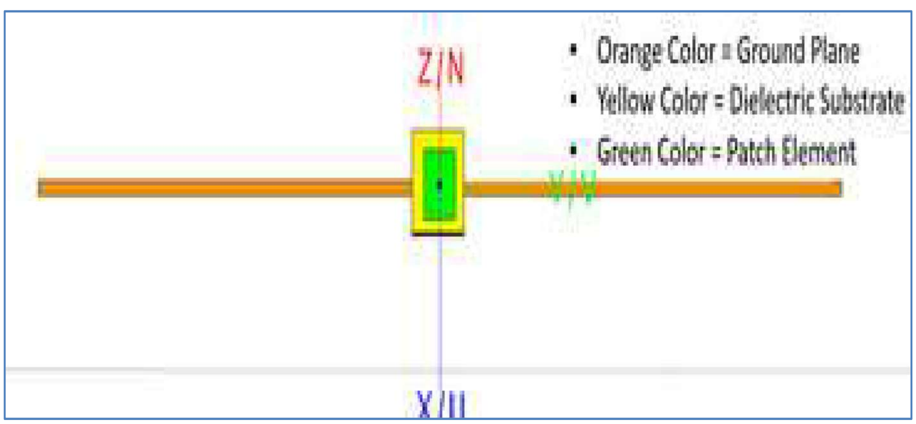


Figure 2.1: GNSS patch antenna operating at 1.555 [GHz] (Top View)

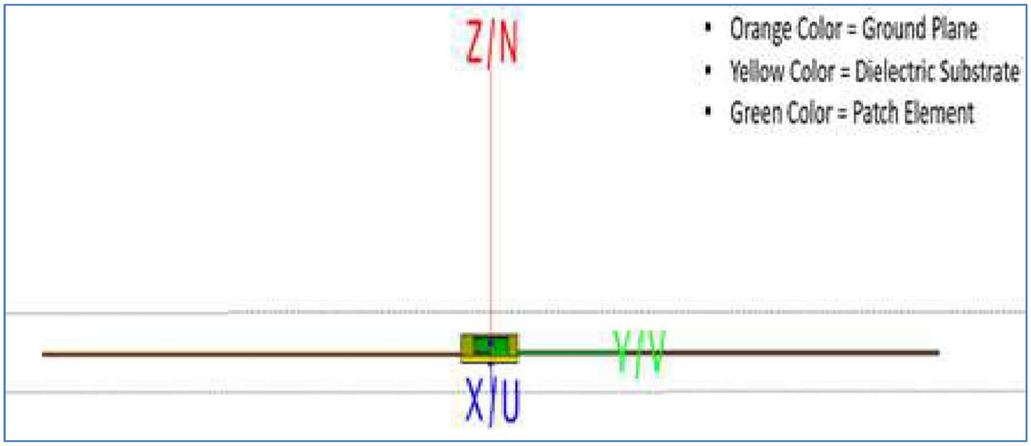


Figure 2.2: GNSS patch antenna operating at 1.555 [GHz] (Cross Section View)

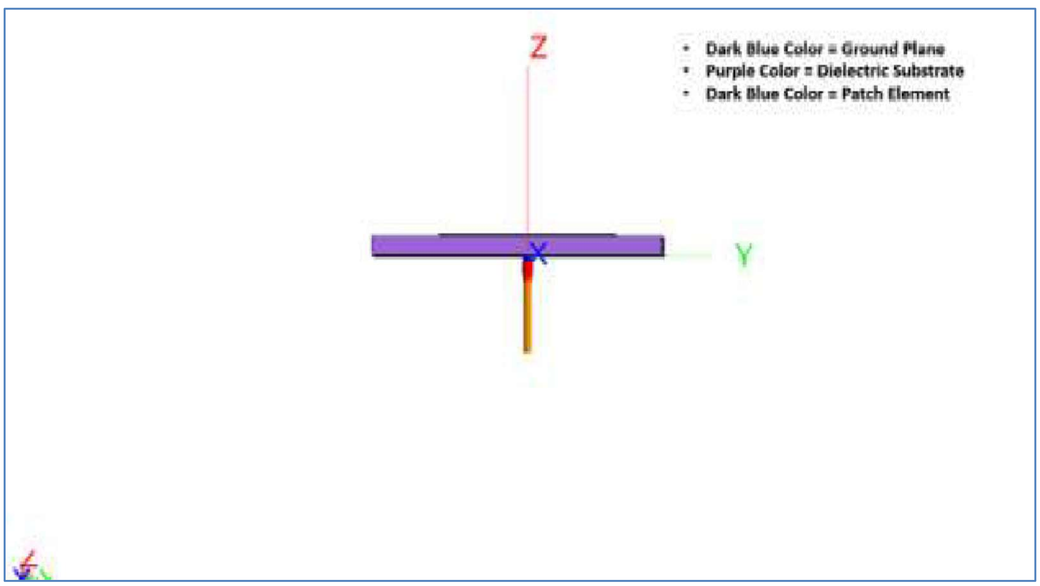


Figure 2.3: GNSS patch antenna operating at 1.555 [GHz] (Cross Section View)

2.5 FEKO Simulated Far Field of GNSS Patch Antenna

Figure 2.4 show a simulation of the passive gain for the proposed antenna, and we selected the substrate material to be ceramic or porcelain with a dielectric constant or relative permittivity = 5.1 [mm] to model, design, and simulate the presented GNSS patch antenna with a center frequency = 1.555 [GHz]. In the 2D model plot from Figure 2.4, we can see an approximate 0.55 [dBi] passive gain by taking the difference in gain between 30 and 90 degrees.

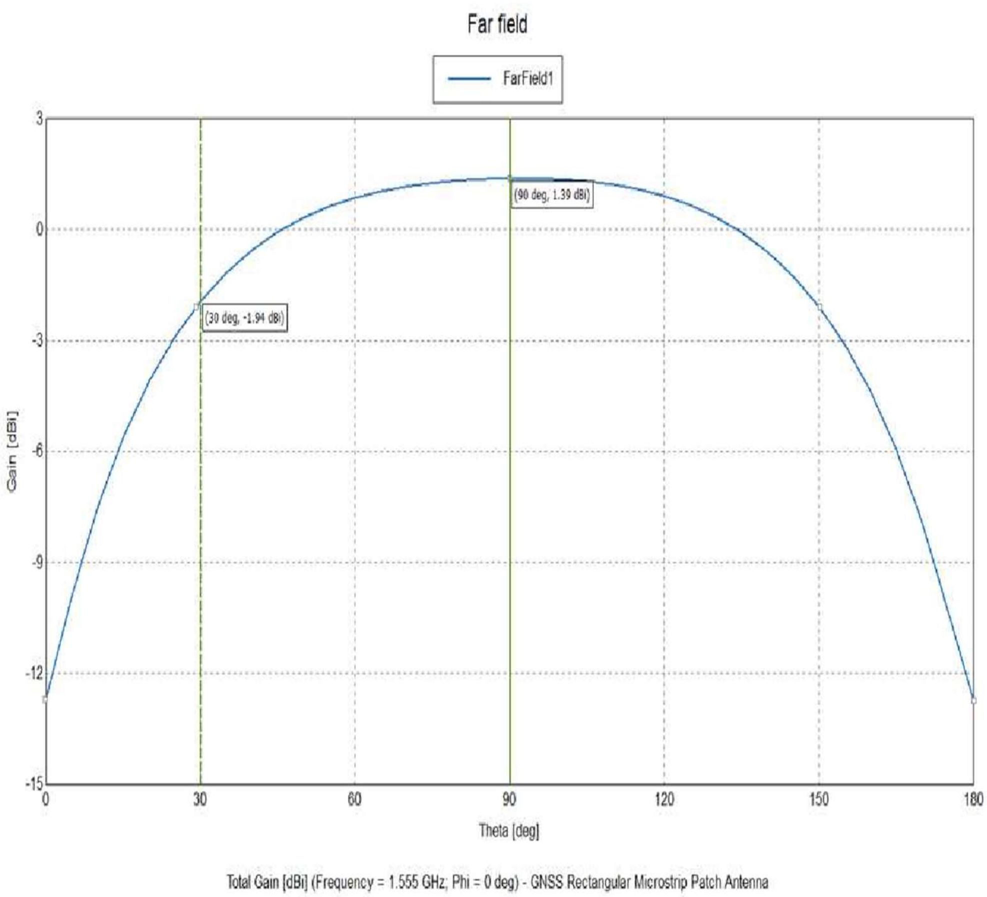


Figure 2.4: GNSS patch antenna passive gain at 1.555 [GHz] rectangular 2D plot

CHAPTER THREE

DESIGN OF EXPERIMENTS (DOE)

3.1 Design of Experiments Advantages

Design of Experiments is an optimization methodology that can be applied to Electromagnetic design problems, such as various types of antenna design and optimizations, namely the patch antenna and Radio-Frequency Identification (RFID) antenna. One of its applications is in the emerging field of L2/L2+ Advanced Driver Assistance Systems (ADAS) and L3 Automated Driving (AD) systems. Design of Experiments is a way to optimize an antenna design efficiently and effectively [7]. Some of the Design of Experiments advantages are outline below:

1. It allows for the design cycle of an antenna to be reduced
2. It supports the design problems and process with more efficiency
3. It allows for substantial timesaving and leads to a short design cycle by reducing the number of required simulations; in this work, it allowed for a fewer number of FEKO simulation runs for the presented GNSS patch antenna design, model, and simulation
4. It provides an efficient design and analysis of an antenna

More specifically, Design of Experiments allows for the design cycle of an antenna to be reduced by cutting down the number of simulations runs to a more manageable size, which in turn will create efficiency and less use of computational power, allowing for fewer simulations in an engineering optimization problem study.

3.2 Design of Experiments Mathematical Model Equation

We have designed a new GNSS (GPS and GLONASS) patch antenna and investigated how to change our design three input parameters, namely the ground plane length, ground plane width, and the substrate dielectric constant. These parameters affect the antenna performance, such as the output passive gain, and this can be handled and answered with the Design of Experiments method. Furthermore, we looked at the design parameters (x1, x2 and x3) as an input relationship versus the passive gain output response parameter (y).

A Design of Experiments mathematical model equation that represents our design parameters input and passive gain output response can be observed in Equation (3) below.

Equation (3) DoE antenna input and output response relation.

$$\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j \qquad (5)$$

2^k factorial design mathematical model equation.

where

βi = The main effect

βij = Two factor interactions

Xi = The input design parameters

y hat = The predicted value of an output response variable

Equation (3) offers a mathematical interaction model for 2^k factorial, where we can see the antenna design input and output response parameter. We created our GNSS (GPS and GLONASS) patch antenna geometry model for the Design of Experiments within the

CADFEKO [4] and obtained the corresponding passive gain parameter values within the POSTFEKO [4] environment.

CHAPTER FOUR

P-TRANSFORM ALGORITHM ANALYSIS AND IMPLEMENTATION

4.1 P-Transform Analysis Details [6]

According to Abdelnaby [6], the P-Transform algorithm can be used to find the global maximum of an objective function. The transformation of the objective function, f (x) where x is an n-dimensional vector, is performed by a nonlinear operator,

which is given by P{f(x)} → G(t) (2)

Where t represents the time as a scalar quantity that is taken to be pointwise Lebesgue's division of the object function f(x), in which the inequality equation needs to be satisfy

$$min(f(x)) = t0 < t1 < t2...ti < tmax = max(f(x))$$

Parameter D represents the set on which the f(x) function is to be determined and D* is a subset of D on which f(x) also satisfies the constraints. Let Di be the set on which

abs (f(x))> ti.

Given a H(x) function such that H(x) can take either a value of 0 at D/D* or 1 value at D*

$H(x) = 0 \text{ at } D/D*$ (4)

or

H(x) = 1 at D* (4)

By applying the Riemann integral on the equation 4 function set Di results equal to its measure μi in Equation (5) below.

$$\int Di ... \int H(x) dxi ... dxn = \mu i \quad (5)$$

The continuous objective function from Figure 1.27 can be estimated from the equation (5) Riemann integral and Di can be computed using statistical tests. We let the Pi represent the probability that a point x randomly chosen from D* and D* belongs to Di and it can be approximated by the ratio of s(r)/r, where r is the number of randomly chosen points x (length of a and b and s(r) represents the number of successes. Thus, for any $\varepsilon > 0$, as $r \rightarrow \infty$, the ratio s(r)/r can mimic the measure μi of the Di set.

$$\lim \Pr \left(\frac{S(r)}{r} - \text{Pi} \right) > \varepsilon = 0 \qquad (6)$$

$\gamma \rightarrow \infty$

$\mu i = s(r)/r$

Once we have the μi 's we can estimate the quadratic function R(t) as shown in Equation (7) below.

$$\mathrm{R(t)} = \mathrm{a}_{\mathrm{o}} t^2 + \mathrm{a}_1 t + \mathrm{a}_2 \qquad (7)$$

where a_{o}, a_1, and a_2 are the roots of quadratic equation (7) and it can be found by utilizing the least squares approach with the following assumptions:

$$\begin{bmatrix} a0 \\ a1 \\ a2 \end{bmatrix} = \varphi \mathrm{T} \begin{bmatrix} \mu 1 \\ \mu 2 \\ \mu 3 \end{bmatrix} \qquad (8)$$

$$\varphi = \begin{bmatrix} t_1^2 & t_1 & 1 \\ t_2^2 & t_2 & 1 \\ t_3^2 & t_3 & 1 \end{bmatrix} \qquad (9)$$

4.2 P-Transform Algorithm Implementation Steps [6]

Outlined below are the implementation steps for the P-Transform technique:

1. Generate N random vectors x_{n}

2. Check the constraints for each x_i
3. Evaluate the function $f(x_n)$ for all x_i 's that satisfy the constraints
4. Let t_1= (min f(x) + max f(x))/2
5. Calculate μi as defined in Equation (6)
6. Repeat step 5 for each t_i where $t_{i+1} = t_i + \Delta t$ until the condition in Equation (6) is no longer valid
7. Extrapolate G(t) using R(t) in Equation (7)
8. Find the roots for this quadratic equation, R(t) = 0 by calculating Equation (8)
    a. if $a_o < 0$, then the global maximum F (x *) = max (R_1, R_2), where R_1, R_2 are the roots of R(t)
    b. if $a_o > 0$ then F (x *) = min (Real (R_1, R_2))
9. Repeat the algorithm until ΔF (x *) << ε

4.3 FEKO Simulation Combination Run and P-Transform Results in the Experiments

Table 4.1 below shows our analysis and a pictorial representation of the FEKO [4] simulation combination design runs conducted in the experiment at a 1.555 [GHz] center frequency, as well as its corresponding simulated GNSS rectangular microstrip patch antenna design parameters and passive gain results.

4.4 P-Transform Technique Optimization Process and Block Diagram Representation

The GNSS (GPS and GLONASS) patch antenna passive gain optimization was achieved by using a global optimization P-Transform algorithm [6] and was given a neural network genetic algorithm. To be direct, the P-Transform algorithm typically conducts a maximization of optimization problems; however, in this work, the focus was on performing the minimization for the purpose of obtaining an optimal GNSS patch antenna passive gain. The minimization of the GNSS patch antenna was conducted by modifying the original P-Transform built-in function, coupled with the utilization of the Radial Basis Function (RBF) to fit the data curve within the MATLAB environment. The Radial Basis

Function was applied to approximate functions, data, and the system, so that the assessment of the approximation function or system could take place more easily. The Radial Basis Function can be applied in the field s of Neural Network, Learning Theory, solving a set of Linear Systems using matrix decomposition, and it is also applicable in almost any dimension of Euclidean space [50].

The high-level steps involved in the GNSS patch antenna passive gain optimization are outlined below:

1. Read the antenna .csv file, which contains the inputs and output design parameters:
    a. Input parameters = (x1, x2, x3) = (antenna ground plane length, antenna ground plane width, substrate material dielectric constant)
    b. Output response = (y) = GNSS Patch Antenna Passive Gain (Objective Function)
2. Train the system that is based on neural network by using response surface technique and one of them is the Radial Basis Function [50], to get a best fit curve and mathematical Equation (4) below from a series of inputs and to obtain the corresponding output neuron parameters can be model by the relation Equation 4 below:

Equation (4)

$$\hat{y}_i = f(\mathbf{x}_i) = \sum_{j=1}^{m} w_j \phi(\mathbf{x}_i) = \sum_{j=1}^{m} \phi\left(\|\mathbf{x}_i - \mu_j\| / \sigma_j\right)$$ [50]

where:

m = Number of neuron or number of basis function

μj = Center vector for neuron j

w j = Weight of neuron j

phi = Neuron/basis function

σj = Width of basis function

Conducted GNSS patch antenna passive gain optimization operation by using the original P-Transform built in function in the MATLAB environment to get our GNSS patch antenna output, which is our optimized passive gain (objective function).

To be more specific, in our case, each simulation runtime using the Student Version of FEKO software package took approximately two minutes. We generated a set of data based on Design of Experiments (DOE) [5] and a Radial Basis Neural Network (RBN) [50] was used to train the system to generate a response surface. The created response surface model was then used as a black box system in lieu of FEKO simulations. This allowed us to perform hundreds of thousands of optimization iterations in a fraction of time. MATLAB from MathWorks was used for generating the response surface and optimization using the P-Transform technique. Furthermore, simulation runs are expensive; they take a lot of resources, memory allocation, processing power, and time. Therefore, it was deemed necessary to explore and use a Design of Experiments (DoE) methodology to come up with the FEKO simulation runs and then apply the P-Transform algorithm on the results of the DoE runs, in terms of GNSS patch antenna design parameters and passive gain output response. This was done to optimize the GNSS patch antenna passive gain.

Moreover, the steps listed below were executed to determine the optimized and robust objective function and/or passive gain value we desired.

1. Create Design of Experiments, FEKO simulation runs.
2. Create the surface response by using the given Radial Basis Function (RBF).
3. Generate the input and output black box relationship model, which represents our system.
4. Apply the P-Transform to our inputs and output black box mathematical equation model and system.

Table 4.1 FEKO simulation design runs of our GNSS patch antenna

	L	W	DC					
Min	10	10	5.1	Parameters which can be change				Initial design: 2^7=128 ~125 runs
Max	1000	1000	5.9					
	Design Parameters					(L, W, Dielectric Constant)	Average Passive Gain	
	X1	X2	X3		# of Runs	(X1,X2,X3)	G(X1,X2,X3) [dBi]	A desirable vs non-desirable antenna
0%	10	10	5.1		1	10,10,5.1	0.55	A good antenna
25%	257.5	10	5.1		2	257.5,10,5.1	2.75	Not a good antenna
50%	505	10	5.1		3	505,10,5.1	1.27	Not a good antenna
75%	752.5	10	5.1		4	752.5,10,5.1	2.92	Not a good antenna
100%	1000	10	5.1		5	1000,10,5.1	2.36	Not a good antenna
	10	257.5	5.1		6	10,257.5,5.1	1.5	A good antenna
	257.5	257.5	5.1		7	257.5,257.5,5.1	7.77	A good antenna
	505	257.5	5.1		8	505,257.5,5.1	9.07	Ok antenna
	752.5	257.5	5.1		9	752.5,257.5,5.1	19.52	Ok antenna
	1000	257.5	5.1		10	1000,257.5,5.1	11.01	Not a good antenna
	10	505	5.1		11	10,505,5.1	3.02	A good antenna
	257.5	505	5.1		12	257.5,505,5.1	5.79	Ok antenna
	505	505	5.1		13	505,505,5.1	8.67	Ok antenna
	752.5	505	5.1		14	752.5,505,5.1	18.17	Ok antenna
	1000	505	5.1		15	1000,505,5.1	12.92	Not a good antenna
	10	752.5	5.1		16	10,752.5,5.1	0.99	A good antenna
	257.5	752.5	5.1		17	257.5,752.5,5.1	8.24	Ok antenna
	505	752.5	5.1		18	505,752.5,5.1	8.77	Ok antenna
	752.5	752.5	5.1		19	752.5,752.5,5.1	19.36	Ok antenna
	1000	752.5	5.1		20	1000,752.5,5.1	9.56	Ok antenna
	10	1000	5.1		21	10,1000,5.1	1.85	A good antenna
	257.5	1000	5.1		22	257.5,1000,5.1	6.86	Ok antenna
	505	1000	5.1		23	505,1000,5.1	9.11	Ok antenna
	752.5	1000	5.1		24	752.5,1000,5.1	18.26	Ok antenna
	1000	1000	5.1		25	1000,1000,5.1	xx	Due to the limition of Student Edition of Feko, unable to run this case
	10	10	5.3		26	10,10,5.3	0.55	A good antenna
	257.5	10	5.3		27	257.5,10,5.3	2.33	Ok antenna
	505	10	5.3		28	505,10,5.3	1.6	Not a good antenna
	752.5	10	5.3		29	752.5,10,5.3	2.82	Not a good antenna
	1000	10	5.3		30	1000,10,5.3	2.07	Not a good antenna
	10	257.5	5.3		31	10,257.5,5.3	1.5	A good antenna
	257.5	257.5	5.3		32	257.5,257.5,5.3	7.76	Ok antenna
	505	257.5	5.3		33	505,257.5,5.3	9.27	Ok antenna
	752.5	257.5	5.3		34	752.5,257.5,5.3	19.71	Ok antenna
	1000	257.5	5.3		35	1000,257.5,5.3	11.02	Not a good antenna
	10	505	5.3		36	10,505,5.3	2.99	A good antenna
	257.5	505	5.3		37	257.5,505,5.3	5.81	Ok antenna
	505	505	5.3		38	505,505,5.3	6.87	Ok antenna
	752.5	505	5.3		39	752.5,505,5.3	18.16	Ok antenna
	1000	505	5.3		40	1000,505,5.3	12.91	Not a good antenna
	10	752.5	5.3		41	10,752.5,5.3	1.02	A good antenna
	257.5	752.5	5.3		42	257.5,752.5,5.3	8.27	Ok antenna

By executing the optimization flowchart from Figure 4, we were able to obtain our optimized passive gain of 0.2084 [dBi], with the corresponding design parameters as follows:

1. Ground plane length = 493.7 [mm]
2. Ground plane width = 503 [mm]
3. Dielectric constant = 5.492 [mm]

by using the P-Transform [6].

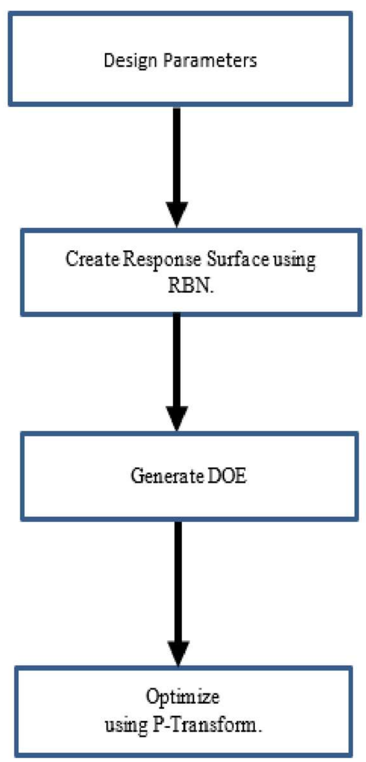


Figure 4.1: Optimization block diagram flowchart

The entire process can be summarized in the following block diagram and flowchart representation:

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

5.1 Conclusion

In this work we have presented, described, and investigated a new GNSS (GPS and GLONASS) path antenna design with a center frequency of 1.555 [GHz] with models and simulations using the student FEKO software package. We also demonstrated the Design of Experiments (DoE) methodology by applying a P-Transform algorithm on the GNSS patch antenna passive gain in the process. More specifically, the GNSS patch antenna passive gain, DoE, P-Transform technique were utilized and discussed accordingly.

The proposed GNSS patch antenna can be used in non-automotive, modern automotive components, systems, autonomous vehicle spaces, and it also finds application in a wide area of other scientific and engineering disciplines. The optimized version of the GNSS patch antenna passive gain was obtained at 0.2084 [dBi], with the corresponding Design Parameters of ground plane length = 493.7 [mm], ground plane width = 503 [mm], and dielectric constant = 5.492 [mm] by using the P-Transform technique [6] with MATLAB products created by MathWorks.

Furthermore, we demonstrated that the GNSS patch antenna will meet the need of future automotive applications. Moreover, the DoE and the P-Transform technique were used to simplify an advanced optimization problem. This problem included global (Maximum or Minimum), optimal, and robust solution generations for cases where the objective function was either defined and/or not within the MATLAB environment. The investigation of such problems was the emphasis of this paper.

5.2 Future Research Work

For future research, simulation studies can be extended to focus on a GNSS patch antenna model, simulation coupled with a prototype creation and conducting component and vehicle level verification, validation, and evaluation by considering each of the following:

1. By using a substrate material that is different than porcelain. A FR4 substrate material with a dielectric constant in the range of 4.0 [mm] to 5.0 [mm] can be utilized
2. A prototype of the proposed Microstrip GNSS patch antenna can be created, designed, and the developed prototype patch antenna can be tested for an optimal mounting location within a vehicle roof location area that provides an optimal metallic ground plane for the prototype antenna
3. The vehicle level testing, assessment, and evaluation of the proposed GNSS patch antenna can be carried out in Anechoic Chamber and/or Indoor Antenna Range, to measure the basic antenna characteristics, such as Gain, Radiation Pattern, Radiation Efficiency, Directivity, Impedance, Bandwidth, Polarization and Current draw and/or Antenna Surface Current
4. The presented GNSS patch antenna basic performance parameters can be measured at a RF Antenna Range by using Figure 5.1. The block diagram representation from below can be coupled with various types of instrumentations. These may include a Network Analyzer, a computer that is preloaded with an Antenna Measurement Software, a Transmit source and Receive test antenna, an Amplifier, low-loss RF coaxial cables, a Positioner Unit, and a Positioner Controller

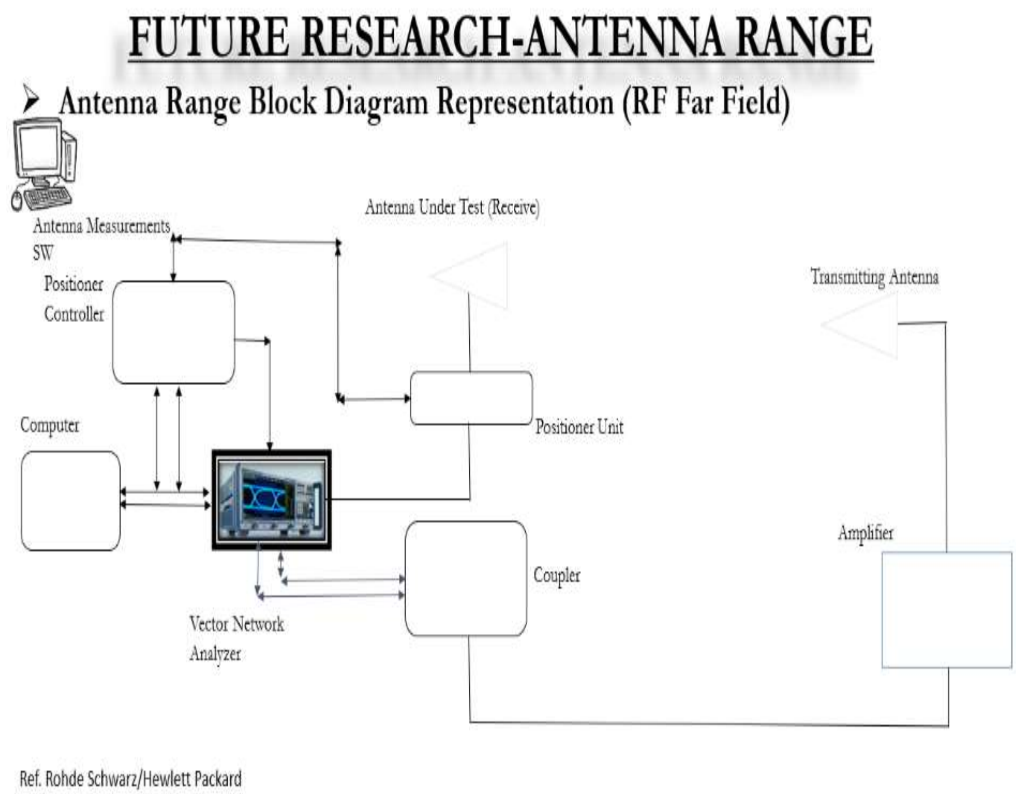


Figure 5.1: Antenna range measurement system block diagram

APPENDIX A

IMAGE REPRESENTATION OF WIDE AREA AUGMENTATION SYSTEM

Wide Area Augmentation System [55] is used to increase GPS and/or Differential Global Positioning System (dGPS) performance to meet and compile with user specification requirements, improve signal availability, and provide better performance than using a standard GPS service.

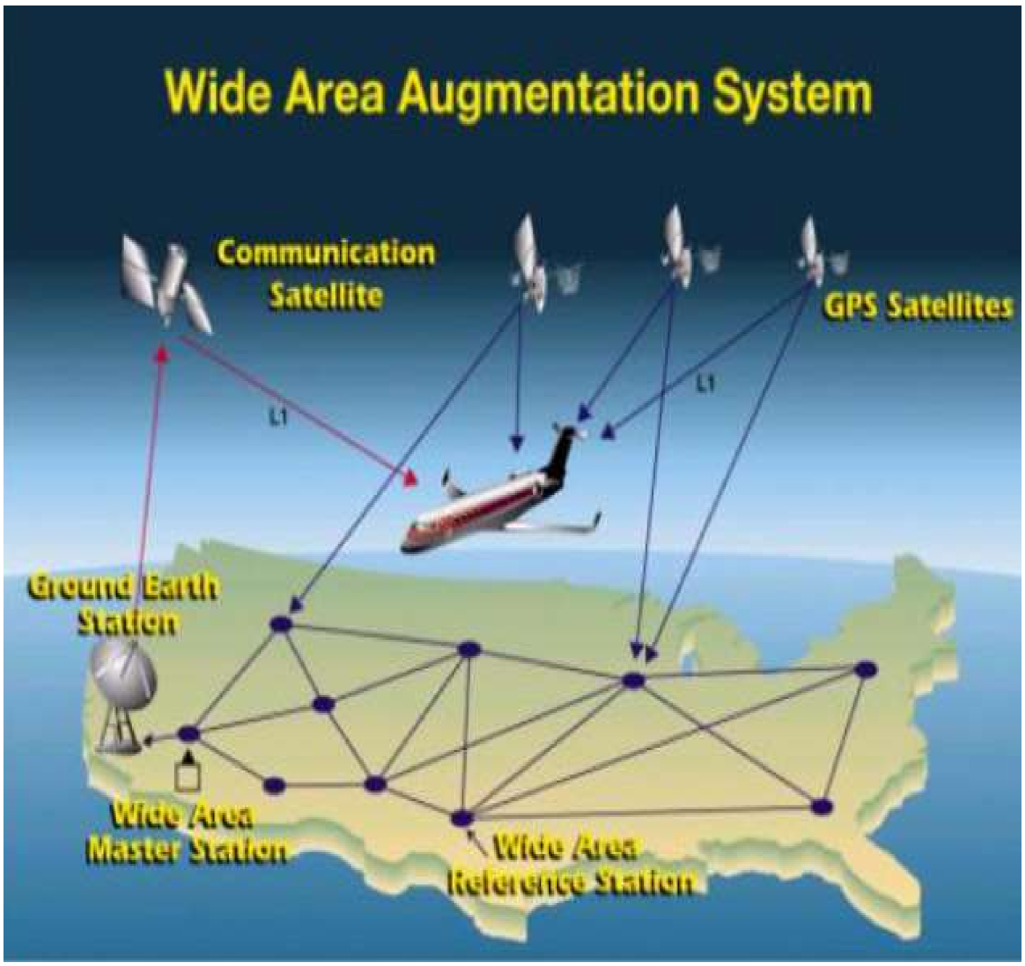


Figure A.1: Pictorial Representation of Wide Area Augmentation System

APPENDIX B

FEKO DEFINITION AND ANTENNA DESIGN PROCESS

What is FEKO?

FEKO is an electromagnetic field simulator based on a Method of Moments that can be used to compute an antenna's basic characteristics, such as gain, input impedance, radiation pattern, S-parameters, and antenna electric currents. In other words, the FEKO software package is an engineering tool used for simulation, modeling, design, verification, validation, and analysis of an electromagnetic device in engineering and scientific disciplines. FEKO generates models of simple to a complex structure antenna. These models must be carefully put together and made certain that the proposed antenna design satisfies the electrical, mechanical, and environmental requirements of the antenna. The main process involved in a classic, embedded, and smart antenna design in FEKO space is illustrated in Figure D.1.

APPENDIX C

LIST OF PUBLISHED JOURNAL AND REFEREED CONFERENCE PAPERS

C-I Refereed Journal Papers

C-I-1 Modeling and Designed of a Monopole Antenna that Operate at 3.3 [GHz] for Future 5G sub 6 [GHz]

C-I-2 Evaluation of (GPS/GLONASS) Patch Versus RF GPS (L1) Patch Antenna Performance parameter

C-II Refereed Conference Papers

C-II-1 GNSS Patch Antenna Design Parameter Optimization using FEKO, Design of Experiments & P-Transform Technique

C-II-2 Comparison of GNSS Patch Versus GPS L1 Patch Antenna Performance Characteristic

C-I-1 Refereed Journal Papers

"Modeling and Designed of a Monopole Antenna that Operate at 3.3 [GHz] for Future 5G sub 6 [GHz]"

International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-10 Issue-5, June 2021

Modeling and Designed of a Monopole Antenna that Operate at 3.3 [GHz] for Future 5G sub 6 [GHz]

Gholam D Aghashirin, MagedKafafy, Hoda S. Abdel-Aty-Zohdy, Mohamed A. Zohdy, Adam Timmons

Abstract: Antenna unit is an importantpart of ADAS L2, L2+ and Automated Driving L3 systems. It needs to function as needed in dGPS, HD Map Correction Services, OEM Radios and Navigation Systems. The presented monopoleantenna model for 5G below 6 [GHz] operating at 3.3 [GHz] is developed. This work demonstrates the modeling, design, and determining of monopoleantenna with intended targeted applications within the automotive system emerging autonomous vehicles space and as well as 5G Wireless Cellular Technology domain. FEKO simulation is undertaken rather than mathematical modeling to create the structure and conduct the analysis of the proposed monopole antenna.In order to support the fifth generation (5G) of wireless communication networks, SOS messages, vehicle tracking, remote vehicle start, Advanced Driver Assistance Systems (ADAS) L2, L2+/ Autonomous Driving (AD) L3 systems self-driving vehicles powered by 5G with rapidly growing sets of ADAS and AD features and functions within the autonomous space, USA cellular carriers mobile phone communication standard 4G MISO and 5G MIMO, LTE1, LTE2, connected functions, features/services, IoT, DSRC, V2X, and C-V2X applications and 5G enable vehicles destined for the NAFTA (USA, Canada and Mexico) market, a new single monopole antenna that operate at 3.3 [GHz] for future 5G (MIMO) below 6 [GHz] modeling, design and simulation with intended automotive applicability and applications is proposed.

The presented novel new 5G below 6 [GHz] monopoleantenna:

1. ***Is not being investigated on the literatures review and published papers studied.***
2. ***No paper exists on these frequency bands.***
3. ***The desired monopole antenna is a new antenna with fewer components, reduction in size, low profile, competitive cost, better response to received RF signals for frequencies for future 5G below 6 [GHz] with each of the following:***
   a. ***Range of operating frequencies, 0.6 [GHz] to 5.9256 [GHz].***
   b. ***Centerfrequency = 3.2628 [GHz] ~ 3.3 [GHz] for the above band.***
   c. ***Lambda (λ) = (3.0 x10^8 [m/sec^2])/(3.3x10^9 [Hz])=0.090 [m] = 90 [mm], lambda (λ) /4 = (0.090 [m])/4=0.0225 [m]=22.5 mm ~ 23 [mm], the overall monopole antenna height.***

To be more direct, simulation studies are carried out and are done utilizing FEKO software package from Altair to model the proposed monopole antenna for 5G below 6 [GHz] frequency band. The focus is on the frequency band for 5G sub 6 [GHz] cellular system.

The paper will introduce the following key points:

1. ***Modelled and anayzed single element 5G sub 6 [GHz] monopole antenna.***
2. ***Student version of CAD FEKO program was used to design our desired monopole antenna with a wire feed excitation coupled with step-by-step instructions is undertaken to highlight the model geometry creation of our monopole antenna. POST FEKO program is used to plot and view our simulation results.***
3. ***We report the development of 5G below 6 [GHz] for fifth generation (5G) system that meets automotive and vehicle homologation specification requirement of antenna height < 70 [mm]. So that the proposed monopole antenna can easly be integrated into multi tuned cellular antenna system.***
4. ***The FEKO simulation is conducted in 2D and 3D element model, in terms of Far-Field Vertical Gain as a function of an Elevation Angle plots.***
5. ***Future research work and study for the next steps will be recommended.***

Keywords: Differential Global Positioning System (dGPS), Advanced Driver Assistance Systems (ADAS), Automated Driving (AD), Long Term Evolution1 (LTE1), Long Term Evolution2 (LTE2), Multiple Input Single Output (MISO), Multiple Input Multiple Output (MIMO), Internet of Things (IoT), Dedicated Short Range Communications (DSRC), Vehicle to Everything (V2X), Cellular Vehicle to Everything (C-V2X), High-Frequency Structure Simulator (HFSS), Ultrawideband (UWB) and Wireless Local Area Network (WLAN)

I. INTRODUCTION

An antenna in general could be defined as a wireless communication transducer, such as a single piece of wire (Monopole) for radiating and/or capturing traveling and/or impinging electromagnetic wave. To be specific, antenna is reciprocal module, which can be utilized as a launching and/or as receiving device. Electromagnetic field emitted by an antenna satisfies James Maxwell's set of differential and integral form equations, which are used to describe the relations of the field vectors, charge densities, and current densities at any time and at any point in space per Balanis [3].

Manuscript received on June 15, 2021.
Revised Manuscript received on June 18, 2021.
Manuscript published on June 30, 2021.
* Correspondence Author
Gholam D Aghashirin*, Departmentof Electrical & Computer Engineering, Oakland University, Rochester, Michigan, USA
Maged Kafafy, Department of Electrical & Computer Engineering, Oakland University, Rochester, Michigan, USA
Hoda S. Abdel-Aty-Zohdy, Department of Electrical & Computer Engineering, Oakland University, Rochester, Michigan, USA
Mohamed A. Zohdy, Departmentof Electrical & Computer Engineering, Oakland University, Rochester, Michigan, USA
Adam Timmons, Departmentof Mechanical Engineering, McMaster University, Hamilton, Canada.

Curl $\vec{E} = -j\omega\mu\vec{H}$
Curl $\vec{H} = \vec{J} + j\omega\mathcal{E}\vec{E}$

Where:

$\vec{E}$ = Vector Electric Field Intensity (volts/meter)
$\vec{H}$ = Vector Magnetic Field Intensity (amperes/meter)
$\vec{J}$ = Electric Current Density (amperes/square meter)
$\mathcal{E}$ = Time-Varying Permittivity of the Medium (farads/meter)
μ = Time-Varying Permeability of the Medium (henries/meter)
ω = Angular Frequency

According Balanis [1], wire or linear antennas are some of the simplest, cheapest and in many cases are the most versatile for many applications.

It is deemed necessary to use an antenna that provides an optimum coverage coupled with a constant gain over its service area and simultaneously suppresses undesired electromagnetic wave fronts and/or interference impinging signals on its input terminal. The proposed 5G below 6 [GHz] monopole antenna would successfully meet and satisfy the above requirements. The electromagnetic wave signal fronts arriving at monopole antenna is a planar Transverse Electromagnetic (TEM) wave, which indicates the Electric Field vector ($\vec{E}$) and Magnetic Field vector ($\vec{H}$) are everywhere perpendicular to each other and orthogonal to the direction of electromagnetic wave propagation. More preciously, the angle between our two vector field quantities, $\vec{E}$, $\vec{H}$ and direction of wave traveling is a 90 [degrees].

Our proposed monopole antenna system consists of:

1. A vertically polarized radiating elementmonopolewire antenna with its corresponding length of 23 [mm].
2. The conducting rectangular ground plane with the dimensions $40\,x\,40$ [mm]^2 supports as a base for our monopole antenna.
3. A feeding pin with a length of 0.5 [mm].

And it is designed to have a gain pattern that is a function of elevation angle.

A Student Edition of FEKO software package is an electromagnetic wavesimulatoralong with numberical technique, such as the Method of Momments was used to design the 3D geometric model of our 5G below 6 [GHz] monopole antenna along the z-axis.Fig. 1, below shows our model. This model being excited by a voltage source of excitation with each of the following set of scalar parameters:

1. Magnitude = 1 [V]
2. Phage Shift = 0 [Degrees]
3. Impedance = 50 [Ohm]

At the conclusion of the above process of our monopole antenna model creation in the CADFEKO environment, a 3D Radiation Pattern, and 2D Far-Field/Gain were ploted generated by using the POSTFEKO program.

To be more specific, monopole antenna,have a lot ofapplications across multiple areas of scientific and engineeringdiscipline and it plays a significant role in wirelesscommunication systems, inautomotive space involving Radios, Navigation Systems,ADAS/Automated Driving L2 and L3 Systems, precise positioning andmobile phones. Because of its low profile and effective cost, itconsidered as a better antenna solution choice in wide varietyof applications. We investigated and presented our monopoleantenna geometry model creation within the "CADEFEKO programandthan "POSTFEKO was used to obtain our antenna solution in terms of Far field/passive gain results.

Deng [4], covered a coplanar waveguide-fed monopole antenna that is made up of a rectangular monopole patch notched at the bottom with a T shaped coplanar waveguide as its ground plane. Their study was carried out via simulation with HFSS and experimential method, in order to achieve "a fractional impedance bandwidth of 164% for S11 $\leq$ -10 [dB], which is about 2.3 times of the conventional one. Furthermore, Deng [4] highlighted monopole antenna has been largely utilized in wireless communication system because of their less costs, simple structure, omnidirectional radiation pattern and it is also suitable for portable mobile ultrawideband (UWB) applications.Wen [7], proposed a monopole antenna that made up of a capacity loaded matching patch two resonators, two meandering monopoleantenna.Wen's, paper presents a compact monopole antenna with filtering response for WLAN related applications.Wen's work focuses mainly on the simulation versus an experimental measurement results that points out their proposed monopole "antenna has a wide impedance bandwidth of 16% for S11<-10 [dB]" plus an omnidirectional radiation pattern was achieved and realized by their study. Hong [5], has shown a trapezoid patch monopole radiator that isplaced on a "quasi-fractal" solid ground plane, where the antenna system operates in a dual band that covers the frequency range of WLAN, "1.74-2.38 and 4.46-5.56 [GHz]". Chen [5], reports a triband planar monopole antenna with dual inverted L-slot are etched, to obtain three radiating elelments that functions in three resonant modes of operation with WLAN/WiMAX applications as its intended focus. Different monopole antenna structure with various radiating element shapes coupled with variety of ground plane designed with applications related to WLAN, and WLAN/WiMAX (Chen [6]) published papers studied, however observed that there is a problem related to cellular 5G below 6 [GHz] monopole antenna coupled with an antenna solution that would satisfy the automotive and vehicle homologatioin specification of an antenna height < 70 [mm], which has not been investigated. In this work, a compact, robust, low profile monopole antenna solution is proposed and designed via FEKO simulation tool to cover cellular 5G sub 6 [GHz] frequency band with an overall antenna height of appromimately 23 [mm].

Retrieval Number: 100.1/ijeat.E28320610521
DOI:10.35940/ijeat.E2832.0610521
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication

2. We selected and set the antenna model unit to millimeters [mm] in CADFEKO space as shown in Fig.3.

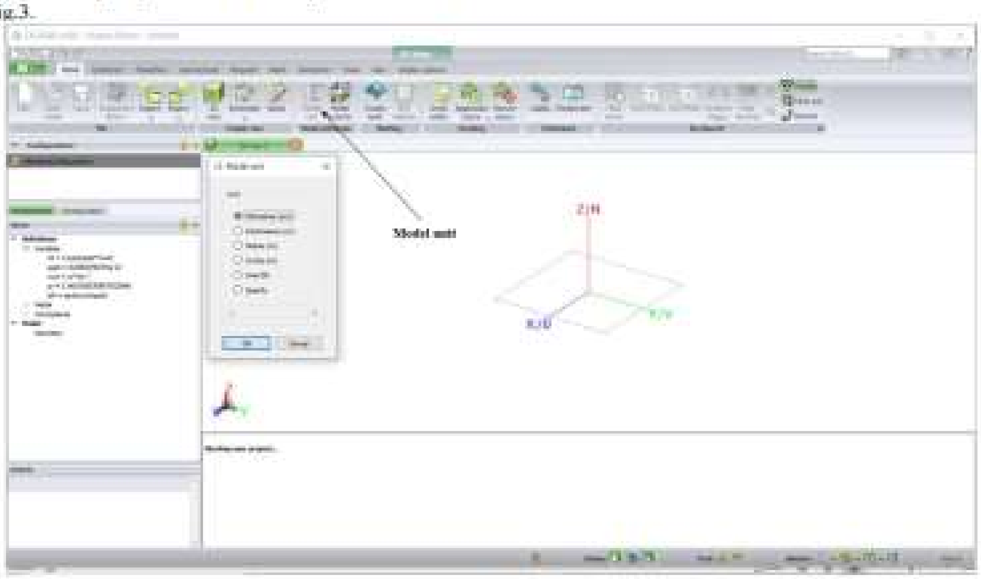


Fig. 3. "CADFEKO" Modeling Window ("Model unit")

3. Next, declaredadded variables, such as the operating frequency, ground plane length, ground plane width, monopole antenna length, feeding pin lengththat defined the antenna geometry as indicated in Fig. 4.

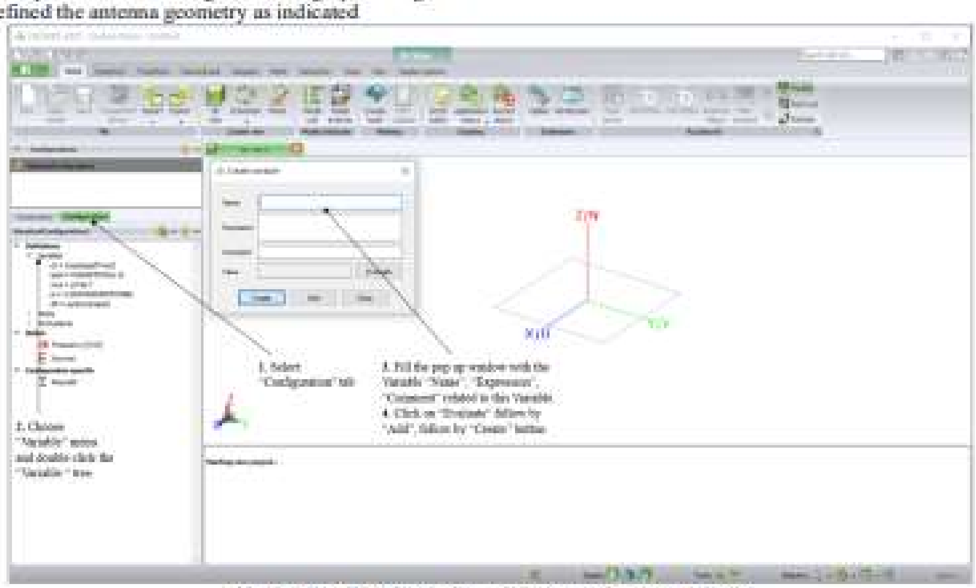


Fig. 4. "CADFEKO" Modeling Window ("Create variable")

Retrieval Number: 100.1/ijeat.E28320610521
DOI:10.35940/ijeat.E2832.0610521
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication

4. A "Rectangular" [3] ground plane surface geometry with its corresponding media type was selected to be a Metallic was created by clicing on the "Rectangle" icon function located under the "Construct" tab as displayed in Fig. 5.

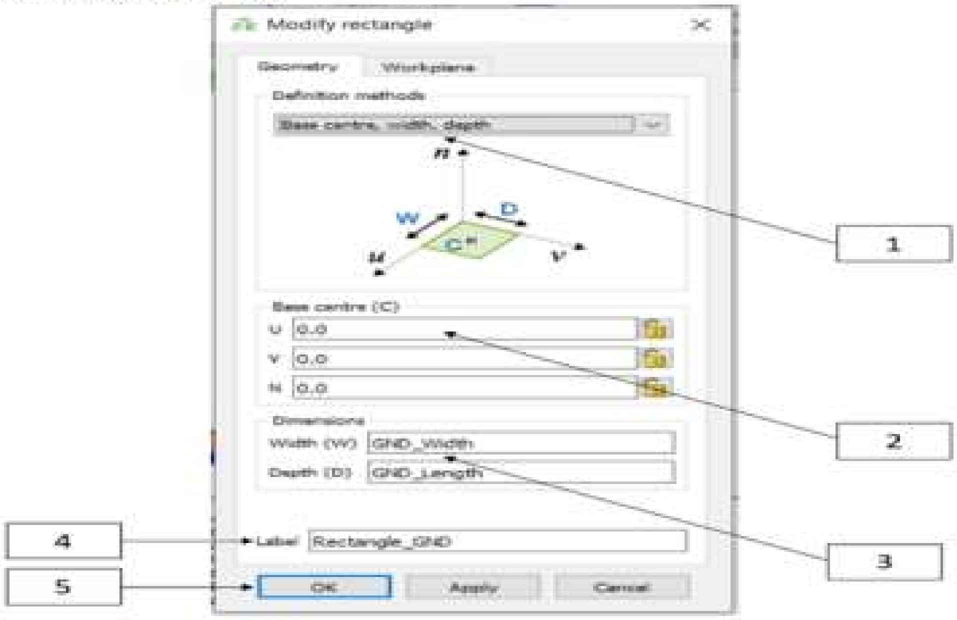


Fig. 5. "CADFEKO" Modeling Window ("Create variable")

From the above popup window, under the "Definition methods", "Base", "centre", "width", "depth" option was picked from the drop-down menu first. "Base centre (C)" coordinates for U=0, V=0, & N=0 was filled second. The "Dimensions" of our ground plane in terms of the defined variables were inputed into the "Width (W)" and "Depth (D)" field third. A label was filled in the "Label" field area next. Lastly, we clicked on the "OK".

5. Added our radiating elelment by selecting the "Line" [3] function.
6. Created the feed pin by using the "Line" [3] curve function to excite or energize our antenna.
7. Added a wire port at the start of the Line location followed that by a source of excitation, such as a voltage source was placed at this port.
8. Requested the "Far fields" [3] solution from under the "Configuration" [3] tab.
9. Used the "Union" [3] function to group each component or elements of the overall GNSS patch antenna geometry together.
10. Set the operation and/or simulation frequency.
11. Run the "Create mesh" [3] function followed by the "CEM validate" [3] feature, in order perform the "Meshing" [3] and "Computational electromagnetic validation" [3].
12. Conducted and executed the "Feko solver" [4] function and after the simulation is finished, next run and launch the "POSTFEKO" [4] post-processing program.
13. "POSTFEKO" [3] environment was used to plot the 2D Average Gain and/or Far fields and view the Passive Gainresults.

Due to FEKO LITE (Student Version of FEKO) limitedcapabilities, one may need to use the Full version, the nonacademicvariant of the FEKO software package in theirsimulation studies, in order to reduce uncertainty, errors barand ultimately enhance the mathematical calculationcapabilities of the desired model meshing.

C. 5G sub 6 [GHz] Monopole Antenna Design Parameters Electrical, Mechanical and Environmental Detail Requirements

Table-I, indicates the design, modeling, and simulation ofthe monopole antenna geometry creation numeric parametervalues and Table-II, shows the model meshing valueswhitnin the CADEFEKO space.

Table-I:Model Creation Parameters of MonopoleAntenna Structure

Electrical Requirements	
Range of Operating Frequency	0.6 [GHz] to 5.9256 [GHz]
Center Frequency	3.3 [GHz]
Full Lambda (λ)	90 [mm]
Impedance	50 [Ω]
Excitation Source (Voltage)	Magnitude = 1 [V] Phase Shift = 0 [Degrees]
Mechanical Requirements	
Monopole Antenna Length, Lambda (λ)/4	23 [mm]
Feeding Pin Length	0.5 [mm]
Ground Plane Length	40 [mm]
Ground Plane Width	40 [mm]
Environmental Requirements	
Operating Temperature	-40 [degrees] to +85 [degrees]

Table-II:Feko Meshing Parameter Value

5G sub 6 [GHz] MonopoleAntenna Meshing Parameter (Wire Segment Radius)	0.01 [mm]

D. 5G sub 6 [GHz] Monopole Antenna 3D Model in CADFEKO andPOSTFEKO Environment

Fig. 1, plot illustratesour monopoleantenna structure with a rectangular orangecolor ground plane and a line radiating element modeled.

Fig. 1, and Fig. 2, indicates the Top View and Cross SectionView within the "CADFEKO" [3] space. Fig. 3, captures theCross Section View of themonopoleantenna within the"POSTFEKO" [3] environment.Fig. 4, depicts our monopoleantenna 3D omni-directional radiation pattern in the"POSTFEKO" [3] space.

Fig. 1 and Fig. 2, depicts our monopole antenna model in the"CADFEKO" [3] page.

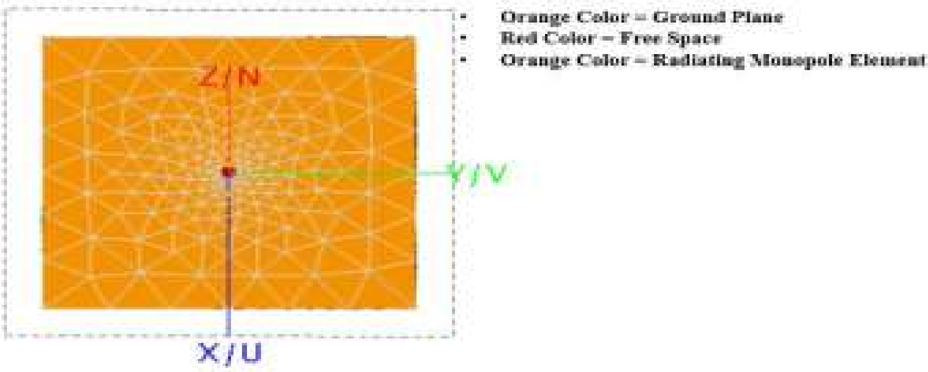


Fig. 1. 5G below 6 [GHz] monopole antenna operating at 3.3 [GHz] (Top View).

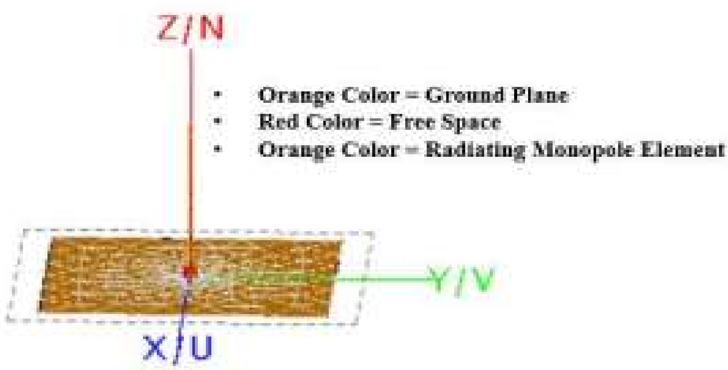


Fig. 2. 5G below 6 [GHz] monopoleantenna operating at 3.3 [GHz] (Cross Section View).

Fig. 3 and Fig. 4, indicates our 5G below 6 [GHz] monopoleantenna model coupled with the 3D pattern in the"POSTFEKO" [3] page.

Retrieval Number: 100.1/ijeat.E28320610521
DOI:10.35940/ijeat.E2832.0610521
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication

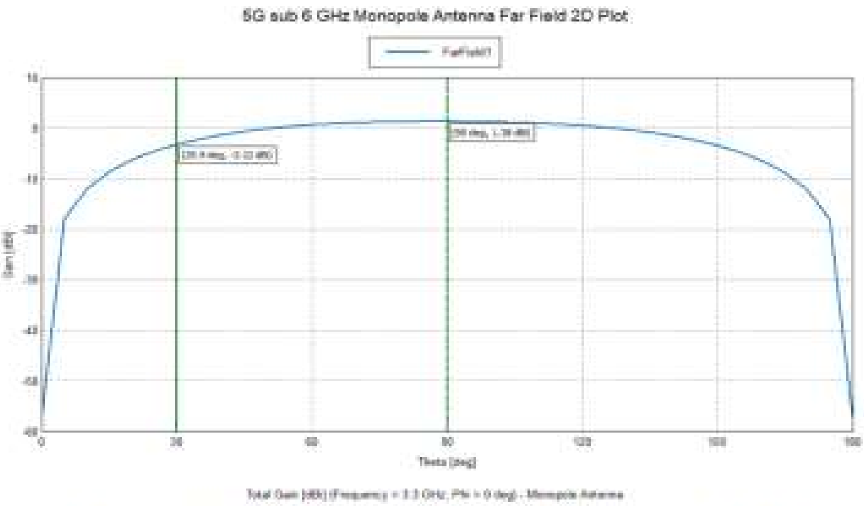


Fig. 5. 5G below 6 [GHz] monopole antenna operating at 3.3 [GHz] (Rectangular 2D plot).

III. CONCLUSION AND FUTURE WORK

In this paper we have presented, investigated, and has been discussedthe NEW cellular 5G sub 6 [GHz] with center frequencyat 3.3 [GHz] monopole antenna design, modeling and simulationby using FEKO software package. We have successfully demonstrated the creation of our proposed monopole antenna geometry, configuration model in the CADFEKO space and obtained results in terms 2D Far-Field, Gain plots coupled with 3D Radiation Pattern in the POSTFEKO domain.

The proposed monopole antenna finds applications in cellular wireless communication networks, modern automotive components, systems,autonomous vehicle space and it also finds application in wideareas of other scientific and engineering disciplines. Ourmonopleantenna model was created, simulated and then it iscorresponding antenna characteristic, such as Far-field/vertical gain wasfound to be 1.84 [dBi] for monopole antenna delta between30 and 90 [degrees] within the POSTFEKO [3] environment. The emphasis of this paper was to examine and investigate the design of a new cellular monopole antenna that operate in the frequency band of 0.6 [GHz] to 5.9256 [GHz], met the automotive vehicle homologation requirement with our proposed monopole antenna λ /4 overall height of 23 [mm] and the this was successfully achieved.

For future work, the simulation studies can be extended tofocus on a single monopoleantenna that will supportmulti-band frequencies and its operating frequency upper limit can be extended up to 7.125 [GHz] [8] band of frequencies. A physical prototype for the proposed 5G below 6 [GHz] monopole antenna can be created, installed, and mounted on an optimal location on a vehicle body structure and/or vehicle roof location areafor the purpose of core vehicle level Verification and Validation testing. The presented monopole antenna solution can also be a Device Under Test (DUT) as a receiving test antenna at an Anechoic Chamber and/or Indoor Antenna Range in support of the measuring the basic antenna characteristics such as Gain, Radiation Pattern, Radiation Efficiency, Directivity, Impedance, Bandwidth, Polarization and Current draw and/or Antenna Surface Current.

REFERENCES

1. Constantine A. Balanis, "Antenna Theory Analysis and Design", 2nd ed., New York: Wiley, 1997, p. 133-135.
2. Constantine A. Balanis, "Advanced Engineering Electromagnetics", United States of America: John Wiley & Sons, Inc., 1989, p. 1-7, 24-31.
3. "CADEFEKO & POSTFEKO v2021-Student Edition".
4. Chao Deng, Yong-junXie and Ping Li, "CPW-Fed Planar Printed Monopole Antenna With Impedance Bandwidth Enhanced", IEEE Antennas and Wireless Propagation Letters, Vol. 8, 2009.
5. Tao Hong, Shu-Xi Gong, Ying Liu and Wen Jiang, "Monopole Antenna With Quasi-Fractal Slotted Ground Plane for Dual-Band Applications, IEEE Antennas and Wireless Propagation Letters, Vol. 9, 2010.
6. Hong Chen, X. Yang, Y.Z. Yin, S.T. Fan and J.J. Wu, "Triband Planar Monopole Antenna With Compact Radiator for WLAN/WiMAX Applications", IEEE Antennas and Wireless Propagation Letters, Vol. 12, 2013.
7. Leh Wen, Steven Gao, Qingling Yang and Qi Luo, School of Engineering and Digital Arts, University of Kent, Canterbury CT2 7NT, United Kingdom, Yingzeng Yin, National Key Laboratory of Antennas and Microwave Technology, Xidian University, Xian 710071, China, Xiaofei Ren and Jian Wu, Innovation and Research Center, China Research Institute of Radiowave Propagation, Qingdao, 266107, China, "A Compact Monopole Antenna With Filtering Response for WLAN Applications", China Research Institute of Radiowave Propagation, and in part by EPSRC grantsEP/N032497/1, EP/S005625/1, and EP/P015840/1.
8. Ravilla Dilli, Electronics and Communication Engineering, Manipal Institute of Technology, Manipal, Karnataka, India, dilli.ravilla@manipal.edu, "Analysis of 5G Wireless Systems in FR1 and FR2 Frequency Bands", Proceedings of the Second International Conference on Innovative Mechanisms for Industry Applications (ICIMIA 2020) IEEE Xplore Part Number: CFP20K58-ART; ISBN: 978-1-7281-4167-1.

Retrieval Number: 100.1/ijeat.E28320610521
DOI:10.35940/ijeat.E2832.0610521
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication

AUTHORS PROFILE

GholamAghashirin, graduated from Ryerson University, Toronto, Ontario Canada with a B.Eng. in Electrical, Electronics and Communication Systems, earned his M.Sc. in Electrical and Computer Engineering from Oakland University, Rochester, Michigan, USA and he is currently a Ph.D. candidate in Electrical and Computer Engineering at Oakland University, Rochester, Michigan, USA. He has worked as an Engineer in advanced engineering projects, assignments in the automotive industries at various level of complexity and leadership roles in the field and space of Global Telematics, Automotive Radio Head Units, Navigation Systems, Instrument Clusters, Voice Recognition, Dialog, Hands-Free Systems, Electrical and Electronics ADAS L2/L2+, Automated Driving L3 Systems and OTA updates of Connected and ADAS modules/features/functions. His research interests include Electromagnetics, location technologies, antenna design, modelling, simulations at the component, vehicle level, and antenna experimental measurements.

Hoda S. Abdel-Aty-Zohdy, received the B.A.Sc. degree (with First Class Honors) in Electrical and Communications Engineering from Cairo University, the M.A.Sc and Ph.D. degrees in Electrical Engineering from the University of Waterloo, ON, Canada. Dr. AbdelAty-Zohdy is a Professor of Electrical and Computer Engineering, The John F. Dodge Chair Professor of Engineering, 2012-2014; Director of the Microelectronics & Bio-Inspired Systems Design Lab at Oakland University, Rochester, MI, USA. Her research and teaching focus on Circuits, Devices, VLSIC, H/W deep-learning, Electronic-Nose, and Bio-Inspired IC chips for high fidelity classifications. She organized, chaired, served on several conferences and committees for the IEEE/CASS and as Distinguished Lecturer 2004-2006.

Adam Timmons, received the Ph.D. degree in Materials Science from Dalhousie University, Halifax, Nova Scotia, Canada. Dr. Adam is an Adjunct Professor within the Department of Mechanical Engineering at McMaster University, Hamilton, ON, Canada. He has many professional and academic appointments and holds a large number of patents.12 Computer Science & Information Technology (CS & IT)

Mohamed A. Zohdy, received the B.A.Sc degree in Electrical Engineering from University of Cairo, the M.A.Sc and Ph.D. (Medal) from the University of Waterloo, ON, Canada. Dr. Mohamed is a Professor of Electrical and Computer Engineering at Oakland University, Rochester, MI, USA. Professor Mohamed research focus is in the area of Advanced control and estimation, intelligent pattern information processing, neural, fuzzy, evolutionary systems, chaos control, smart simulation, hybrid systems.

Maged A. Kafafy, received the Bachelor of Science in Mechanical Engineering, Lawrence TechnologicalUniversity, Southfield MI, USA, Master of Science in Mechanical Engineering with Manufacturing Option and the PhD. in Electrical and Computer Engineering at Oakland University, Rochester

C-I-2 Refereed Journal Papers

"Evaluation of (GPS/GLONASS) Patch Versus RF GPS (L1) Patch Antenna Performance Parameter"

1. INTRODUCTION

GPS constellation system that is managed and maintained by the United States Department of Defense since the early 70s. GPS is a space base radio navigation system that supplies an estimated position, velocity and timing information to a GPS antenna/receiver module on the global. GPS system is mainly consisting of three parts, namely the space component, ground control station and user segment.GPS constellation we have 31 fully operational satellites positioned at an altitude of 20, 000 km (12, 427 miles) and it moves around the earth twice a day. Where each satellite transmits ranging and navigation data on the L1 (1.57542 GHz), L2 (1.22760 GHz), and L5 (1.17645 GHz) carrier frequencies [3].

In order to support an array of applications across various industries, wireless communication (Satellite, Spacecraft), Missile, Mobile Devices such as a Cell Phone, Ground Reference Station, spaces, platforms and automotive sector that requires accurate timing and precious positioning data, messages, signals information to be deliver to a domestic and non-domestic vehicles destined to USA, Canada, Mexico and European markets plus as a result of rapid growth in an automotive applications related to connected services, automotive radio head unit features, functions and navigation systems, an antenna that can receive both RF GPS L1 passive patch and active GPS/GLONAS Spatch antenna frequencies is needed. Therefore, due to its low cost and profile targeting applications across various sectors of automotive and non-automotive industries, the following two proposed antennas is investigated and compared in this research work:

1) RF GPS L1 passive patch antenna

2) Active GPS/GLONAS Spatch antenna

The RF GPS L1 passive patch antenna has radiating element size of 12.25 x 12.25 mm and it operates at the GPS L1 1.57542 GHz frequency. While on the other hand, the active GPS/GLONAS Spatch antenna has 12.25 x 12.25 mm with resonate frequency of 1.5925 GHz.

The RF GPS L1 passive patch and active GPS/GLONAS Spatch is model, simulated, designed, simulation results obtained and constructed on a 5.5 mm ceramic/porcelain substrate material and ground plane length and width size for each antenna of 95 by 95 mm respectively in the CADFEKO page were defined and antenna far field/passive gain were obtained in the POSTFEKO environment. To be more direct, FEKO simulation software package was used to model, simulate and design both antennas.

We are interested to know the antenna characteristic performance parameter, such as the passive gain of the two proposed antenna. Initially, both antennas design parameters were defined, FEKO models for each respective presented antenna were created, by creating the radiating element, dielectric substrate, ground plane, feed pin, add a port to the created feed pin, added a voltage source of excitation, set the simulation frequency, union antenna parts together, mesh the generated antenna model geometry followed by simulating the model by running the FEKO Solver all within the CADFEKO environment.

POSTFEKO was used to obtain the passive gain expected results, 2D plots of simulated Far Field, top/side view of the studied antennas and use the simulation results from the POSTFEKO environment to compare passive gain results and determine an optimal antenna solution and make recommendations for the automotive industries with intended applications targeting automotive radios and navigation systems that requires GPS and GPS/GLONASS signals.

Upon comparing the obtained simulation results of the RF GPS L1 patch and GPS/GLONASS patch antenna structure from the POSTFEKO environment in this research work, it was found and concluded that the simulated results of the proposed GPS/GLONAS Santenna is a better antenna solution for the automotive applications related to automotive radios and navigation systems.

An antenna could be defined as a wireless communication device or module such as a piece of wire for radiating or receiving electromagnetic wave propagating in a communication channel, such as guided structure transmission line and then getting transmitted into a free space and/or vice versa in the receiving mode. Furthermore, we present the passive gain of the RF GPS only patch and GPS/GLONASS antenna structure using FEKO electromagnetic simulation software package, in order to support automotive applications. Plus, this study describes the modeling, design, simulation and analysis of RF GPS only (L1) patch and GPS/GLONASS patch antenna. According to Constantine A. Balanis, the antenna is the transitional structure between free-space and a guiding device, for wireless communication systems, the antenna is one of the most critical components. For the past few decade Microstrip Patch Antenna were used heavily in high performance aircraft, spacecraft, satellite and missile where size, weight, cost, performance, ease of installation, and aerodynamic profile are constraints. Low profile antennas maybe required [1] for packaging and/or aesthetic constraints. The active GPS/GLONASS patch antennas play a significant role in today's modern communications, i.e. they nicely meet automotive specification requirements, most antenna designers and OEMs mainly preferred and select this rectangular/square active GPS/GLONASS patch antenna, in order to mount, install, place and position it on their production vehicles.

This research work main contribution is the RF GPS L1 passive only patch versus active GPS/GLONASS passive gain comparison through modeling and simulation within the FEKO (CADFEKO and POSTFEKO) environment.

The question/problem to address of how to obtain the same and/or equivalent amount of antenna passive gain in a GPS/GLONASS versus GPS L1 antenna is the objective of this research work. The problem has not been solved, no solution is available on the shelf.

The verification and validation of antenna characteristic performance parameter testing of proposed antenna can be conducted at the automotive bench, vehicle level, and at an antenna range with no limitations or deficiencies by using antenna measurements with a presented Antenna Under Test (AUT) component, Antenna Measurement Software, DC Power Supply, Bias-Tee, and Vector Network Analyzer (VNA). The accurate far field and/or proposed antenna passive gain measurements can be performed fast.

1.1. Patch Antenna Geometry Photo

Figure 1 below shows the patch antenna basic structure model in general, where we have a metallic rectangular radiating element, which we call it patch that is place over a dielectric substrate material with a specific relative permittivity and at the bottom of substrate is a conducting base layer that acts as a rectangular conducting ground plane.

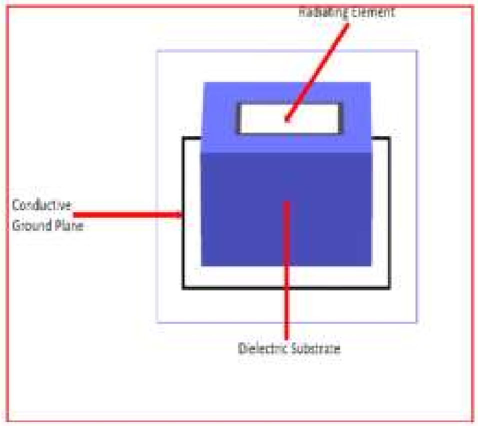


Figure 1. Patch Antenna Structure

1.2. GPS Constellation System Photo

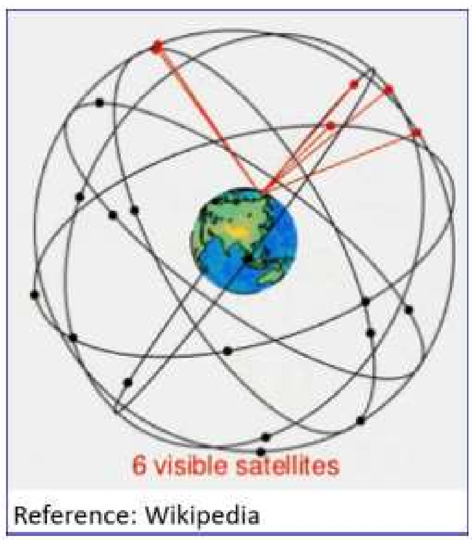


Figure 2. GPS Satellites Constellation

This research work is organized into six Sections. In Section 1, we highlight our Introduction followed by a Patch Antenna skeleton geometry in general. In Section 2, we are discussing Antenna Performance Characteristics and set of Design Equations. In Section 3, we offer Antenna Design, FEKO Simulation Studies, and Discussion of Results. In Section 4, we demonstrate FEKO Design Parameters and further Simulation Results. In Section 5, we present our Findings and Conclusions. Lastly, in Section 6, we have our Future Work Suggestions.

2. ANTENNA PERFORMANCE CHARACTERISTICS

In the following below are illustration of mathematical model/equations that define the antenna gain, efficiency, directivity, input impedance, patch actual length and width dimension.

Equation 1Expresses, the Antenna Gainas:

$$gain = 4\pi \frac{radiationintensity}{totalinput(accepted)power} = 4\pi \frac{U(\theta,\varphi)}{Pin} (dimensionless) \quad [1]$$

Also, Antenna Gain is defined in terms of Antenna Efficiency and Antenna Directivity according to Fawwaz T. Ulaby:

$$G = \varepsilon D \quad (\text{dimensionless}) \quad [2]$$

where g=antenna gain, ε=antenna efficiency, and d=antenna directivity

Equation 2 Expresses the Antenna Radiation efficiency as follows:

$$\varepsilon = \frac{Prad}{Pt} (\text{dimensionless}) \quad [3]$$

Where P rad=Radiated Power, Pt=Transmitter Power

In general, the overall Antenna Efficiency can be express as below

$$e_0 = e_r e_c e_d \quad [4]$$

Where e_0=Total Efficiency (dimensionless)

e_c= Conduction Efficiency (dimensionless)

Γ= Voltage reflection coefficient at the input terminals of the antenna

e_d= Dielectric Efficiency (dimensionless)

Equation 3 Expresses, the Antenna Directivity

$$D = 4\frac{\pi}{\Omega_p} (dimensionless) \quad [5]$$

Where Ω_p= Pattern Solid Angle = $\iint_{4\pi} F(\theta,\varphi)\,(d\,\Omega)$ and

$F(\theta,\varphi)$ = Normalized Radiation Intensity = (Elevation Angle, Azimuth Angle)

Equation 4 Highlights, the Antenna Input Impedance, defined as:

$$\text{Input Impedance} = Z_A = R_A + jX_A \text{ (ohms)} \quad [6]$$

5

Where ZA = antenna impedance at the input terminals of an antenna when it operates in transmitting mode (ohms)

R_A = antenna resistance at the input terminals of an antenna when it operates in transmitting mode (ohms)

X_A = antenna reactance at the input terminals of an antenna when it operates in transmitting mode (ohms)

In general, the R_A parameter from below **Equation** is mainly made up of two resistances (R_r and R_L) of the antenna

$$\text{Resistive component} = R_A = R_r + R_L \quad \text{(ohms)} \qquad [7]$$

Where

Rr = Represents the radiation resistance of the antenna (ohms)

RL = Represents the loss resistance of the antenna (ohms)

If we assume that the antenna is connected/attached to a signal/function generator/source with internal impedance, when the antenna is used in the transmitting mode of operation then internal impedance is defines as listed below:

$$\text{Internal impedance } (Z_g) = R_g + jX_g \quad \text{(ohms)} \qquad [8]$$

Where

Rg = Represents the resistance of signal source/generator impedance (ohms)

Xg = Represents the reactance of signal source/generator impedance (ohms)

solving these equations above at high level will permits to obtain the some of the antenna characteristics. where on the other hand feko simulator/simulation software package is based on the method of moments (mom) integral formulation of james maxwell's equations, in order to solve for antenna characteristics, such as antenna gain, antenna input impedance, etc.

per constantine a. balanis the following simplified rectangular patch antenna equations and formulas can be utilized to design microstrip antenna for a given relative permittivity and/or dielectric constant of the substrate material (epsilon r, εr), the resonate frequency (fr), and the substrate height (h):

Equation 5 Determine the patch width W:

$$\text{Patch Width} = W = \frac{v0}{2fr}\sqrt{2/(\varepsilon r + 1)} \quad \text{(cm and/or in)} \qquad [9]$$

Where v0= The velocity of light in free-space (Constant value)

fr = The resonant frequency

εr = The dielectric constant of the substrate

Equation 6 Determine the actual patch length L:

$$\text{Patch Length} = L = \frac{1}{2fr\sqrt{\varepsilon reff}\sqrt{\varepsilon 0\mu 0}} - 2\Delta L \quad \text{(cm and/or in)} \qquad [10]$$

Where ΔL = The extended incremental length of the patch =

$$h\,(0.412)x(\varepsilon reff + 0.3)\left(\frac{W}{h} + 0.264\right)/(\varepsilon reff - 0.258)\left(\frac{W}{h} + 0.8\right)$$

fr = The resonant frequency

$$\varepsilon reff = \text{The effective dielectric constant} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}x\left(1 + 12\frac{h}{W}\right)^{-1/2}$$

$\varepsilon 0$ = The permittivity of free space

$\mu 0$ = The permeability of free space

h = The substrate height

W= The patch width

εr = The dielectric constant of the substrate

Equation 5 and equation 6 above allows for the computation of a rectangular microstrip antenna mechanical dimensions such the actual patch length and width for the purpose of a practical design of patch antenna

3. Antenna Design Aessessment Simulation and Discussion of Results

The testing, experimental, comparison and evaluation of the square RF GPS only passive patch and active GPS/GLONAS Spatch antenna design and simulation of the proposed two antennas is performed using FEKO which has not been previously investigated and/or studied at the FEKO simulation level. The RF GPS only passive patch and active GPS/GLONASS patch antenna will be compared and contrasted mostly from the total passive gain in FEKO simulation environment viewpoint. The photo of each of the respective two test and presented antennas under evaluation and assessment are outlined and shown in Figure 3, Figure 4, Figure 5, and Figure 6. Figure 3 depicts the Front View of the dual band active GPS/GLONASS antenna. From the Figure 4 we can see the Top View of the dual band active GPS/GLONASS antenna. Figure 5 depicts the Front View of the RF GPS only L1 square/rectangular passive patch antenna. From the Figure 6 we can see the Top View of the RF GPS only L1 square/rectangular passive patch antenna.

3.1. Active GPS/GLONASS Patch Antenna Front View Photo

Figure 3. Dual Band Constellation Active GPS/GLONASS Patch Antenna

3.2. Active GPS/GLONASS PatchAntenna Top View Photo

Figure 4. Dual Band Constellation Active GPS/GLONASS Patch Antenna

3.3. RF GPS Only Passive Patch Antenna Front View Photo

Figure 5. RF GPS Only Passive Patch Antenna

3.4. RF GPS Only Passive Patch Antenna Top View Photo

Figure 6. RF GPS Only Passive Patch Antenna

3.5. RF GPS Antenna Samples Consideration for the Evaluation

Table 1. One sample of each antenna used for the model simulation in the FEKO environment

Dual-Band Active GPS/GLONASS Patch Antenna	1
RF GPS Only Passive Patch Antenna	1

3.6. Range of Operating and Simulation Frequency Requirements

The active GPS/GLONASS patch, RF GPS Only L1 passive patch antenna frequencies were used for the purpose of this paper test and simulation activities:

- RF GPS Only L1 passive patch antenna Frequency, GPS (L1): 1.57542 GHz
- Active GPS/GLONASS patch antenna: 1575 to 1610 MHz, Center Frequency (fc)= 1.5925 GHz)

The proposed antennas [RF GPS L1 Passive Patch and active GPS/GLONASS] patch antenna characteristic was simulated by using FEKO simulation software package. An analysis was conducted next and finally total gain for each of the sample antenna were observed from the POSTFEKO environment.

4. FEKO DESIGN PARAMETERS AND SIMULATION RESULTS

We initially performed and conducted the proposed two antennas physical dimension measurements of patch length/width, substrate length/width/height followed that by antenna modelling, simulation and data results analysis activities within the CADFEKO and POSTFEKO software package domain for the following antenna samples:

- RF GPS Only L1 passive patch antenna
- Active GPS/GLONASS patch antenna

Figure 7outlined below indicates the CADFEKO RF GPS patch antenna model that is pin fed voltage source of excitation (1 V, 50 Ω) Top View, Figure 8plot below shows graphic representation of the Cross Section Image of the GPS only (L1 frequency, 1.57542 GHz) passive patch antenna on a finite square/rectangular orange color ground plane, square purple color substrate with dielectric constant value of 5.5 mm and a square dark blue color radiating element created in POSTFEKO. Figure 9 and Figure 10 depict the Front and Side View of the RF GPS only passive patch antenna generated in the POSTFEKO environment.

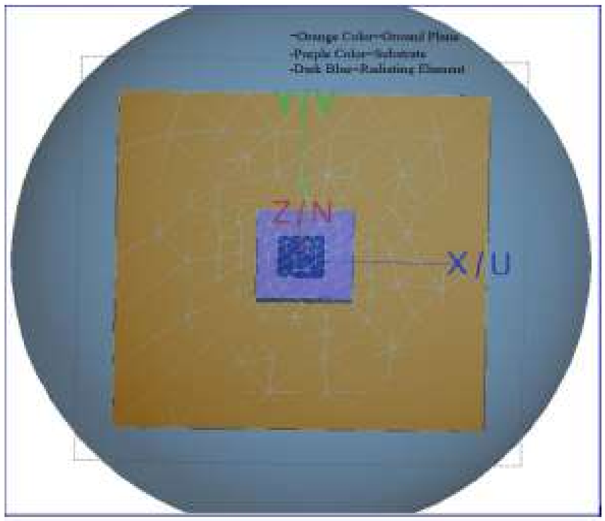


Figure 7. RF GPS Patch antenna operating at 1.57542 GHz (Top View-CADFEKO v2020)

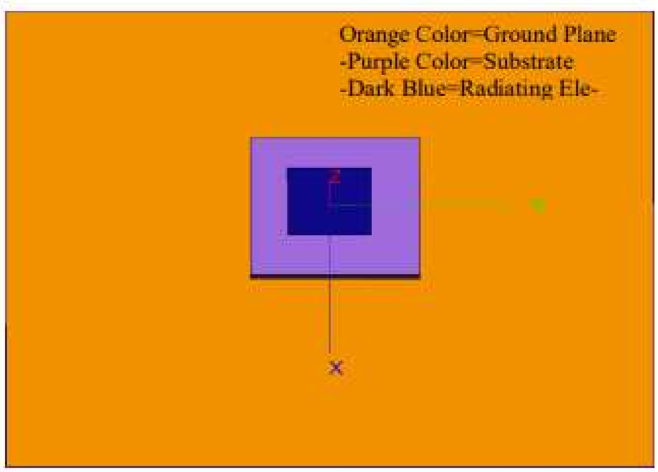


Figure 8. RF GPS Patch operating at 1.57542 GHz (Cross Section Image-POSTFEKO v2020)

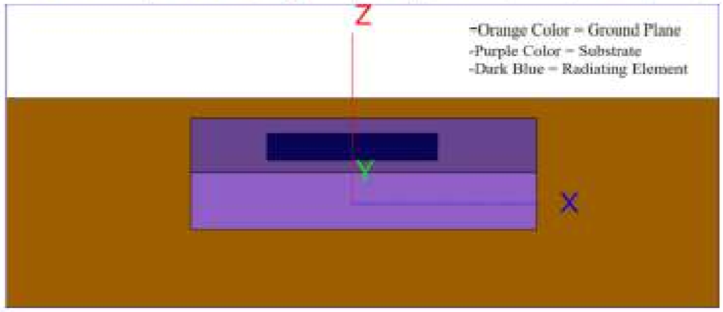


Figure 9. RF GPS Passive Patch operating at 1.57542 GHz (Front View-POSTFEKO v2020)

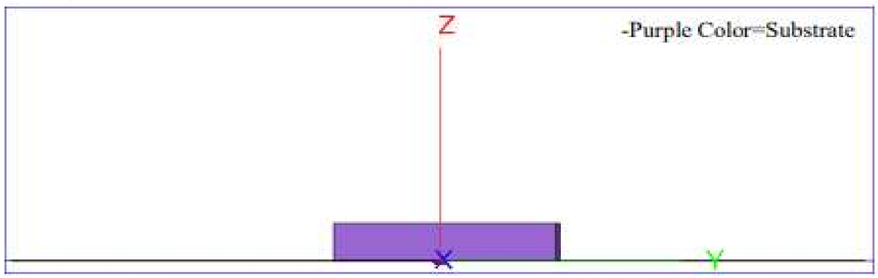


Figure 10. RF GPS Passive Patch operating at 1.57542 GHz (Side View-POSTFEKO v2020)

4.4. Simulated Far Field of Reference RF GPS only Structure Passive Patch Antenna

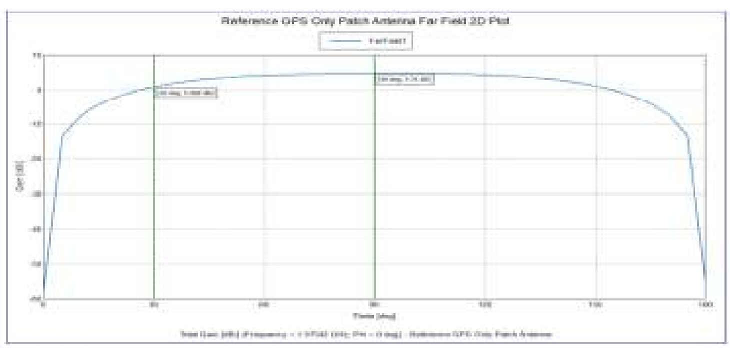


Figure 11. Patch antenna operating at 1.57542 GHz rectangular plot

Using Figure 11, the passive gain is approximately 3.791dBi of the presented antenna and it can be determined by taking the difference in gain angle/delta between 30 and 90 degree angles in the 2D plot graphic.

Figure 11 shows the simulated passive gain of the proposed antenna and we selected substrate material to be Ceramic/Porcelain with dielectric constant/relative permittivity=5.5 mm to model, design, and simulate the presented RF GPS (L1) only passive patch antenna.

4.5. Device Under Test (DUT) Active GPS/GLONASS Patch Antenna

Modeling, design, and simulation based on the following design parameters listed in table 5 below.

Table 5. Design Parameters of Device Under Test (DUT) Active GPS/GLONASS Structure Patch Antenna

Parameter	Value
Feed Length	0.5 mm
Operating Frequency	1.5925 GHz
Ground Plane Length	95 mm
Ground Plane Width	95 mm
Radiating Element Length	12.25 mm
Radiating Element Width	12.25 mm
Substrate Length	24.7 mm
Substrate Width	24.7 mm
Substrate Thickness	4.5 mm
Substrate Dielectric Constant (Relative Permittivity) for Ceramic/Porcelain Material	5.5 mm

Figure 12 plot shows the Top View of the active GPS/GLONAS Spatch antenna geometry with a square/rectangular orange color ground plane, square purple color substrate with dielectric constant value of 5.5 mm and a square dark blue color radiating element where the model was created in CADFEKO. Figure 13, Figure 14, and Figure 15 depicts the Cross Section View, Front View, and Side View respectively of the active GPS/GLONAs Spatch antenna within the POSTFEKO environment.

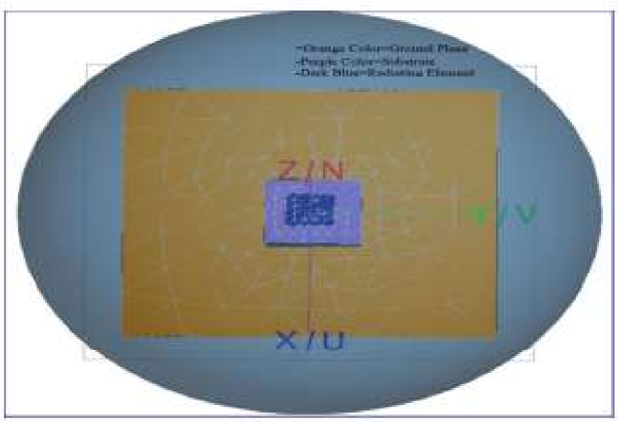


Figure 12. GPS/GLONASS Patchoperating at 1.5925 GHz(Top View-CADFEKO v2020)

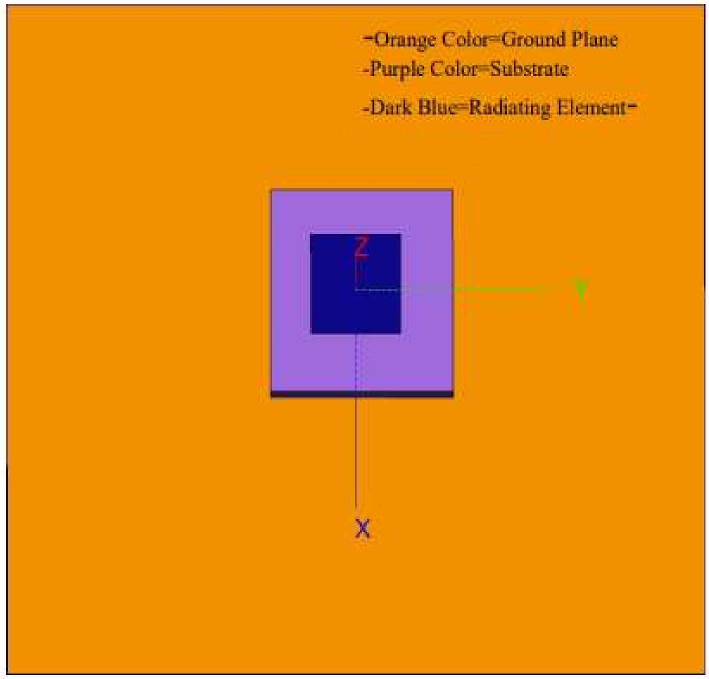


Figure 13. GPS/GLONASS Patch operating at 1.5925 GHz (Cross Section-POSTFEKO v2020)

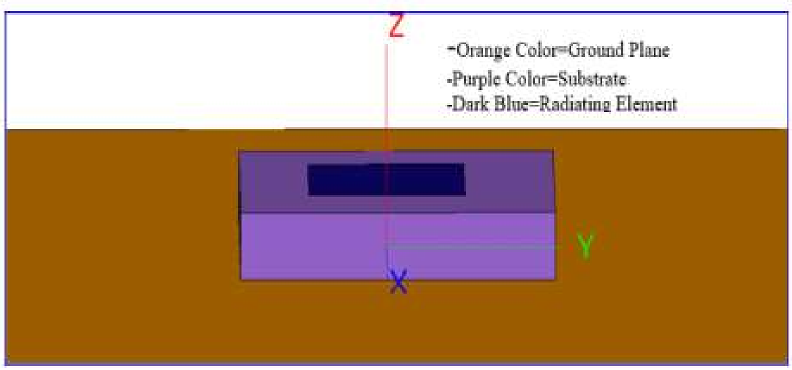


Figure 14. GPS/GLONASS Patch operating at 1.5925 GHz (Front View)

14

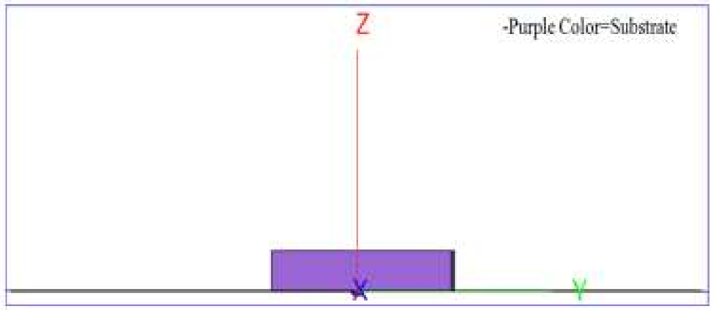


Figure 15. GPS/GLONASS Patch operating at 1.5925 GHz (Side View)

4.6. Simulated Far Field of GPS/GLONASS Structure Patch Antenna

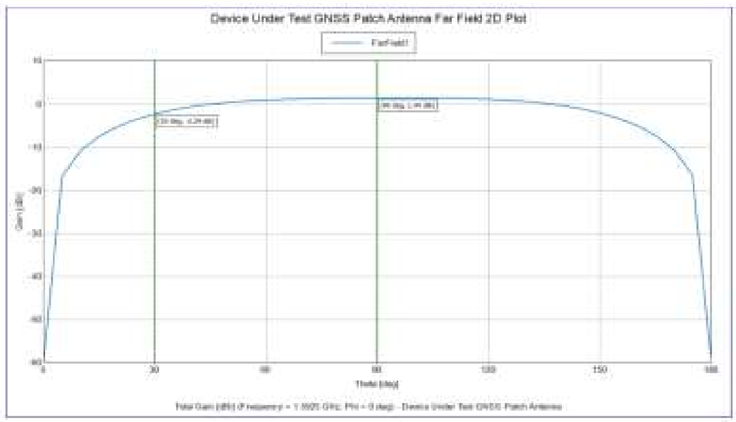


Figure 16. Patch antenna passive gain at 1.5925 GHz rectangular plot

In the 2D model plot from Figure 16, we can see about 0.85dBi passive gain, by taking the difference in gain between 30 and 90 degrees.

Figure 16 simulated the passive gain of the proposed antenna and we selected substrate material to be Ceramic/Porcelain with dielectric constant/relative permittivity=5.5 mm to model, design, and simulate the presented GPS/GLONASS patch antenna.

5. CONCLUSION

This paper describes the GPS (L1 1.57542 GHz) frequency)patch antenna performance and compares it to that of GPS/GLONASS patch antenna with ceramic/porcelain substrate material. These two antennas can be used in modern automotive applications. The models for each antenna were developed and then simulated on FEKO. The performance characteristic, such as passive gain in dBi were found, 3.791 dBi for GPS and 0.85 dBi for GPS/GLONASS delta between 30 and 90 degrees. The simulated results show an improved passive gain for the antenna. Thus, the proposed GPS/GLONASS will meet the needs of future automotive applications in robust way .Furthermore, other characteristics such as wide band width and efficiency are examined.

6. Future Work Suggestions

In future work this presented antenna can be modified, further studied and simulated in each of the following manners:

- The substrate material type can be changed from ceramic/porcelain to non-ceramic version/variant.
- The proposed antenna performance can be further improved by selecting a thick substrate whose relative permittivity is in the lower/smaller value than the presented dielectric constant of 5.5 mm.
- The mechanical dimensions of each antenna can be altered and simulated, in order to enhance antenna major performance parameters, such as Directivity, Impedance, Current and Polarization.
- The verification, validation and testing of the proposed RF GPS only patch and GPS/GLONASS patch antenna component can also be conducted at the system vehicle level, where each of the presented antenna can be installed and mounted on an optimal vehicle roof location area prior to the start of the testing and antenna performance parameters experimental measurement can be ascertained.
- The testing, assessment and evaluation of the presented RF GPS only (L1 1575.42 MHz frequency) and GPS/GLONASS patch antenna can be carried out in Anechoic Chamber and/or Indoor Antenna Range, in order to measure the basic antenna performance parameters and/or characteristics, such as Radiation Pattern, Radiation Efficiency, Directivity, Impedance, Polarization and Current draw and/or Antenna Surface Current.

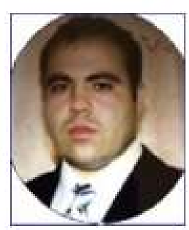
References

[1] Constantine A. Balanis, Antenna Theory Analysis and Design, 2nd ed., New York: Wiley, 1997, p. 1-3, 58-61, 73-77, 722-750, 839-871

[2] Fawwaz T. Ulaby, Fundamentals of Applied Electromagnetics, 2001 Media Edition, Prentice Hall, p.347-354

[3] Wikipedia, https://www.wikipedia.org

AUTHORS



Gholam Aghashirin graduated from Ryerson University, Toronto, Ontario Canada with a B.Eng. in Electrical, Electronics and Communication Systems, earned his M.Sc. in Electrical and Computer Engineering from Oakland University, Rochester, Michigan, USA and he is currently a Ph.D. candidate in Electrical and Computer Engineering at Oakland University, Rochester, Michigan, USA. He has worked as an Engineer in advanced engineering projects, assignments in the automotive industries at various level of complexity and leadership roles in the field and space of Global Telematics, Automotive Radio Head Units, Navigation Systems, Instrument Clusters, Voice Recognition, Dialog, Hands-Free Systems, Electrical and Electronics ADAS and Automated Driving L2 and L3 Systems. His research interests include Electromagnetics, Location Technologies, antenna design, modeling, simulations at the component, vehicle level, antenna range and antenna experimental measurements.

Hoda S. Abdel-Aty-Zohdy received the B.A.Sc. degree (with First Class Honors) in Electrical and Communications Engineering from Cairo University, the M.A.Sc and Ph.D. degrees in Electrical Engineering from the University of Waterloo, ON, Canada. Dr.AbdelAty-Zohdy is a Professor of Electrical and Computer Engineering, The John F. Dodge Chair Professor of Engineering, 2012-2014; Director of the

Microelectronics & Bio-Inspired Systems Design Lab at Oakland University, Rochester, MI, USA. Her research and teaching focus on Circuits, Devices, VLSIC, H/W deep-learning, Electronic-Nose, and Bio-Inspired IC chips for high fidelity classifications. She organized, chaired, served on several conferences and committees for the IEEE/CASS and as Distinguished Lecturer 2004-2006,

Adam Timmons received the Ph.D. degree in Materials Science from Dalhousie University, Halifax, Nova Scotia, Canada. Dr. Timmons is a Adjunct Professor within the Department of Mechanical Engineering at McMaster University, Hamilton, ON, Canada. He has many professional and academic appointments and holds a large number of patents.

Mohamed A. Zohdy received the B.A.Sc degree in Electrical Engineering from University of Cairo, the M.A.Sc and Ph.D. (Medal) from the University of Waterloo, ON, Canada. Dr. Mohamed is a Professor of Electrical and Computer Engineering at Oakland University, Rochester, MI, USA. Professor Zohdy research focus is in the area of Advanced control and estimation, intelligent npattern information processing, neural, fuzzy, evolutionary systems, chaos control, smart simulation, hybrid systems.

C-I-1 Refereed Conference Papers

"GNSS Patch Antenna Design Parameter Optimization using FEKO, Design of Experiments & P-Transform Technique"

Kafafy [6] has proposed the improved P-Transformation algorithm, which can be utilized to solve global optimization problems and its application can be extended to cover both probabilistic and deterministic problems. Furthermore, they demonstrated that their improved P-Transformation is an efficient technique for global optimization algorithms as a universal heuristic optimization methodology. Moreover, Zohdy [10] covered a new robust and optimal global non-sequential search technique for an optimization in n-dimensions by using a stochastic approach. Moreover, Adamczyk [9], presented the P-Transformation algorithm as an efficient method and technique in finding the global maximum of an objective function. Nguyen [28] highlighted that microstrip patch antenna are used in a lot of application because of its low profiles, light weight, low cost and patch antenna ground plane is one of the most significant part of it because if effects many of antenna characteristics, such as Gain, Bandwidth and Radiation Pattern.

A. Patch Antenna Structure Configuration and Design Equations

Fig. 1, shows the patch antenna basic structure model in general, where we have a rectangular metallic patch, that is place over a dielectric substrate material with a specific relative permittivity and at the bottom of "Cuboid" [4] substrate is a conducting base sheet that acts as a conducting ground plane.

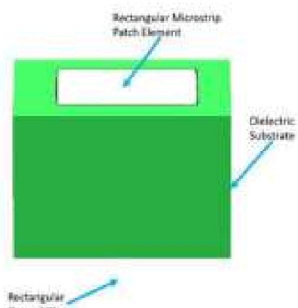


Fig. 1. Microstrip Patch Antenna Geometry.

Per Constantine A. Balanis [1], a simplified rectangular patch antenna equation from below can be used to design microstrip antenna for a given dielectric constant of the substrate material (Relative Permittivity = Epsilon r = εr), the Resonant Frequency (fr), and the Substrate Height (h). Equation (1) Determine the Patch Width W:

Patch Width = W = $\frac{v0}{2fr}\sqrt{2/(\varepsilon r+1)}$ (cm and/or in) [1]

Where v0 = The velocity of light in free-space (Constant value)

fr = The resonant frequency

εr = The dielectric constant of the substrate material

Equation (2) Determine the Patch Length L:

Patch Length = L = $\frac{1}{2fr\sqrt{\varepsilon reff}\sqrt{\varepsilon 0\mu 0}} - 2\Delta L$ (cm and/or in) [1]

Where ΔL = The extended incremental length of the patch =

h (0.412)x$(\varepsilon reff+0.3)\left(\frac{W}{h}+0.264\right)/(\varepsilon reff-0.258)\left(\frac{W}{h}+0.8\right)$

fr = The resonant frequency

$\varepsilon reff$ = The effective dielectric constant =
$\frac{\varepsilon r+1}{2}+\frac{\varepsilon r-1}{2}\text{x}\left(1+12\frac{h}{W}\right)^{-1/2}$

$\varepsilon 0 =$ The permittivity of free space $= 8.854 \, x \, 10^{-12}$ (farads/metre)

$\mu 0 =$ The permeability of free space $= 4\pi \, x \, 10^{-7}$ (henry/metre)

h = The substrate height
W= The patch width
εr = The dielectric constant of the substrate

Equation (1) and Equation (2) allows for the calculation of a rectangular microstrip antenna actual patch length and width of a practical design of patch antenna. The shape of the radiating patch element antenna needs to be rectangular in general as its depicted in Fig. 1, and we are considering this as a constraint, where our design parameter x1=x2=rectangular and x1 ≠x2=square.

B. Model of Design of Experiments Method in General

Attached below in Fig. 2, we are showing the general model of Design of Experiments (DoE). Equation 1 below indicates a design parameter as an input versus output response of an antenna.

where

y hat = The predicted value of an output response variable
xi = The input factors and design parameters of an antenna
K = The design parameter in the summation symbol

βi = The coefficient proportional to the main effect, where the main effect represents the degree of a parameter individual influence on an output response variable,
βij = The coefficient proportional to the two-factor interaction of the main effect.

To be direct, βi and βij are the unknown coefficients proportional to the main effect.

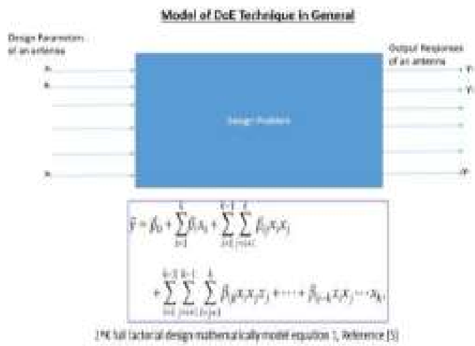


Fig. 2. Design of Experiment Input, Design Problem and Output Response Model.

Here we are looking at the 2^k full factorial design, where we conducted 120 simulation combination runs, were conducted in the experiment and the simulation operating frequency was set to 1.555 [GHz]. In our study here the value of k = 7, which resulted in 2^7 = 128, ~120 simulation runs. For each FEKO simulation run we are varying three input factor design parameters, namely ground plane length, ground plane width and dielectric constant of substrate material and we are seeking the antenna average and/or passive gain for each simulation run from the POSTFEKO environment.

C. P-Transform Objective Function 2D Plot

We are defining and setting our true objective function to be equal 1/passive gain. For each of the FEKO simulation runs the new patch antenna average gain was obtained and then we conducted a mathematical inverse operation on our output passive gain parameter, which in term provided us with the true objective function.

Fig. 3, below we are depicting the objective function rectangular graph [6].

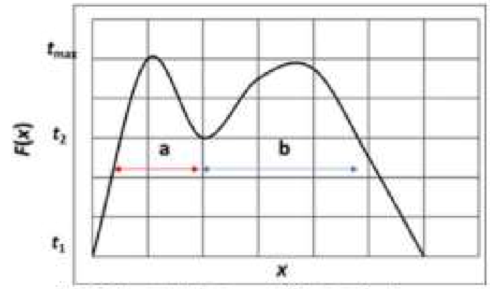


Fig. 3. Type 1 – Continuous Objective Function.

II. GNSS Patch Antenna Design, Modeling And Simulation

A. FEKO Model Creation of the GNSS Patch Antenna

The proposed new GNSS (GPS and GLONASS) patch antenna is designed, modeled, simulated by using FEKO simulation software package. The FEKO is an electromagnetic field simulator and it can be used to design, model and analyze a simple to large and complex antenna structure. FEKO is a commercial software tools chain that is based on the Method of Moments. A student version of FEKO was used to design, model, and conduct the simulation runs in this work.

The desired GNSS metallic patch antenna was positioned on a substrate material with varying the relative permittivity or dielectric constant ranging from 5.1 to 5.9 [mm] was simulated and run by using FEKO software package.

While conducting the FEKO simulation run, the conducting rectangular ground plane mechanical length and width dimension and as well its substrate dielectric constant was varied during each simulation run and the entire GNSS antenna model was constructed within the "CADFEKO" environment [4].

The steps outlined below highlights the FEKO geometry generation of the GNSS (GPS and GLONASS) patch antenna within the "CADFEKO" [4] and the antenna results were obtained from the "POSTFEKO" [4] environment:

1. We selected and set the antenna model unit to millimeters [mm].
2. Next declare the design parameters or variables, such as the operating frequency, ground plane length, ground plane width, substrate length, substrate width, patch length, patch width, etc. that define the antenna geometry and substrate material.

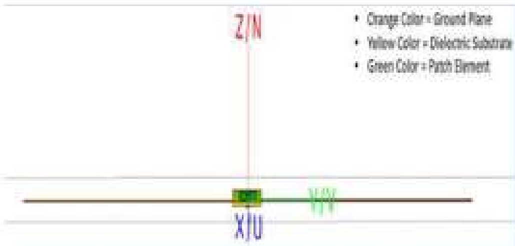


Fig. 5. GNSS Patch antenna operating at 1.555 [GHz] (Cross Section View).

Fig. 6, Depicts our GNSS patch antenna model in the "POSTFEKO" [4] page.

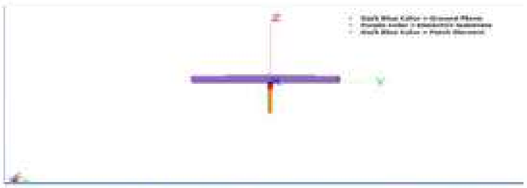


Fig. 6. GNSS Patch antenna operating at 1.555 [GHz] (Cross Section View).

E. FEKO Simulated Far Field of GNSS Patch Antenna

Fig. 7, simulated the passive gain of the proposed antenna and we selected substrate material to be ceramic or porcelain with dielectric constant or relative permittivity=5.1 [mm] to model, designed, and simulated the presented GNSS patch antenna with center frequency = 1.555 [GHz]. In the 2D model plot from Fig. 7, we can see about 0.55 [dBi] passive gain, by taking the difference in gain between 30 and 90 degrees.

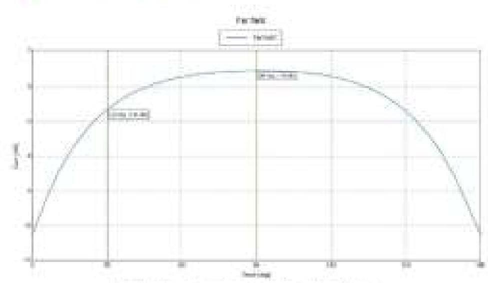


Fig. 7. GNSS patch antenna passive gain at 1.555 [GHz] rectangular 2D plot

III. Design Of Experiments (DoE)

Design of Experiments is an optimization methodology that can be applied to the Electromagnetic design problems, such as various types of antenna design and optimization, namely patch antenna, Radio-Frequency Identification (RFID) antenna. One of its applications is in the emerging field of L2 Advanced Driver Assistance Systems (ADAS) and L3 Automated Driving (AD) systems. Design of Experiments as a way to optimize an antenna design efficiently and effectively [7]. Outlined below are some of the Design of Experiments advantages:

1. It allows for the design cycle of an antenna to be reduced.
2. It supports the design problems and process with more efficiency.
3. It allows for substantial time saving and it led to a short design cycle by reducing the number of requirement simulations, in our context here, a smaller number of FEKO simulation runs for the presented GNSS patch antenna design, modelling and simulation.
4. Efficient design and analysis of an antenna.

To be specific, Design of Experiments allows for the design cycle of an antenna to be reduced by cutting down the number of possible simulations runs from a large test runs to a manageable size, which in turn will support more efficiency, huge time saving, less use of computer computational power and resources because it will allow for running fewer number of simulations in an engineering optimization problem study.

We have designed a new GNSS (GPS and GLONASS) patch antenna and investigate how change our design three input parameters, namely ground plane length, ground plane width and the substrate dielectric constant effects the antenna performance, such as the output passive gain and this can be handled and answered with a Design of Experiments method. Furthermore, we have looked at the design parameters (x1, x2 and x3) as an input relationship versus the passive gain output response parameter(y).

A Design of Experiments mathematical model equation that represents our design parameters input and passive gain output relation can be observed in Equation 3 below.

Equation (3) DoE antenna input and output response relation.

$$\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j \qquad (5)$$

2^k factorial design mathematical model equation.

where

βi = The main effect
βij = Two factor interactions
Xi = The input design parameters
y hat = The predicted value of an output response variable

In equation (3), we are looking at a mathematical interaction model for 2^k factorial, where we can see the antenna design input and output response parameter.

We have created our GNSS (GPS and GLONASS) patch antenna geometry model for the Design of Experiments within the CADFEKO [4] and obtain the corresponding passive gain parameter values within POSTFEK [4] environment.

IV. P-Transform Algorithm Analysis And Implementation

A. P-Transform Analysis Details [6]

According to Maged Abdelnaby [6]: P-Transform algorithm can be used to find the global maximum of an objective function. The transformation of the objective function, f (x) where x is an n-dimensional vector is performed by a nonlinear operator,

which is given by P{f(x)} a G(t) (2)

Where t represents the time as a scalar quantity that is taken to be pointwise Lebesgue's division of the object function f(x), in which the inequality equation needs to be satisfy

$$m(f(x)) = t0 < t1 < t2 \ldots. ti < tmax = \max(f(x)) \qquad (3)$$

Parameter D represent the set on which the f(x) function is to be determined and D* is a subset of D. Given a H(x) function such that H(x) can take either a value of 0 at D/D* or 1 value at
D*a
H(x) = {0 at D/D* 1 at D*} (4)
By applying the Riemann integral on the equation 4 function set Di results equal to its measure μi in Equation (5) below.

∫ Di . . ∫ H(x)dxi . . dxn = μi (5)

The function from Fig. 3, can be estimated from the equation (5) Riemann integral and Di can be computed using statistical tests. We let the Pi represent the probability that a point x randomly chosen from D* and D* belongs to Di and it can be approximated by the ratio of s(r)/r, where r is the number of randomly chosen points x and parameter a, b and s(r) represents the number of successes. Thus, for any ε > 0, as r → ∞, the ratio s(r)/r can mimic the measure μi of the Di set.

lim Pr (S(r)/r − Pi) > ε = 0 (6)
γ→∞
μi = s(r)/r

Once we have the μi 's we can estimate the quadratic function R(t) as shown in Equation (7) below.

R(t) = a0t 2 + a1t + a2 (7)

where a0, a1, and a2 are the roots of quadratic equation (7) and it can be found by utilizing the least squares approach with the following assumptions:

$$\begin{bmatrix} a0 \\ a1 \\ a2 \end{bmatrix} = \varphi \mathrm{T} \begin{bmatrix} \mu1 \\ \mu2 \\ \mu3 \end{bmatrix} \qquad (8)$$

$$\varphi = \begin{bmatrix} t_1^2 & t_1 & 1 \\ t_2^2 & t_2 & 1 \\ t_3^2 & t_3 & 1 \end{bmatrix} \qquad (9)$$

B. P-Transform Algorithm Implementation Steps [6]

Outlined below are the implementation steps for the P-Transform technique:

1. Generate N random vectors xn.
2. Check the constraints for each xi.
3. Evaluate the function f(xn) for all xi 's that satisfy the constraints.
4. Let t1 = (min f(x) + max f(x))/2.
5. Calculate μi as defined in Equation (6).
6. Repeat step 5 for each ti where ti+1 = ti + Δt until the condition in Equation (6) is no longer valid.
7. Extrapolate G(t) using R(t) in Equation (7).
8. Find the roots for this quadratic equation, R(t) = 0 by calculating Equation (8):
   a. if a0 < 0, then the global maximum F(x *) = max(R1, R2).
   b. if a0 > 0 then F(x *) = min(Real(R1, R2)).
9. Repeat the algorithm until ΔF(x *) << ε.

C. FEKO Simulation Combination Run and P-Transform Results in the Experiment

Table 3 below indicates the FEKO [4] simulation combination runs conducted in the experiment at 1.555 [GHz] center frequency and its corresponding simulated Passive Gain (Objective Function) results obtained.

Table 3 Simulation of Passive Gain Results

Rectangular Microstrip Patch Antenna Design Parameter and Passive Gain			
Parameter Upper and Lower Limit	Ground Plane Length (L=x1) [mm]	Ground Plane Width (W=x2) [mm]	Substrate Dielectric Constant (x3) [mm]
Minimum Value	10	10	3.1
Maximum Value	1000	1000	5.8
Design Parameter			Passive Gain (Objective Function) [dBi]
x1	x2	x3	obj_fun
277.5	10	5.8	0.25
10	10	3.1	0.55
10	10	3.3	0.551
10	10	5.5	0.552
10	10	3.7	0.56
10	10	5.8	0.562
752.5	10	5.8	0.7
1000	10	5.9	0.72
10	752.5	3.1	0.98
10	752.5	3.3	1.02
10	752.5	5.5	1.05

D. *P-Transform Technique Optimization Process and Block Diagram Representation*

GNSS (GPS and GLONASS) patch antenna passive gain optimization was achieved by using a global optimization P-Transform algorithm [6] and given a neural network genetic algorithm. To be direct, in general P-Transform does maximization of optimization problems however in this work the focus was to perform the minimization for the purpose of obtaining optimal GNSS patch antenna passive gain. The minimization of GNSS patch antenna was done by modifying the original P-Transform built in function coupled with the utilization of the Radial Basis Function (RBF) to fit the data curve within the MATLAB environment. Radial Basis Function are applied to approximate functions, data, and system, so that the assessment of the approximation function or system can take place more easily. Radial Basis Function finds application in the field of Neural Network, Learning Theory, solving a set of Linear Systems using matrix decomposition and it is applicable in almost any dimension of Euclidean space [50].

The high-level steps involved in the GNSS patch antenna passive gain optimization is outlined below:

1) Read the antenna .csv file, which contains the inputs and output design parameters:

a) Input parameters = (x1, x2, x3) = (antenna ground plane length, antenna ground plane width, substrate material dielectric constant).
b) Output response = (y) = GNSS Patch Antenna Passive Gain (Objective Function).

2) Train the system that is based on neural network by using response surface technique and one of them is the Radial Basis Function [49], to get a best fit curve and mathematical Equation 4 below from a series of inputs and to obtain the corresponding output neuron parameters can be model by the relation Equation 4 below:

Equation (4)

$$\hat{y}_i = f(\mathbf{x}_i) = \sum_{j}^{m} w_j \phi(\mathbf{x}_i) = \sum_{j}^{m} \phi\left(\|\mathbf{x}_i - \mu_j\| / \sigma_j\right) \quad [49]$$

where:

m = Number of neuron or number of basis function
μj = Center vector for neuron j
w j = Weight of neuron j
phi = Neuron/basis function
σj = Width of basis function

3) Conducted GNSS patch antenna passive gain optimization operation by using the original P-Transform built in function in the MATLAB environment to get our GNSS patch antenna output, which is our optimized passive gain (objective function).

To be more specific, each simulation runtime using the Student Version of FEKO software package takes approximately 2 minutes in our case. We generated a set of data based on Design of Experiments (DOE) [5] and a Radial Basis Neural Network (RBN) [49] was used to train the system to generate a response surface. The created response surface model can then be used as a black box system in lieu of FEKO simulations. This will let us perform hundreds of thousands of optimization iterations in a fraction of time. MATLAB from MathWorks was used for generating the response surface and optimization using the P-Transform technique. Furthermore, simulation run is expensive, it takes a lot of resources, memory allocation, processing power and a long time, therefore its deemed necessary to explore and use Design of Experiments (DoE) to come up with the FEKO simulation runs and then apply the P-Transform algorithm on the results of DoE runs in terms of GNSS patch antenna design parameters and passive gain output response, to optimize the GNSS patch antenna passive gain.

Moreover, the listed steps from below were executed, to come up with our optimized and robust objective function and/or passive gain desired value.

a) Create Design of Experiments, FEKO simulation runs.
b) Create the surface response by using the given Radial Basis Function (RBF).
c) Generate the input and output black box relationship model, which represents our system.
d) Apply the P-Transform to our inputs and output black box mathematical equation model and system.

To be more precise, the entire process can be summarized in the following block diagram and flowchart representation:

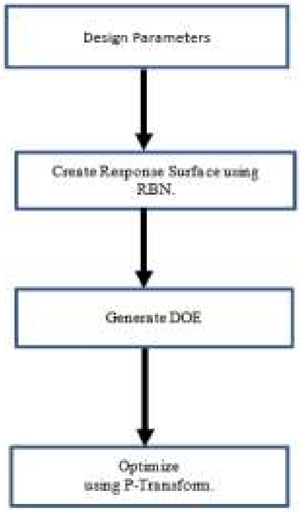


Fig. 8. Optimization block diagram flowchart

By executing the optimization flowchart from Fig. 8, we were able to obtain our optimized passive gain of 0.2084 [dBi], with the corresponding design parameter as follows:

a) Ground Plane Length = 493.7 [mm]
b) Ground Plane Width = 503 [mm]
c) Dielectric Constant = 5.492 [mm]

by using the P-Transform [6].

V. Conclusion And Future Work

In this paper we have presented, described, and investigated the NEW GNSS (GPS and GLONASS) with center frequency at 1.555 [GHz] patch antenna design, modelling and simulation by using FEKO software package. We also demonstrated the Design of Experiments (DoE) and as well as by applying a P-Transform algorithm on the GNSS patch antenna Passive Gain (Objective Function) in the process. To be specific, the GNSS patch antenna passive gain, DoE, P-Transform technique has been discussed. The proposed GNSS patch antenna can be used in non-automotive, modern automotive components, systems, autonomous vehicle space and it also finds application in wide areas of other scientific and engineering disciplines. The GNSS patch antenna model was developed, simulated and then it's corresponding antenna characteristic, such as passive gain was found to be 0.55 [dBi] for GNSS patch antenna delta between 30 and 90 degrees within the FEKO [4] environment. The corresponding optimized version of the GNSS patch antenna passive gain was obtained to be 0.2084 [dBi] using the P-Transform technique [6] with MATLAB products created by MathWorks.
Furthermore, we demonstrated that the GNSS patch antenna will meet the need of future automotive applications. Moreover, the DoE and P-Transform technique, which can be used in an advance optimization problem global (Maximum or Minimum), optimal and robust solution generation for cases where the objective function is either defined and/or not within the MATLAB environment were examined, investigated were the emphasis of this paper.

For future work, the simulation studies can be extended to focus on a GNSS patch antenna substrate material that is different than porcelain and as well conducting the testing, assessment and evaluation of the proposed GNSS patch antenna can be carried out in Anechoic Chamber and/or Indoor Antenna Range, in order to measure the basic antenna characteristics, such as Gain, Radiation Pattern, Radiation Efficiency, Directivity, Impedance, Bandwidth, Polarization and Current draw and/or Antenna Surface Current.

References

[1] Constantine A. Balanis, "Antenna Theory Analysis and Design", 2nd ed., New York: Wiley, 1997, p. 1-3, 58-61, 73-77, 722-750, 839-871
[2] Fawwaz T. Ulaby, "Fundamentals of Applied Electromagnetics", 2001 Media Edition, Prentice Hall, p.347-354
[3] "Wikipedia", https://www.wikipedia.org
[4] "A student version of FEKO simulator (CADFEKO &
[5] Yen-Sheng Chen and Ting-Yu Ku, "Efficiency Improvements of Antenna Optimization Using Orthogonal Fractional Experiments", http://downloads.hindawi.com/journals/ijap/2015/708163.pdf, Hindawi Publishing Corporation International Journal of Antennas and Propagation Volume 2015, Article ID 708163, 12 pages, p. 1-3
[6] Maged Abdelnaby Kafafy, Mohamed Zohdy and Syed Faisal Haider, "Assessment of Improved P-Transformation for Global Optimization with Application on Double Inverted Pendulum Control", ICIC International 2018 ISSN 1881-803X, pp. 991-999
[7] "Dassault Systems, Design of Experiments as a way to efficiently and effectively optimize antennas", https://events.3ds.com/design-of-experimentsantennas#_ga=2.254880456.1725322526.1601439666-9847b8c0-02b7-11eb-ae4c-53256bd2443f
[8] V. K. Chichinadze, "The Ψ-transform for solving linear and nonlinear programming problems", Automatica, vol.5, pp.347-355, 1969
[9] B. Adamczyk, M. A. Zohdy and A. A. Khan, "Global optimization of stochastic multivariable functions", American Control Conference, San Francisco, 1993
[10] M. A. Zohdy, A. A. Khan and M. S. Kamel, "Global optimization of stochastic multivariable functions", IEEE Proc. of the 26th Southeastern Symposium on System Theory, 1994
[11] V. K. Chichinadze, "Solution of nonlinear nonconvex optimization problems by Ψ-transformation method, Computer and Mathematics with Applications", vol.21, pp.7-15, 1991.
[12] K. Deb, "Multi-Objective Optimization Using Evolutionary Algorithms", John Wiley & Sons, 2002
[13] D. E. Goldberg, "Genetic Algorithms in Search, Optimization and Machine Learning", Addison-Wesley, Massachusetts, 1989

[14] C. M. Fonseca and P. J. Fleming, "Genetic algorithms for multiple objective optimization: Formulation, discussion and generalization", Proc. of the 5th International Conference on Genetic Algorithms and Their Application, Morgan Kaufmann Publishers, San Mateo, CA, USA, 1993

[15] X. S. Yang, "Test Problems in Optimization, Engineering Optimization: An Introduction with Metaheuristic Application", John Wiley & Sons,2010.

[16] "Types of Experimental Designs":https://www.youtube.com/watch?v=10tkXret7Lk

[17] "Scientific Experiment":https://www.youtube.com/watch?v=JpKcbCXjWCE

[18] "Experimental Design":https://www.youtube.com/watch?v=UN206cSaF0k

[19] "Design of experiments (DOE)":https://www.youtube.com/watch?v=k3lUo0XYG3E

[20] "Introduction of Experimental Design":https://www.youtube.com/watch?v=5zkg1w5zoQ0

[21] "Planning of Designed Experiment (DOE)":https://www.youtube.com/watch?v=gsD8V2_eZ0A

[22] "Factorial Design":https://www.youtube.com/watch?v=5lFa7h5capM

[23] Minitab DOE-Full Factorial Analysis:https://www.youtube.com/watch?v=v3Epk5de8MQ

[24] "Minitab Tutorial-Set up a DOE":https://www.youtube.com/watch?v=uJewUIQ1qXU

[25] "Everything you Need to Know to use Minitab":https://www.youtube.com/watch?v=nSv88y3mqf4

[26] G.V.P.Pranathi, Dr.N.Deepika Rani,Dr.M.Satyanarayana, Prof.G.T.Rao, "Patch Antenna Parameters Variation with Ground Plane Dimensions", IJAREEIE Vol. 4, Issue 8, August 2015,

[27] https://www.ijareeie.com/upload/2015/august/74_20_Patch.pdf

[28] By D. Orban, G.J.K. Moernaut, Orban Microwave Products, "The Basics of Patch Antennas, Updated", http://orbanmicrowave.com/wpcontent/uploads/2014/12/Orban-Patch-Antennas-2009-rev.pdf

[29] Minh Tuan Nguyen, Byoungchul Kim, Hosung Choo,Ikmo Park, "Effects of Ground Plane Size on a Square Microstrip Patch Antenna Designed on a Low-Permittivity Substrate with an Air Gap", 978-1-4244-4885-2/10 2010 IEEE, https://ieeexplore-ieeeorg.huaryu.kl.oakland.edu/stamp/stamp.jsp?tp=&arnumber=5464869

[30] Sotoudeh Hamedi-Hagh, Joseph Chung, Sooseok Oh,Ju-Ung Jo, Noh-Joon Park and Dae-Hee Park,"Design of a High Performance Patch Antenna for GPS Communication Systems", 282 Journal of Electrical Engineering & Technology Vol. 4, No. 2, pp. 282~286, 2009

[31] Luigi Boccia, Giandomenico Amendola, Giuseppe Di Massa, "A High-Performance Dual Frequency Microstrip Antenna for Global Positioning System", 0-7803-7070-8/10 /$ IO.OO 0200 1 IEEE

[32] Nasimuddin, Karu P. Esselle, and A. K. Verma, "Wideband Circularly Polarized Stacked Microstrip Antennas, IEEE Antennas and Wireless Propagation Letters, vol. 6, 2007

[33] Chufarov M.V., Lvova L.A., Babushkin A.V., "Double-Band Circularly-Polarized Antenna for GLONASS-GPS Applications", 978-1-4244-3861-7/09/$25.00 c2009 Crown

[34] Oluyemi P. Falade, Masood Ur Rehman, Yue (Frank) Gao, Xiaodong Chen and Clive G. Parini, "Single Feed Stacked Patch Circular Polarized Antenna for Triple Band GPS Receivers", 0018-926X/$31.00 c 2012 IEEE

[35] Yinting Liu, Dan Shi, Shuyi Zhang, and Yougang Gao, "Multiband Antenna for Satellite Navigation System", 1536-1225 c 2015 IEEE

[36] Minkil PARK, Duyeun Lee, Taeho Son, "Thin Ceramic GPS antenna, The 2015 International Workshop on Antenna Technology", 978-1-47997717-8 c2015 IEEE

[37] M. M. Bilgic and K. Yegin, "Modified Annular Ring Antenna for GPS and SDARS Automotive Applications", 1536-1225 c 2015 IEEE

[38] Jae-Hoon Bang, Wan-Ju Kim, and Bierng-Chearl Ahn, "Two-Element Conformal Antenna for Multi-GNSS Reception", 1536-1225 (c) 2016 IEEE, IEEE Antenna and Wireless Propagation Letters

[39] Xinyi Tang, Nasimuddin, Xianming Qing, Zhi Ning Chen, "A Circularly Polarized Beam-Steering Antenna System for GNSS Applications", 978-1-5090-2597-8/16/$31.00 c 2016 IEEE

[40] Muhammad Qazafi, Abdel Razik Sebak, Electrical and Computer Engineering, Concordia University, Montreal Canada, mq_muham@ece.concrodia.ca, abdo@ece.concordia.ca, "Tri-Band CP Microstrip Patch Antenna for WLAN Applications"

[41] Richard B. Langley, University of New Brunswick, "A Primer on GPS Antennas", Jae-Hoon

[42] S. E Jasim, M. A. Jusoh, M. H. Mazwir and S. N. S. Mahmud, Faculty of Industrial Sciences & Technology, University Malaysia Pahang, Kuantan, Pahang, Malaysia, E-Mail: ashry@ump.edu.my, "Finding the Best Feeding Point Location of Patch Antenna", using HFSS, Vol. 10, No. 23, December 2015 ISSN 1819-6608, ARPN Journal of Engineering and Applied Sciences, 2006-2015 Asian Research Publishing Network (ARPN)

[43] Jinping Ma,Ammar B. Kouki, and Rene Landry Jr., Xidian University, Xian 710071, China, LACIME Laboratory, E' cole de Technologie Sup_erieure, 1100 Notre-Dame Street West, Montreal, Quebec, H3C 1K3 Canada; Corresponding author: ammar.kouki@etsmtl.ca, " Wideband Circularly Polarized Single Probe-Fed Patch Antenna", Microwave and Optical Technology Letters/Vol. 54, No. 8, August 2012 DOI 10.1002/mop

[44] D. Orban and G.J.K. Moernaut, Orban Microwave Products, www.orbanmicrowave.com, "The Basics of Patch Antennas, Updated", As seen in the September 29, 2009 edition of the RF Globalnet (www.rfglobalnet.com) newsletter

[45] Amotech Advance Material on Technology, "GPS Patch Antenna Considerations"

[46] Abracon Corporation, "1575.42MHz; 25x25x4mm GPS Patch Antenna"

[47] Iuliia Goncharova and Stefan Lindenmeier, Institute of High Frequency Technology and Mobile Communication,University of the Bundeswehr, Munich, Germany, stefan.lindenmeier@unibw.de, " An Interoperable Antenna for GPS and GLONASS Services on a Car", 978-1-4799-7815-1/15/$31.00 c2015 IEEE

[48] A Tallysman Accutenna, "TW1721 / TW1722 Dual Feed Embedded BeiDou/Galileo/GPS/GLONASS Antenna", www.tallysman.com

[49] Mona S. Abdallah , Ying Wang, Wael M. Abdel-Wahab , and Safieddin Safavi-Naeini, "Design and Optimization of SIW Center-Fed Series Rectangular Dielectric Resonator Antenna Array With 45° Linear Polarization", IEEE Transactions on Antennas and Propagation, Vol. 66, No.1, January 2018

[50] https://en.wikipedia.org/wiki/Radial_basis_function_network

[51] http://www.scholarpedia.org/article/Radial_basis_function

C-I-2 Refereed Conference Papers

"Comparison of GNSS Patch Versus GPS L1 Patch Antenna Performance Characteristic"

COMPARISON OF GNSS PATCH VERSUS GPS L1 PATCH ANTENNA PERFORMANCE CHARACTERISTIC

Gholam Aghashirin[1], Hoda S. Abdel-Aty-Zohdy[1], Mohamed A. Zohdy[1], Darrell Schmidt[2] and Adam Timmons[3]

[1]Department of Electrical and Computer Engineering, Oakland University, Rochester, Michigan, USA
[2]Department of Mathematics and Statistics, Oakland University, Rochester, USA
[3]Department of Mechanical Engineering, McMaster University, Hamilton, Canada

ABSTRACT

Antenna module is a vital component of automated driving systems, it should function as needed in dGPS, HD map correction services, and radio and navigation systems. The proposed antenna model for GPS only patch antenna operating at 1.57542 GHz and the GNSS patch antenna resonating at 1.5925 GHz are developed. This work presents the design, modelling, determining passive gain of the GPS patch vs. GNSS antenna with intended targeted applications within the automotive system. Simulation are undertaken to evaluate the performance of the proposed GNSS antenna. Simulation conducted in FEKO software rather than mathematical modelling. The two antennas are also compared from the size standpoint. The goal of this paper is to test, measure and evaluate the performance of GPS against GNSS antennas. Another emphasis of this paper is how to obtain the equivalent amount of total passive gain in a GPS vs. that of GNSS antenna.

KEYWORDS

Differential Global Position System (dGPS), Global Navigation Satellite System (GNSS), Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS), Advanced Driver Assistance Systems (ADAS), Automated Driving (AD), Modelling, comparison, measurements, analysis

1. INTRODUCTION

An antenna could be defined as a wireless communication device or module such as a piece of wire for radiating or receiving electromagnetic wave propagating in a communication channel, such as guided structure transmission line and then getting transmitted into a free space and/or vice versa in the receiving mode. We present the passive gain of the GPS only patch and GNSS (GPS/GLONASS) antenna structure using FEKO electromagnetic simulation software package, in order to support automotive applications. This study describes the modelling, design, simulation and analysis of GPS only (L1) patch and GNSS (GPS/GLONASS) patch antenna. According to Constantine A. Balanis, the antenna is the transitional structure between free-space and a guiding device, for wireless communication systems, the antenna is one of the most critical components. For the past few decade Microstrip Patch Antenna were used heavily in high performance aircraft, spacecraft, satellite and missile where size, weight, cost, performance, ease

David C. Wyld et al. (Eds): ICAITA, CDKP, SAI, NCO, CMC, SOFT, MLT, AdNLP - 2020
pp. 01-12, 2020. CS & IT - CSCP 2020 DOI: 10.5121/csit.2020.100901

of installation, and aerodynamic profile are constraints. Low profile antennas maybe required [1] for packaging and/or aesthetic constraints. The GNSS (GPS/GLONASS) antennas play a significant role in today's modern communications, i.e. they nicely meet automotive specification requirements, most antenna designers and OEMs mainly preferred and select this rectangular/square GNSS (GPS/GLONASS) patch antenna, in order to mount, install, place and position it on their production vehicles.

2. Antenna Performance Characteristics

In the following below are illustration of mathematical model/equations that define the antenna gain, efficiency, directivity and input impedance.

Equation 1 Expresses, the antenna gain as:

Gain G =4(π)(radiation intensity)/total input(accepted) power=4(π)*(U((Elevation Angle, Azimuth Angle)))/Pin (dimensionless) [1] (1)

Also, Antenna Gain (G) = Antenna Efficiency (€)*Antenna Directivity (D) [2]

Equation 2 Expresses the antenna Radiation efficiency:

€ = Prad/Pt (dimensionless) (2)

Where Prad = Radiated Power, Pt = Transmitter Power [2]

In general, the overall antenna efficiency can be express as below

$e_O = e_r \, e_c \, e_d$

Where e_O is the total efficiency (dimensionless)

e_r= reflection (mismatch) efficiency = (1-|voltage reflection coefficient at the input terminals of the antenna|^2) (dimensionless)

e_c = conduction efficiency (dimensionless)

e_d = dielectric efficiency (dimensionless) [1]

Equation 3 Expresses, the antenna directivity

D=4(π)/Ω (3)

Where Ω=Pattern Solid Angle= $\iint_{4*Pie}$ F(Elevation Angle, Azimuth Angle)(d Ω)
F (Elevation Angle, Azimuth Angle) =Normalized Radiation Intensity [2]

Equation 4 Highlights, the antenna input impedance, defined as:

Input Impedance = $Z_A = R_A + jX_A$ (ohms) [1] (4)

Where

Z_A = antenna impedance at the input terminals of an antenna when it operates in transmitting mode (ohms)

R_A = antenna resistance at the input terminals of an antenna when it operates in transmitting mode (ohms)

X_A = antenna reactance at the input terminals of an antenna when it operates in transmitting mode (ohms)

In general, the R_A parameter from
Equation 5 is mainly made up of two resistances (R_r and R_L) of the antenna
Resistive component = $R_A = R_r + R_L$ (ohms) [1] (5)

Where

R_r = Represents the radiation resistance of the antenna (ohms)

R_L = Represents the loss resistance of the antenna (ohms)

If we assume that the antenna is connected/attached to a signal/function generator/source with internal impedance, when the antenna is used in the transmitting mode of operation then internal impedance is defines as listed below:
Internal impedance (Z_g) = $R_g + jX_g$ (ohms) [1] (6)

Where

R_g = Represents the resistance of signal source/generator impedance (ohms)

X_g = Represents the reactance of signal source/generator impedance (ohms)

Solving these equations at high level will allow to obtain the some of the antenna characteristics. Where on the other hand FEKO simulator/simulation software package is based on the Method of Moments (MoM) integral formulation of James Maxwell's equations, in order to solve for antenna characteristics, such as antenna gain, antenna input impedance, etc.

3. ANTENNA DESIGN STRUCTURE AND ANTENNA EVALUATION

The testing, experimental, comparison and evaluation of the square GPS only patch and GNSS (GPS/GLONASS) patch antenna design and simulation of the proposed two antennas is performed using FEKO which has not been previously investigated and/or studied at the FEKO simulation level. The GPS only patch and GNSS (GPS/GLONASS) patch antenna will be compared and contrasted mostly from the total passive gain in FEKO simulation environment viewpoint. The photo of each of the respective two test and presented antennas under evaluation and assessment are outlined and shown in Figure 1, Figure 2, Figure 3, and Figure 4. Figure 1 depicts the front view of the dual band GNSS (GPS/GLONASS) antenna. From the Figure 2 we can see the top view of the dual band GNSS (GPS/GLONASS) antenna. Figure 3 depicts the front view of the GPS only L1 square/rectangular patch antenna. From the Figure 4 we can see the top view of the GPS only L1 square/rectangular patch antenna.

3.1. GNSS (GPS/GLONASS) Patch Antenna Front View Photo

Figure 1. Dual Band Constellation GNSS Patch Antenna

3.2. GNSS (GPS/GLONASS) Patch Antenna Top View Photo

Figure 2. Dual Band Constellation GNSS Patch Antenna

3.3. GPS Only Passive Patch Antenna Front View Photo

Figure 3. GPS Only Patch Antenna

3.4. GPS Only Passive Patch Antenna Top View Photo

Figure 4. GPS Only Patch Antenna

3.5. GPS Antenna Samples Consideration for the Evaluation

Table 1. One sample of each antenna used for the model simulation in the FEKO environment

Dual-Band GNSS (GPS/GLONASS) Patch Antenna	1
GPS Only Passive Patch Antenna	1

3.6. Range of Operating and Simulation Frequency Requirements

The GNSS (GPS/GLONASS), GPS Only L1 frequencies were used for the purpose of this paper test and simulation activities:

- GPS Only L1 Frequency, GPS (L1): 1.57542 GHz
- GNSS (GPS/GLONASS): 1575 to 1610 MHz, Center Frequency (fc)= 1.5925 GHz)

The proposed antennas [GPS Passive Patch and GNSS (GPS/GLONASS)] characteristic was simulated by using FEKO simulation software package. An analysis was conducted next and finally total gain for each of the sample antenna were observed from the POSTFEKO environment.

4. FEKO Design Parameters and Simulation Results

4.1. Antenna Samples for FEKO Simulation

Table 2. Antenna substrate and radiating element dimensions

Patch Size & Application	Reference & Device Under Test (DUT) Antenna
GPS Only Single Passive Patch Antenna (L1-, 1.57542 GHz) • Substrate Size: 24.9 x 24.8 x 4.5 mm • Radiating Element Size: 12.25 x 12.25 mm	Reference
Dual Band GPS/GLONASS Antenna (GNSS-1.5925 GHz) • Substrate Size: 24.7 x 24.7 x 4.5 mm • Radiating Element Size: 12.25 x 12.25 mm	DUT

4.2. Design Parameters within FEKO Simulation Environment

Table 3. FEKO Mesh and Loss Tangent Parameters for GPS only Patch and GNSS Patch Antenna

GPS and GNSS Antenna Component	Parameter	Value
GPS only Patch Antenna Operating at , 1.57542 GHz	Mesh-Wire Segment Radius	1.587e-3 mm
	Dielectric Loss Tangent for Porcelain Material	2.1e-14 mm
GNSS (GPS/GLONASS) Patch Antenna Operating at 1.5925 GHz	Mesh-Wire Segment Radius	1.569e-3 mm
	Dielectric Loss Tangent for Porcelain Material	2.0e-14 mm

4.3. Reference GPS only L1 Patch Antenna

Modelling, design, and simulation based on the following design parameters listed in Table 4 below.

Table 4. Design Parameters of Reference GPS only Structure Antenna

Parameter	Value
Feed Length	0.5 mm
Operating Frequency	1.57542 GHz
Ground Plane Length	95 mm
Ground Plane Width	95 mm
Radiating Element Length	12.25 mm
Radiating Element Width	12.25 mm
Substrate Length	24.8 mm
Substrate Width	24.9 mm
Substrate Thickness	4.5 mm
Substrate Dielectric Constant (Relative Permittivity) for Ceramic/Porcelain Material	5.5 mm

Figure 5 plot below shows graphic representation of a pin fed voltage source of excitation. The Top View of the GPS only (L1 frequency, 1.57542 GHz) passive patch antenna on a finite square/rectangular orange color ground plane, square purple color substrate with dielectric constant value of 5.5 mm and a square dark blue color radiating element. Figure 6 depict the Side View of the GPS only patch antenna.

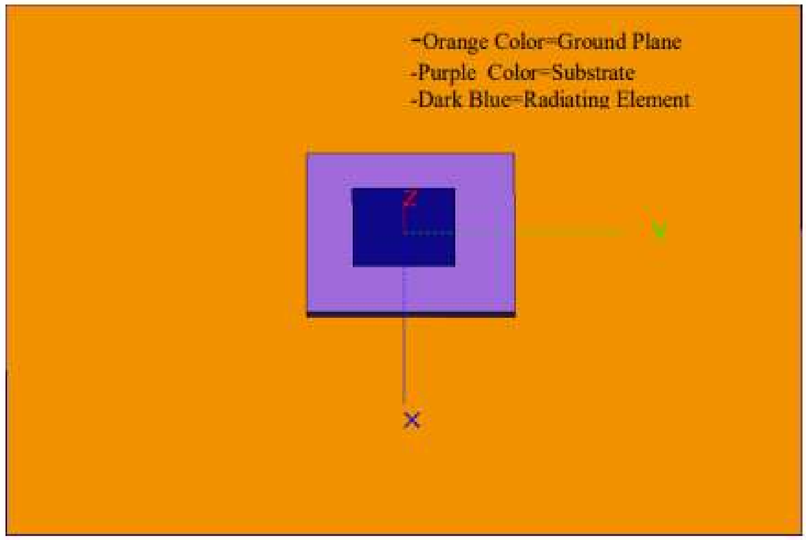


Figure 5. GPS Patch antenna operating at 1.57542 GHz (Top View/Cross Section Image)

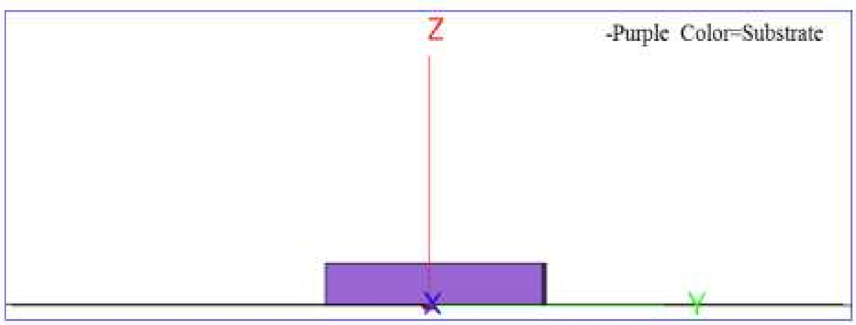


Figure 6. GPS Patch antenna operating at 1.57542 GHz (Side View)

4.4. Simulated Far Field of Reference GPS only Structure Patch Antenna

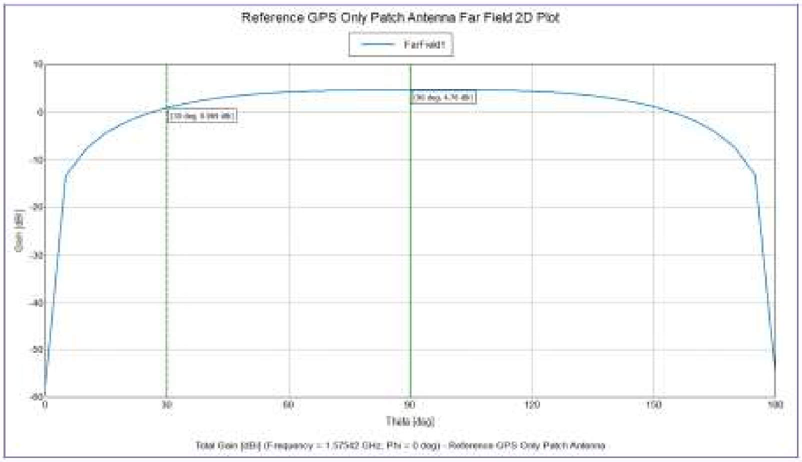


Figure 7. Patch antenna operating at 1.57542 GHz

Using Figure 7, the passive gain is approximately 3.791 dBi of the presented antenna and it can be determined by taking the difference in gain angle/delta between 30 and 90 degree angles in the 2D plot graphic.

Figure 7 shows the simulated passive gain of the proposed antenna and I selected substrate material to be Ceramic/Porcelain with dielectric constant/relative permittivity=5.5 mm to model, design, and simulate the presented GPS (L1) only patch antenna.

4.5. Device Under Test (DUT) GNSS Patch Antenna

Modelling, design, and simulation based on the following design parameters listed in table 5 below.

Table 5. Design Parameters of Device Under Test (DUT) GNSS (GPS/GLONASS) Structure Patch Antenna

Parameter	Value
Feed Length	0.5 mm
Operating Frequency	1.5925 GHz
Ground Plane Length	95 mm
Ground Plane Width	95 mm
Radiating Element Length	12.25 mm
Radiating Element Width	12.25 mm
Substrate Length	24.7 mm
Substrate Width	24.7 mm
Substrate Thickness	4.5 mm
Substrate Dielectric Constant (Relative Permittivity) for Ceramic/Porcelain Material	5.5 mm

Figure 8 plot shows the Top View of the GNSS (GPS/GLONASS) patch antenna with a square/rectangular orange color ground plane, square purple color substrate with dielectric constant value of 5.5 mm and a square dark blue color radiating element. Fig 9 depict the Side View of the GNSS (GPS/GLONASS) patch antenna.

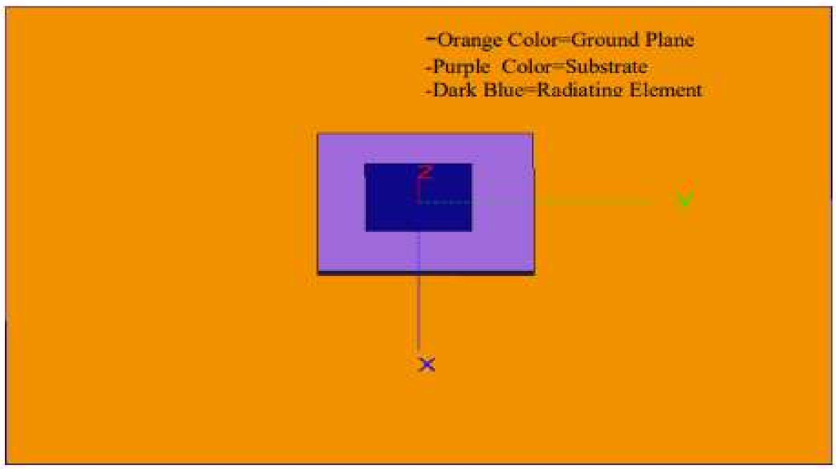


Figure 8. DUT GNSS Patch antenna operating at 1.5925 GHz (Top View/Cross Section Image)

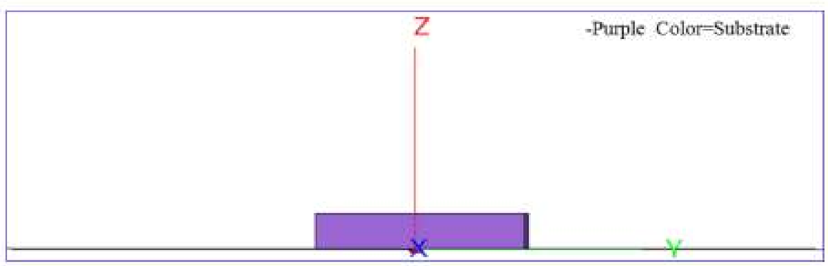


Figure 9. DUT GNSS Patch antenna operating at 1.5925 GHz (Side View)

4.6. Simulated Far Field of DUT GNSS Structure Patch Antenna

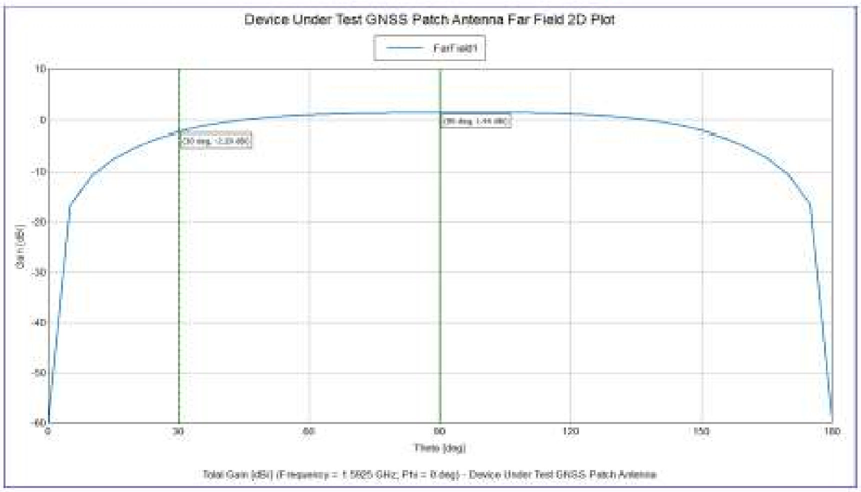


Figure 10. Patch antenna passive gain at 1.5925 GHz

In the 2D model plot from figure 10, we can see about 0.85 dBi passive gain, by taking the difference in gain between 30 and 90 degrees.

Figure 10 simulated the passive gain of the proposed antenna and we selected substrate material to be Ceramic/Porcelain with dielectric constant/relative permittivity=5.5 mm to model, design, and simulate the presented GNSS (GPS/GLONASS) patch antenna.

5. CONCLUSIONS

This paper describes the GPS (L1 1.57542 GHz) frequency) patch antenna performance and compares it to that of GNSS patch antenna with ceramic/porcelain substrate material. These two antennas can be used in modern automotive applications. The models for each antenna were developed and then simulated on FEKO. The performance characteristic, such as passive gain in dBi were found, 3.791 dBi for GPS and 0.85 dBi for GNSS delta between 30 and 90 degrees. The simulated results show an improved passive gain for the antenna. Thus, the proposed GNSS will meet the needs of future automotive applications in robust way. Furthermore, other characteristics such as wide band width and efficiency are examined.

6. FUTURE WORK SUGGESTIONS

In future work this presented antenna can be modified, further studied and simulated in each of the following manners:

- The substrate material type can be changed from ceramic/porcelain to non-ceramic version/variant.

- The proposed antenna performance can be further improved by selecting a thick substrate whose relative permittivity is in the lower/smaller value than the presented dielectric constant of 5.5 mm.

- The mechanical dimensions of each antenna can be altered and simulated enhance antenna major performance parameters, such as Directivity, Impedance, Current and Polarization.

- The verification, validation and testing of the proposed GPS only patch and GNSS patch antenna component can also be conducted at the system vehicle level, where each of the presented antenna can be installed and mounted on an optimal vehicle roof location area prior to the start of the testing and antenna performance parameters experimental measurement can be ascertained.

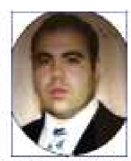
- The testing, assessment and evaluation of the presented GPS only (L1 1575.42 MHz frequency) and GNSS (GPS/GLONASS) patch antenna can be carried out in anechoic chamber and/or indoor antenna range, in order to measure the basic antenna performance parameters and/or characteristics, such as radiation pattern, radiation efficiency, directivity, impedance, polarization and current draw.

REFERENCES

[1] Constantine A. Balanis, Antenna Theory Analysis and Design, 2nd ed., New York: Wiley, 1997, p. 1-3, 58-61, 73-77, 722-750, 839-871

[2] Fawwaz T. Ulaby, Fundamentals of Applied Electromagnetics, 2001 Media Edition, Prentice Hall, p.347-354

AUTHORS



Gholam Aghashirin graduated from Ryerson University, Toronto, Ontario Canada with a B.Eng. in Electrical, Electronics and Communication Systems, earned his M.Sc. in Electrical and Computer Engineering from Oakland University, Rochester, Michigan, USA and he is currently a Ph.D. candidate in Electrical and Computer Engineering at Oakland University, Rochester, Michigan, USA. He has worked as an Engineer in advanced engineering projects, assignments in the automotive industries at various level of complexity and leadership roles in the field and space of Global Telematics, Automotive Radio Head Units, Navigation Systems, Instrument Clusters, Voice Recognition, Dialog, Hands-Free Systems, Electrical and Electronics ADAS and Automated Driving Systems. His research interests include Electromagnetics, location technologies, antenna design, modelling, simulations at the component, vehicle level, and antenna experimental measurements.

Hoda S. Abdel-Aty-Zohdy received the B.A.Sc. degree (with First Class Honors) in Electrical and Communications Engineering from Cairo University, the M.A.Sc and Ph.D. degrees in Electrical Engineering from the University of Waterloo, ON, Canada. Dr. AbdelAty-Zohdy is a Professor of Electrical and Computer Engineering, The John F. Dodge Chair Professor of Engineering, 2012-2014; Director of the Microelectronics & Bio-Inspired Systems Design Lab at Oakland University, Rochester, MI, USA. Her research and teaching focus on Circuits, Devices, VLSIC, H/W deep-learning, Electronic-Nose, and Bio-Inspired IC chips for high fidelity classifications. She organized, chaired, served on several conferences and committees for the IEEE/CASS and as Distinguished Lecturer 2004-2006.

Adam Timmons received the Ph.D. degree in Materials Science from Dalhousie University, Halifax, Nova Scotia, Canada. Dr. Adam is a Adjunct Professor within the Department of Mechanical Engineering at McMaster University, Hamilton, ON, Canada. He has many professional and academic appointments and holds a large number of patents.

Mohamed A. Zohdy received the B.A.Sc degree in Electrical Engineering from University of Cairo, the M.A.Sc and Ph.D. (Medal) from the University of Waterloo, ON, Canada. Dr. Mohamed is a Professor of Electrical and Computer Engineering at Oakland University, Rochester, MI, USA. Professor Mohamed research focus is in the area of Advanced control and estimation, intelligent pattern information processing, neural, fuzzy, evolutionary systems, chaos control, smart simulation, hybrid systems.

APPENDIX D

ANTENNA DESIGN MODEL CREATION AND FLOWCHART BLOCK DIAGRAM REPRESENTATION

Main process highlighted in antenna (Classic, embedded, smart) design in FEKO space is illustrated in Figure D.1.

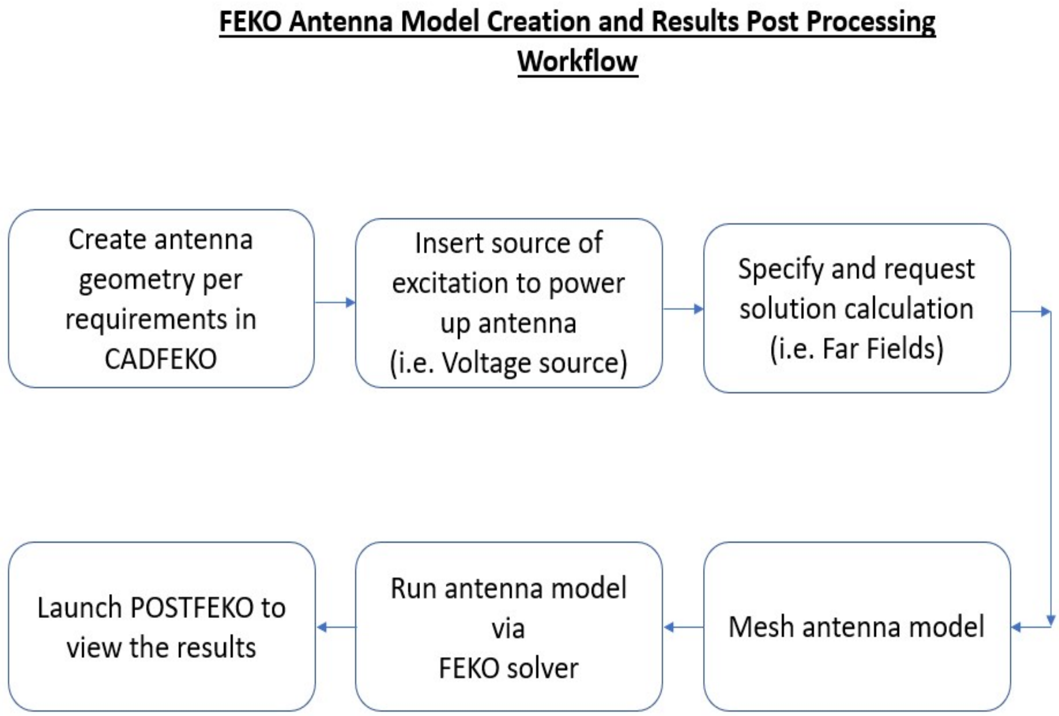


Figure D.1: FEKO antenna model creation and results workflow

The basic workflow and/or main steps involved in antenna design, simulation and analysis in general is shown in Figure D.2.

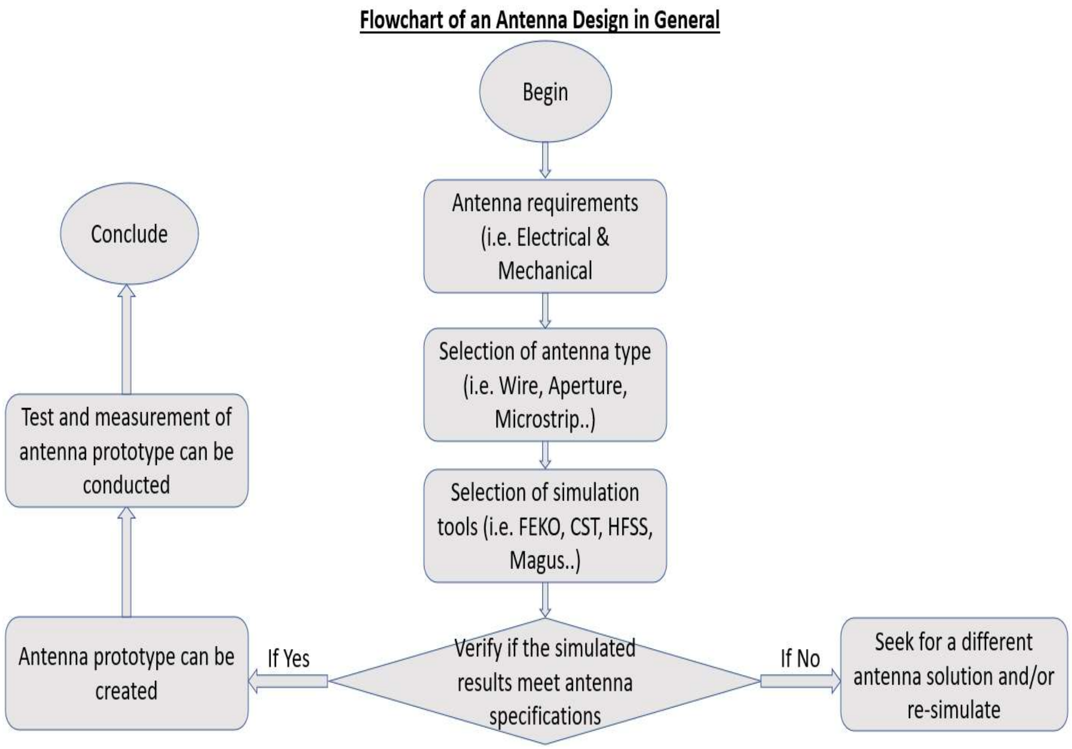


Figure D.2: Flowchart of antenna design process in general

APPENDIX E

BLOCK DIAGRAM REPRESENTATION OF AUTOMOTIVE ANTENNAS

ELECTRICAL INTERNCONNECTION TOPOLOGY

Block diagram representation of GPS, SDAR and SirusXM antenna component, automotive radio setup and RF signal propagation path is illustrated below in each of the following, Figure E.1, E.2, and E.3.

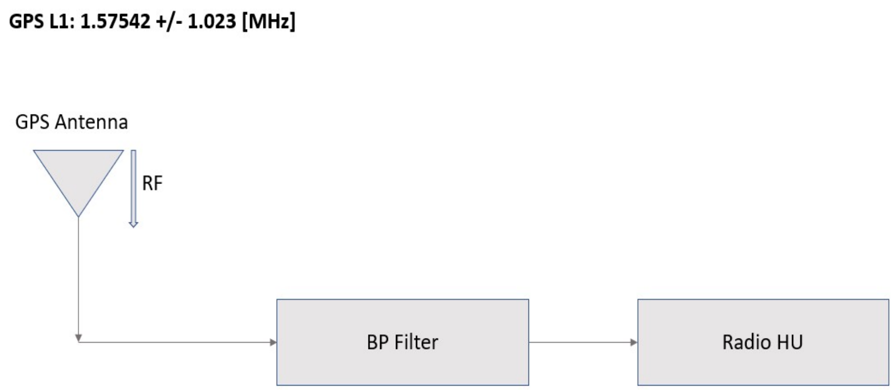


Figure E.1: GPS antenna and automotive radio electrical interconnection

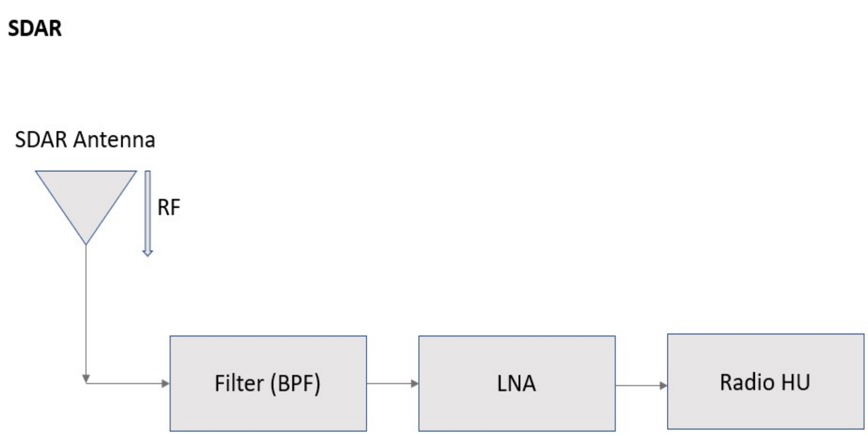


Figure E.2: SDAR antenna and automotive radio electrical interconnection

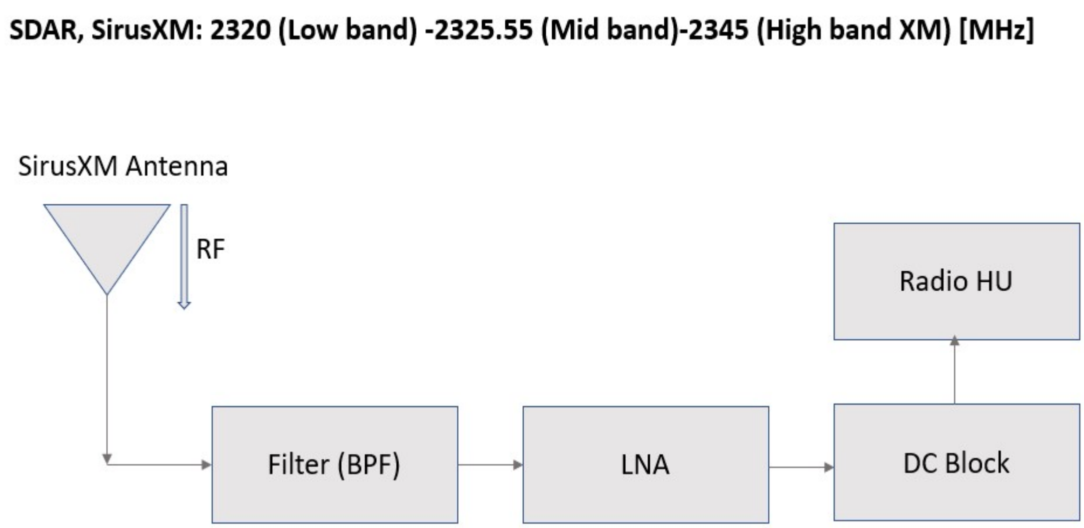


Figure E.3: SDAR and SirusXM antenna and automotive radio electrical interconnection

APPENDIX F

CONFIGURATION OF TRANSMITTER AND RECEIVER ANTENNA ASSEMBLY SYSTEM ARCHITECTURES

Block diagram representation of transmitter and receiver architecture is depicted in Figure F.1 and F.2.

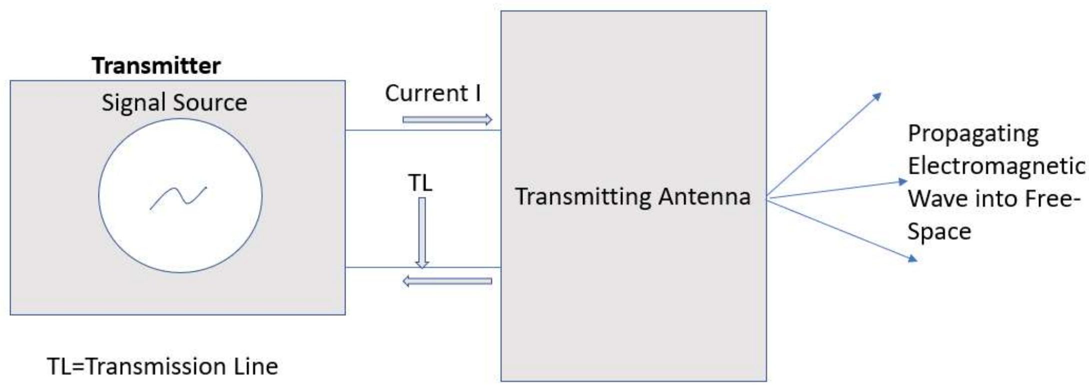


Figure F.1: Transmitter and antenna assembly block diagram

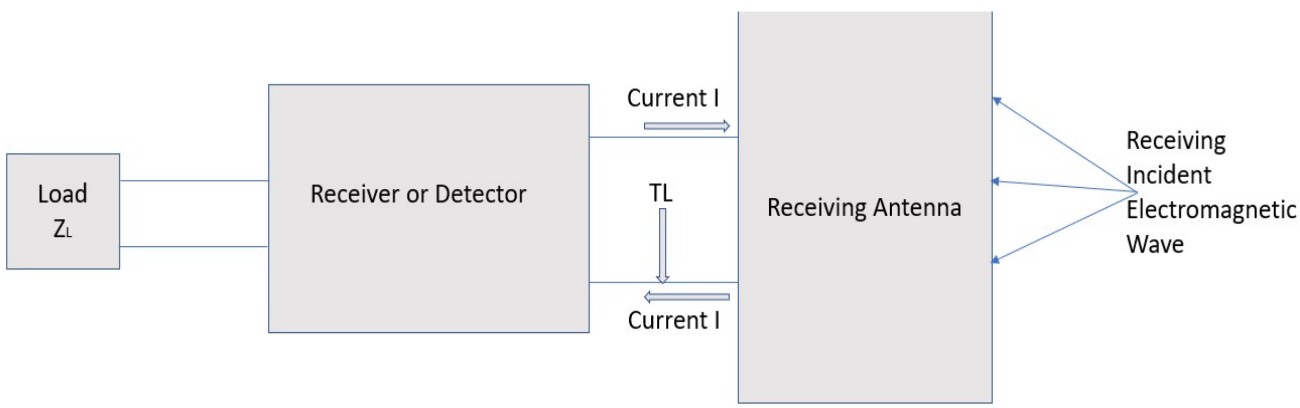


Figure F.2: Receiver, antenna assembly and load block diagram

REFERENCES

[1] Constantine A. Balanis, “Antenna Theory Analysis and Design”, 2nd ed., New York: Wiley, 1997, p. 1-3, 58-61, 73-77, 133-135, 722-750, 839-871

[2] Fawwaz T. Ulaby, “Fundamentals of Applied Electromagnetics”, 2001 Media Edition, Prentice Hall, p.347-354

[3] “Wikipedia”, https://www.wikipedia.org

[4] “A student version of FEKO simulator (CADFEKO & POSTFEKO)”, v2020

[5] Yen-Sheng Chen and Ting-Yu Ku, “Efficiency Improvements of Antenna Optimization Using Orthogonal Fractional Experiments”, http://downloads.hindawi.com/journals/ijap/2015/708163.pdf, Hindawi Publishing Corporation International Journal of Antennas and Propagation Volume 2015, Article ID 708163, 12 pages, p. 1-3

[6] Maged Abdelnaby Kafafy, Mohamed Zohdy and Syed Faisal Haider, “Assessment of Improved P-Transformation for Global Optimization with Application on Double Inverted Pendulum Control”, ICIC International 2018 ISSN 1881-803X, pp. 991- 999

[7] “Dassault Systems, Design of Experiments as a way to efficiently and effectively optimize antennas”, https://events.3ds.com/design-of-experimentsantennas#_ga=2.254880456.1725322526.1601439666-9847b8c0-02b7-11eb-ae4c-53256bd2443f

[8] V. K. Chichinadze, “The Ψ-transform for solving linear and nonlinear programming problems”, Automatica, vol.5, pp.347-355, 1969

[9] B. Adamczyk, M. A. Zohdy and A. A. Khan, “Global optimization of stochastic multivariable functions”, American Control Conference, San Francisco, 1993

[10] M. A. Zohdy, A. A. Khan and M. S. Kamel, “Global optimization of stochastic multivariable functions”, IEEE Proc. of the 26th Southeastern Symposium on System Theory, 1994

[11] V. K. Chichinadze, “Solution of nonlinear nonconvex optimization problems by Ψ-transformation method, Computer and Mathematics with Applications”, vol.21, pp.7-15, 1991

[12] K. Deb, “Multi-Objective Optimization Using Evolutionary Algorithms”, John Wiley & Sons, 2002

[13] D. E. Goldberg, “Genetic Algorithms in Search, Optimization and Machine Learning”, Addison-Wesley, Massachusetts, 1989

[14] C. M. Fonseca and P. J. Fleming, “Genetic algorithms for multiple objective optimization: Formulation, discussion and generalization”, Proc. of the 5th International Conference on Genetic Algorithms and Their Application, Morgan Kaufmann Publishers, San Mateo, CA, USA, 1993

[15] X. S. Yang, “Test Problems in Optimization, Engineering Optimization: An Introduction with Metaheuristic Application”, John Wiley & Sons, 2010

[16] “Types of Experimental Designs”:https://www.youtube.com/watch?v=10ikXret7Lk

[17] “Scientific Experiment”:https://www.youtube.com/watch?v=JpKcbCXjWCE

[18] “Experimental Design”:https://www.youtube.com/watch?v=UN206cSaF0k

[19] “Design of experiments (DOE)”:https://www.youtube.com/watch?v=k3lUo0XYG3E

[20] “Introduction of Experimental Design”:https://www.youtube.com/watch?v=5zkg1w5zoQ0

[21] “Planning of Designed Experiment (DOE)”:https://www.youtube.com/watch?v=gsD8V2_eZ0A

[22] “Factorial Design”:https://www.youtube.com/watch?v=5lFa7h5capM

[23] Minitab DOE-Full Factorial Analysis:https://www.youtube.com/watch?v=v3Epk5de8MQ

[24] “Minitab Tutorial-Set up a DOE”:https://www.youtube.com/watch?v=uJewUlQ1qXU

[25] “Everything you Need to Know to use Minitab”:https://www.youtube.com/watch?v=nSv88y3mqf4

[26] G.V.P.Pranathi, Dr.N.Deepika Rani,Dr.M.Satyanarayana, Prof.G.T.Rao, “Patch Antenna Parameters Variation with Ground Plane Dimensions”, IJAREEIE Vol. 4, Issue 8, August 2015

[27] https://www.ijareeie.com/upload/2015/august/74_20_Patch.pdf

[28] Minh Tuan Nguyen, Byoungchul Kim, Hosung Choo,Ikmo Park, “Effects of Ground Plane Size on a Square Microstrip Patch Antenna Designed on a Low-Permittivity Substrate with an Air Gap”, 978-1-4244-4885-2/10 2010 IEEE, https://ieeexplore-ieeeorg.huaryu.kl.oakland.edu/stamp/stamp.jsp?tp=&arnumber=5464869

[29] By D. Orban, G.J.K. Moernaut, Orban Microwave Products, “The Basics of Patch Antennas, Updated”, http://orbanmicrowave.com/wpcontent/uploads/2014/12/Orban-Patch-Antennas-2009-rev.pdf

[30] Sotoudeh Hamedi-Hagh, Joseph Chung, Sooseok Oh,Ju-Ung Jo, Noh-Joon Park and Dae-Hee Park,“Design of a High Performance Patch Antenna for GPS Communication Systems”, 282 Journal of Electrical Engineering & Technology Vol. 4, No. 2, pp. 282~286, 2009

[31] Luigi Boccia, Giandomenico Amendola, Giuseppe Di Massa, “A High-Performance Dual Frequency Microstrip Antenna for Global Positioning System”, 0-7803-7070-8/10 /$ lO.OO 0200 1 IEEE

[32] Nasimuddin, Karu P. Esselle, and A. K. Verma, “Wideband Circularly Polarized Stacked Microstrip Antennas, IEEE Antennas and Wireless Propagation Letters, vol. 6, 2007

[33] Chufarov M.V., Lvova L.A., Babushkin A.V., “Double-Band Circularly-Polarized Antenna for GLONASS-GPS Applications”, 978-1-4244-3861-7/09/$25.00 c2009 Crown

[34] Oluyemi P. Falade, Masood Ur Rehman, Yue (Frank) Gao, Xiaodong Chen and Clive G. Parini, “Single Feed Stacked Patch Circular Polarized Antenna for Triple Band GPS Receivers”, 0018-926X/$31.00 c 2012 IEEE

[35] Yinting Liu, Dan Shi, Shuyi Zhang, and Yougang Gao, “Multiband Antenna for Satellite Navigation System”, 1536-1225 c 2015 IEEE

[36] Minkil PARK, Duyeun Lee, Taeho Son, “Thin Ceramic GPS antenna, The 2015 International Workshop on Antenna Technology”, 978-1-47997717-8 c2015 IEEE

[37] M. M. Bilgic and K. Yegin, “Modified Annular Ring Antenna for GPS and SDARS Automotive Applications”, 1536-1225 c 2015 IEEE

[38] Jae-Hoon Bang, Wan-Ju Kim, and Bierng-Chearl Ahn, “Two-Element Conformal Antenna for Multi-GNSS Reception”, 1536-1225 (c) 2016 IEEE, IEEE Antenna and Wireless Propagation Letters

[39] Xinyi Tang, Nasimuddin, Xianming Qing, Zhi Ning Chen, "A Circularly Polarized Beam-Steering Antenna System for GNSS Applications", 978-1-5090-2597-8/16/$31.00 c 2016 IEEE

[40] Muhammad Qazafi, Abdel Razik Sebak, Electrical and Computer Engineering, Concordia University, Montreal Canada, mq_muham@ece.concrodia.ca, abdo@ece.concordia.ca, "Tri-Band CP Microstrip Patch Antenna for WLAN Applications"

[41] Richard B. Langley, University of New Brunswick, "A Primer on GPS Antennas", Jae-Hoon

[42] S. E Jasim, M. A. Jusoh, M. H. Mazwir and S. N. S. Mahmud, Faculty of Industrial Sciences & Technology, University Malaysia Pahang, Kuantan, Pahang, Malaysia, E-Mail: ashry@ump.edu.my, "Finding the Best Feeding Point Location of Patch Antenna", using HFSS, Vol. 10, No. 23, December 2015 ISSN 1819-6608, ARPN Journal of Engineering and Applied Sciences, 2006-2015 Asian Research Publishing Network (ARPN)

[43] Jinping Ma,Ammar B. Kouki, and Rene Landry Jr., Xidian University, Xian 710071, China, LACIME Laboratory, E´ cole de Technologie Sup_erieure, 1100 Notre-Dame Street West, Montreal, Quebec, H3C 1K3 Canada; Corresponding author: ammar.kouki@etsmtl.ca, " Wideband Circularly Polarized Single Probe-Fed Patch Antenna", Microwave and Optical Technology Letters/Vol. 54, No. 8, August 2012 DOI 10.1002/mop

[44] D. Orban and G.J.K. Moernaut, Orban Microwave Products, www.orbanmicrowave.com, "The Basics of Patch Antennas, Updated", As seen in the September 29, 2009 edition of the RF Globalnet (www.rfglobalnet.com) newsletter

[45] Amotech Advance Material on Technology, "GPS Patch Antenna Considerations"

[46] Abracon Corporation, "1575.42MHz; 25x25x4mm GPS Patch Antenna"

[47] Iuliia Goncharova and Stefan Lindenmeier, Institute of High Frequency Technology and Mobile Communication,University of the Bundeswehr, Munich, Germany, stefan.lindenmeier@unibw.de, " An Interoperable Antenna for GPS and GLONASS Services on a Car", 978-1-4799-7815-1/15/$31.00 c2015 IEEE

[48] A Tallysman Accutenna, "TW1721 / TW1722 Dual Feed Embedded BeiDou/Galileo/GPS/GLONASS Antenna", www.tallysman.com

[49] Mona S. Abdallah , Ying Wang, Wael M. Abdel-Wahab , and Safieddin Safavi-Naeini, "Design and Optimization of SIW Center-Fed Series Rectangular Dielectric Resonator Antenna Array With 45° Linear Polarization", IEEE Transactions on Antennas and Propagation, Vol. 66, No.1, January 2018

[50] https://en.wikipedia.org/wiki/Radial_basis_function_network

[51] Ground-multi path mitigation via polarization steering of GPS signal | Semantic Scholar

[52] https://gssc.esa.int/navipedia/index.php/File:GPS_constellation.gif

[53] File:GlonassConstellation.JPG - Navipedia (esa.int)

[54] Satellite constellation – Wikipedia

[55] THE FAA's WIDE-AREA AUGMENTATION SYSTEM (WAAS) (utexas.edu)

[56] GPS.gov: Control Segment

[57] The User Segment | GEOG 862: GPS and GNSS for Geospatial Professionals (psu.edu)

[58] Design and implementation of patch antenna (core.ac.uk)

[59] Antenna array – Wikipedia

[60] Erdfunkstelle Raisting 2 - Parabolic antenna – Wikipedia

[61] https://www.youtube.com/watch?v=Y5t0NH-bkx0

[62] https://www.rfcafe.com/references/electrical/dielectric-constants-strengths.htm

[63] http://orbanmicrowave.com/wp-content/uploads/2014/12/Orban-BasicsofGPSAntennas-article-RF-2008-final.pdf

[64] https://www.youtube.com/watch?v=46SbGxS73dY

[65] https://www.youtube.com/watch?v=mA05krI_iwI

[66] https://www.youtube.com/watch?v=sSRVsSALhWU

[67] https://www.youtube.com/watch?v=n8_iSL4xKj8

[68] https://www.youtube.com/watch?v=Ugbw4DfJWxQ

[69] https://www.youtube.com/watch?v=4RbVqpSWk4c

[70] https://www.youtube.com/watch?v=EKOecXPypvw

[71] https://www.youtube.com/watch?v=DhXCdvm-Kl8

[72] http://www.scholarpedia.org/article/Radial_basis_function

[73] https://www.youtube.com/watch?v=VUjeS0Q3KPENipun Haritash

[74] https://www.ece.mcmaster.ca/faculty/nikolova/antenna_dload/current_lectures/L07_Noise.pdf

[75] Noise in Antenna: https://web.stanford.edu/class/ee252/handouts/antenna_noise.pdf

[76] https://ieeexplore-ieeeorg.huaryu.kl.oakland.edu/stamp/stamp.jsp?tp=&arnumber=104252

[77] https://www.haystack.mit.edu/ast/arrays/Edges/EDGES_memos/219.pdf

[78] https://www.haystack.mit.edu/ast/pubs/2011RS004962.pdf

[79] https://www.haystack.mit.edu/edu/undergrad/materials/tut6.html

[80] https://www.haystack.mit.edu/ast/arrays/Edges/EDGES_memos/009.pdf

[81] https://www.haystack.mit.edu/ast/arrays/Edges/EDGES_memos/EdgesMemo.html

[82] https://www.haystack.mit.edu/ast/arrays/Edges/EDGES_memos /313.pdf

[83] https://www.haystack.mit.edu/ast/arrays/Edges/EDGES_memos/282.pdf

[84] https://www.haystack.mit.edu/ast/arrays/Edges/EDGES_memos/266.pdf

[85] https://www.youtube.com/watch?v=l4H4g5uktVw

[86] http://help.agi.com/stk/index.htm#comm/CommRadarB-03.htm

[87] https://en.wikipedia.org/wiki/Antenna_noise_temperature

[88] http://www.antenna-theory.com/basics/temperature.php

[89] https://www.youtube.com/watch?v=CQFpp1c7UQw

[90] https://www.youtube.com/watch?v=x4yoGGUCZmM

[91] https://www.youtube.com/watch?v=9OIXVuspmto

[92] Azremi Abdullah Al-Hadi, "Multi-element Antennas for Mobile Communication Systems: Design, Evaluation and User Interactions," Aalto University School of Electrical Engineering Department of Radio Science and Engineering, PP. 1-78, November 2013

[93] file:///D:/calabration-principles-chapter1.pdf

[94] https://en.wikipedia.org/wiki/Satellite_navigation

[95] David M. Pozar, and Barry Kaufman, "Comparison of Three Methods for the Measurement of Printed Antenna Efficiency", IEEE Transactions on Antenna and Propagation, Vol. 36, No. 1, January 1988

[96] Colloquium Electronics Division, "Advances in the Direct Measurement of Antenna Radiation Characteristics in Indoor Environments", Antenna and Propagation, Monday, 23 January 1989, Digest No 1989/8

[97] C.G. Parini, "The Design of Millimeterwave Antenna Measurement Systems"

[98] B. Rama Rao, M.N. Solomon, M.D. Rhines, L. J. Teig, R. J. Davis, E.N. Rosario, "Research on GPS Antenna at MITRE", The MITRE Corporation Bedford, Massachusetts 01730

[99] L.M. Lobkova, M.B. Protsenko, M.V. Ivashina, A.F. Rozvadovsky, "Measurement Method of Antenna Polarization Characteristics", Sevastopol State Technical University

[100] Rusiru Leelaratne and Richard Langley, "Multiband PIFA Vehicle Telematics Antennas", IEEE Transaction on Vehicular Technology, Vol, 54, No. 2, March 2005

[101] Randall W. Kreutel, Jr., Daniel F. Difonzo, and Christophe. Mahle, "Satellite System Measurements", Proceedings of the IEEE, Vol, 66, No, 4, April 1978

[102] Rus Leelaratne and Richard Langley, "Planar PIFA Telematics Antennas", Haracia European Research and Development Centre, Sittingbourne Research Centre, Kent, Dept. of Electronics University of Kent

[103] Dai Huanyao, Shen Xujian, Li Jinliang, Wang Liandong, “The Measurement Method of Polarization Characteristics of Practical Radar Antenna”, State Key Laboratory of Complex Electromagnetic Environmental Effects on Electronics and Information System Luoyang, 471003 Henan

[104] Chong Li, Tian-Hong Loh, ZhiHao Tian, Qian Xu, Yi Huang, “Evaluation of Chamber Effect on Antenna Efficiency Measurements using Non-Reference Antenna Methods in Two Reverberation Chambers, Electromagnetic Technologies Group, Time Quantum and Electromagnetics Division, National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK

[105] Michael Hillbun, “Practical Antennas”

[106] Warren L. Stutzman, Gary A. Thiele, “Antenna Theory and Design”, 2nd Edition, P 405-412 [107] M.D. Allin, “A Technique for Measuring the Time Dommain Response of a Dual Reflector Antenna”

[108] Jeffrey A. Fordham, “An Introduction to Antenna Test Ranges, Measurements and Instrumentation, The basic principles of antenna test and measurement are discussed along with an introduction to various range geometries, and instrumentation”, Microwave Instrumentation Technologies, LLC

[109] Michael W. Shields, Alan J. Fenn, “A New Compact Range Facility for Antenna and Radar Target Measurements”, Lincoln Laboratory Journal Volume 16, Number 2, 2007

[110] Mark Wright, “MRF24WB0M Indoor and Outdoor Antenna Range Testing”, Microchip technology Inc. 2010 Microchip Technology Inc. Preliminary DS01363A

[111] Agilent Technologies, “Agilent Antenna Test Selection Guide”, 9-3-2009

[112] Agilent Technologies, “Over the Air A-GPS Testing Agilent Technologies and ETS-Lindgren”, 10-05-2009

[113] Troy Alan Jensen, “Evla Memo No. 89 The Evla Outdoor Antenna Test Range Project: Fourth Quarter 2004, Progress Report”, National Radio Astronomy Observatory Array Operations Center, 1003 Lopezville Rd, Socorro, NM 87801 (505) 835-7124, February 8th, 2005

[114] Dr. Donald G. Bodnar, Vice President MI Technologies, “Testing Telematic Antennas”, MPD Microwave Product Digest, May, 2002

[115] Steven S. Holland, “Miniaturization of Microstrip Patch Antennas for GPS Applications”, Masters Theses 1911-February 2014, Dissertations and Theses, University of Massachusetts Amherst, sholland@engin_umass.edu

[116] Arbabi, A., and S. Safavi-Naemi, “Maximum Gain of a Lossy Antenna”, IEEE Transactions on Antennas and Propagation, Volume 60, 2-7, 01/2012, University of Waterloo, Waterloo ON Canada

[117] Biglarbegian, B., M-R. Nezhad-Ahmadi, A. Enayati, G.A.E. Vandenbosch, W. De Raedt, and S. Safavi-Naeini, “A 60-GHz On-Chip Slot-Array Antenna in Integrated-Passive-Device Technology for Antenna-In-Package Applications”, International Journal of RF and Microwave Computer-Aided Engineering, Volume 24, 155-160, 2014, University of Waterloo, Waterloo ON Canada

[118] file:///D:/GPS_L1%20Only%20Patch/TAOGLAS%20-%20GPS%20Patch%20Antenna%20Integration%20 Application%20Note.pdf

[119] https://blog.antenova.com/an-introduction-to-embedded-antenna-placement

[120] M. Gulam Nabi Alsath and Malathi Kanagasabai, “Compact UWB Monopole Antenna for Automotive Communications”, IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 63, NO. 9, SEPTEMBER 2015

[121] Placido De Vita, “AN4190 Application Note Antenna selection guidelines”

[122] Matthew N.O. Sadiku, Elements of Electromagnetics, 2nd ed., Philadelphia, PA, 1989

[123] Stefano Caizzone, Nikola Basta and A Chim Dreher, “Compact GNSS Antenna with Circular Polarization and Low Axial Ratio”, Insitute of Communications and Navigation, German Aerospace Center (DLR), D-82234 Wessling, Germany, 978-1-4673-0292-0/12/$31.00 ©2012 IEEE

[124] M. Maqsood, S. Geo, T.W.C. Brown, M. Unwin, R. de vos Van Steenwijk and J.D.Xu, “A Compact Multipath Mitigating Ground Plan for Multiband GNSS Antennas”, IEEE Transactions on Antennas and Propagation, Vol. 61, No. 5, May 2013

[125] Zhixi Liang, Yuanxin Li and Yunliang Long,, “Multiband Monopole Mobile Phone Antenna With Circular Polarization for GNSS Application”, IEEE Transactions on Antennas and Propagation, Vol. 62, No. 4, April 2014

[126] Ronald H Johnston, “Development of a High Performance GNSS Antenna”, 978-1-4799-3540-6/14/$31.00 ©2014 IEEE

[127] Vladimir N. Shepov, Valery M. Vladimirov and Vladimir V. Markov, "New Antenna Design for GNSS Application", 2015 International Siberian Conference on Control and Communications (SIBCON)

[128] https://www.wranglerforum.com

[129] Amira Bousselmi, Sabri Beldi and Ali Gharsallah, «Multiband Mobile Phone Antenna for GNSS Application", 978-1-4799-8172-4/15/$31.00 ©2015 IEEE1

[130] Ronald H Johnston, "Evolution of a Precision GNSS Antenna", 978-1-4799-7815-1/15/$31.00 ©2015 IEEE

[131] Alexander E. Popugaev, "A Family of High-Performance GNSS Antennas", RF and SatCom Systems Department Fraunhofer Institute for Integrated Circuits IIS Erlangen, Germany alexander.popugaev@iis.fraunhofer.de

[132] Xuan Shao, Yuan Yao, Junsheng Yu, Xiaodong Chen, Xiaoming Liu, Limei Qi and Zhijiao Chen, "Compact Triple Band Antenna Array for GNSS Application"

[133] Mr. Lukhi Vishalkumar, Prof. Khakhariya Sandip, Prof. S.Sreenath Kashyap, "Design of Planar Microstrip Patch Antenna for GPS Application"

[134] Ellie Manesh Applications Engineer Abracon Corporation, "Passive Patch Antenna-Application Note"

[135] M.S. Rabbani, and H. Ghafouri-Shiraz, School of Electronic Electrical and System Engineering, University of Birmingham, 52 Pritchatts Road Edgbaston, B15 2TT, UK, saqibrahhani05@hotmail.com and H.GHAFOURI-SHIRAZ@bham.ac.uk, "IMPROVEMENT OF MICROSTRIP ANTENNA'S GAIN, BANDWIDTH AND FABRICATION TOLERANCE AT TERAHERTZ FREQUENCY BANDS"

[136] B. Rama Rao, M.A. Smolinski, Cuong C. Quach, E.N. Rosario, The MITRE Corporation, Bedford, Massachusetts 01730-1420, brrao@mitre.org, "TRIPLE BAND GPS TRAP LOADED INVERTED L ANTENNA ARRAY", MICROWAVE AND OPTICAL TECHNOLOGY LETTERS, Vol. 38, No.1, July 52003

[137] Constantine A. Balanis, "Advnaced Engineering Electromagnetics", United States of America: John Wiley & Sons, Inc., 1989, p. 1-7, 24-31

[138] "CADEFEKO & POSTFEKO v2021-Student Edition"

[139] Chao Deng, Yong-jun Xie and Ping Li, "CPW-Fed Planar Printed Monopole Antenna With Impedance Bandwidth Enhanced", IEEE Antennas and Wireless Propagation Letters, Vol. 8, 2009

[140] Tao Hong, Shu-Xi Gong, Ying Liu and Wen Jiang, "Monopole Antenna With Quasi-Fractal Slotted Ground Plane for Dual-Band Applications, IEEE Antennas and Wireless Propagation Letters, Vol. 9, 2010

[141] Hong Chen, X. Yang, Y.Z. Yin, S.T. Fan and J.J. Wu, "Triband Planar Monopole Anttenna With Compact Radiator for WLAN/WiMAX Applications", IEEE Antennas and Wireless Propagation Letters, Vol. 12, 2013

[142] Leh Wen, Steven Gao, Qingling Yang and Qi Luo, School of Engineering and Digital Arts, University of Kent, Canterbury CT2 7NT, United Kingdom, Yingzeng Yin, National Key Laboratory of Antennas and Microwave Technology, Xidian University, Xian 710071, China, Xiaofei Ren and Jian Wu, Innovation and Research Center, China Research Institute of Radiowave Propagation, Qingdao, 266107, China, "A Compact Monopole Antenna With Filtering Response for WLAN Applications", China Research Institute of Radiowave Propagation, and in part by EPSRC grants EP/N032497/1, EP/S005625/1, and EP/P015840/1

[143] Ravilla Dilli, Electronics and Communication Engineering, Manipal Institute of Technology, Manipal, Karnataka, India, dilli.ravilla@manipal.edu, "Analysis of 5G Wireless Systems in FR1 and FR2 Frequency Bands", Proceedings of the Second International Conference on Innovative Mechanisms for Industry Applications (ICIMIA 2020) IEEE Xplore Part Number: CFP20K58-ART; ISBN: 978-1-7281-4167-1