EFFECTS OF SELECTED ROOFING MATERIALS ON AIR NAVIGATION SIGNAL PROPAGATION

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A thesis submitted to the Graduate School in partial fulfillment for the requirements of the award of Master of Science Degree in Engineering Systems and Management of Egerton University

EGERTON UNIVERSITY

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DECLARATION AND RECOMMENDATION

Declaration

I, Robert Jere Omusonga declare that this thesis is my original work and has not been wholly or in part presented for the award of a degree in any other university known to me.

Signature………………………………………… Date……………………

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Reg. No: BM12/2074/08

Recommendation

This proposal is the candidate's original work and has been prepared with our guidance and assistance; it is submitted for examination with our approval as university supervisors.

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ABSTRACT

The environment around radio navigation aids systems (navaids) includes buildings whose roofing materials interfere with signal propagation. This interference may cause partial loss of intelligence in communication between navaids and flying aircrafts. Buildings around airports have been restricted partly because they pose threats to flight navigation. This restriction as captured in the Laws of Kenya has not been supported by sufficient data. Previous studies have shown that about half of air accidents occur during landing. However, no data has been availed to determine the contribution of navaids to these accidents. The purpose of this research was to study effects of roofing materials on air navigation signal propagation. The method involved use of a 9.4GHz transmitter, a receiver and a computer to measure signal level transmitted through roofing materials at various angles of incidence. The study considered effects of decra (aluminum-zinc stone-chip coated steel), iron, steel, aluminum, plastic and clay materials on navaids signal strength, transmission distance and wave polarization. Decra gave the highest attenuation whereby 98% of the signal propagated was lost, out of which 53% was due to reflection. Decra also exhibited the lowest desired-to-undesired signal ratio of -27dB which was far below International Civil Aviation Organization recommended value of 20dB. Only iron and clay reported significant figures above the recommended value. Variation of signal strength with transmission distance depended on type of roofing material but generally a negative correlation was registered. Roofing materials had no significant effect on wave polarization. The study challenged flight navigation authorities and construction industry to isolate and develop a compromise roofing material that will have little effect on navaids signal propagation.

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LIST OF SYMBOLS

φ	Polar angle
φ_o	Deviation of antenna from direction of reference
λ_o	Wavelength in free space
l_{el}	Electrical length of an antenna
$\boldsymbol{A}$	Actual signal from detector
$\boldsymbol{a}$	Level of significance
$\boldsymbol{d}$	Distance between transmitter and receiver
$\boldsymbol{D}$	Longitudinal horn antenna diameter of transmitting source
$\boldsymbol{G_r}$	Receiving antenna gain
$\boldsymbol{G_t}$	Transmitting antenna gain
$\boldsymbol{P_r}$	Received power
$\boldsymbol{P_t}$	Transmitted power
$\boldsymbol{r_o}$	Minimum distance required to fulfill far-field condition
$\boldsymbol{U}$	Voltage drop generated by detector
$\boldsymbol{uA}$	Micro amperes

LIST OF ACCRONYMS AND ABBREVIATION

AM	Amplitude Modulation
ATC	Air Traffic Control
CAK	Communication Authority of Kenya
CCK	Communication Commission of Kenya
CGI	Corrugated Galvanized Iron
CSB	Carrier Side Band
D/U	Desired-to-Undesired ratio
dBm	decibel referenced to 1 mW
DME	Distance Measuring Equipment
DVOR	Doppler Very High Frequency Omni-Direction Range
EIRP	Equivalent Isotropically Radiated Power
GP	Glide Path
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineering
ILS	Instrument Landing System
ITU	International Telecommunication Union
LOS	Line of Sight
NASA	National Air Space Agency
Navaids	Air Navigation Aids Systems
NIST	National Institute of Standards and Technology
NM	Nautical Mile
PRSL	Propagated Received Signal Level
$PRSL_o$	Propagated Received Signal Ratio during reference measurements
PRSR	Propagated Received Signal Ratio
PSD	Power Spectrum Density
PIN	Positive Intrinsic Negative
RADAR	Radio Detection and Range
REF	Reference signal
RF	Radio Frequency
RRSL	Reflected Received Signal Level
RRSR	Reflected Received Signal Ratio
RSL	Received Signal Level

RSS	Received Signal Strength
SARPs	Standards and Recommended Practices
SBO	Side Band Only
SM	Space Modulation
VAR	Variable signal

CHAPTER 1
INTRODUCTION

1.1 Background

Kenya is a member of the International Civil Aviation Organization (ICAO) which is a specialized United Nations agency that regulates global civil aviation operations. In the Laws of Kenya, Civil Aviation Act No. 21 (2013) part II article 40 provides procedure for acquisition of land for the purpose of civil aviation, part V article 56 provides orders for restriction of buildings in aviation declared areas and part V article 57 provides regulations for control of structures inside and near aerodromes. This section of legislation is meant to eliminate obstacles and other threats around airports but it lacks scientific data to support its being.

Obstacles that affect radio navigation aid systems (navaids) are structures in the vicinity of aircraft flight path. These obstacles include buildings, hills and mountains, masses of water, reflective ground, clouds, snow and rain. Reflections from these obstacles in the vicinity of the runway may interfere with direct radiating beam from the Instrument Landing System (ILS) and deviate the course-line from a straight line. The occurrence of interference to the ILS signal is dependent on the total environment around the ILS antenna array and the characteristics of the antenna. Any large reflecting objects including vehicles or fixed objects such as structures within the radiated signal coverage have potential to cause multipath interference to the ILS signal source and path structure (Cortesi *et al.*, 2002; Marcum, 2002).

Construction of buildings around airports especially along flight approach path is restricted mainly due to safety and security threats arising from accidents, terrorism and other criminal activities. One major underlying factor is that buildings distort signals radiated by navaids (Cortesi *et al.*, 2002). It is argued that by interfering with navaids radiations, such buildings provide a window for errors that contribute to air accidents. Many of these structures reflect, refract, diffract, absorb, attenuate or augment the navaids signals. Natural obstacles such as mountains, hills, water masses and reflective grounds are minimized by ensuring that airports are sited in areas free of these obstacles (ICAO, 2013a; ICAO, 2013b).

However, buildings around and within the airports are unavoidable especially in a country where land is a fast diminishing commodity. Physical threats are being checked using enhanced aviation security programs and safety management systems as stipulated in the ICAO standards and recommended practices to safeguard against acts of unlawful interference (ICAO, 2010; ICAO, 2011). The Civil Aviation Act No. 21 of 2013 restricts heights of buildings around airports thus leaving roofing materials as the most significant sources of interference.

Kebabjian (2008) in his analysis (Figure 1.1) showed that 51% of air accidents occur during final approach and landing. It was observed that flights maximize usage of navaids in the final stretch but no data was availed to determine the contribution of navaids to the accidents. Effects of obstacles on propagation of navaids signals was not determined.

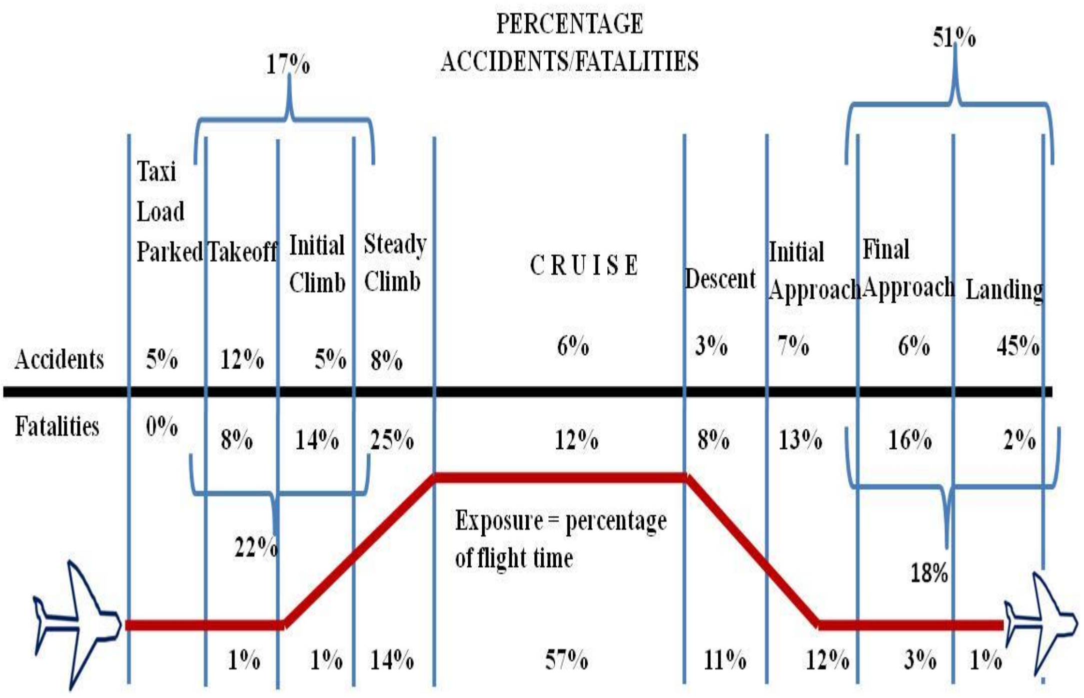

Figure 1.1: Relationship of Flight Sector and Accidents

(Kebabjian, 2008)

Previous research by Chomba *et al.* (2011a), Marcum (2002) and Cortesi *et al.* (2002) studied the effects of some of these obstacles on microwave signal transmission but very little was done to investigate and compare the effects of particular obstacles on navaids signal strength. Similarly, the effects of material obstacles on wave polarization, angle of incidence and transmission distance were not considered. Unlike the ordinary microwave signal, navaids signal intelligence is contained in its significant variables such as direction, distance, orientation and strength. It was therefore necessary to consider the effect of obstacles on these significant variables.

This research focused on the effects of roofing materials on navaids signal propagation. It aimed at investigating the behaviour of radio navigation signals when subjected to obstacles made of aluminum, iron, steel, clay, decra and plastic. The study involved conducting experiments using the provided roofing materials where vulnerable effects with high possibility of causing interference and loss of intelligence in the propagated signals were presented. These effects included attenuation and reflection. The independent variables were types of roofing materials, angles of incidence, wave polarization and transmission distances whereas the dependent variable was signal strength. The measurements were done using received signal level indication via a computer system at the East African School of Aviation (EASA) aeronautical telecommunication laboratory.

1.2 Statement of the Problem

Physical threats to safety and security of aircrafts, life and property are the foremost reasons why buildings around aerodromes must be restricted. However, according to Cortesi *et al.* (2002), the underlying reason is technical rather than physical. The buildings are capable of distorting navaids signals between the aircraft and ground equipment and therefore risking loss of intelligence in the transmissions. Such interference could have devastating effects on flight navigation especially during landing. With controlled heights of buildings, roofing materials remain the most aerially exposed objects that interact with radio navigation signals in aerodromes. The restriction of buildings as captured in Kenya Civil Aviation Act No. 21 of 2013 has not been fully tested and is not supported by sufficient data.

1.3 Objectives

The main objective was to determine effects of roofing materials on propagation of air navigation signal.

Specific objectives were to;

1) Determine effects of selected roofing materials and angle of incidence on navaids signal strength.
2) Determine effects of selected roofing materials on navaids transmission distance.
3) Determine effects of selected roofing materials on navaids wave polarization.

1.4 Research Questions

1) What are the effects of roofing materials and angle of incidence on navaids signal strength?
2) What are the effects of roofing materials on navaids transmission distance?
3) What are the effects of roofing materials on navaids wave polarization?

1.5 Research Justification

With controlled heights of structures around the aerodromes, roofing materials have become very significant since they are more exposed and are bound to affect air navigation signals (Biermann *et al.*, 2008). Comprehensive data on propagation of air navigation signals through roofing materials is lacking and that is why this study strove to generate data on roofing materials based on their effects on navaids signal propagation. The outcome of this study is intended to guide governments and airport authorities in reviewing restrictions governing structures around airports. One example is the approach flight path of Jomo Kenyatta international airport in Nairobi which occupies approximately 7 by 7 kilometers of land with restricted human settlement. Such land has been made virtually unproductive in a country where arable land is a scarce precious resource. If all other flight navigation threats were to be controlled, except human settlements on flight paths, governments would find data resulting from this study vital for reference.

1.6 Scope and Limitations

In the laboratory experiments, a frequency of 9.4GHz was applied, the power transmitted was 10mW, gain of transmit antenna was 63 (18dB), maximum distance between transmitter and receiver was 100cm and common resistance of antennas was 50 Ohms. From the Friis formula of free space loss, it was shown that propagation loss at 9.4GHz was 112dB per km. The study represented a field environment scaled down to a laboratory environment using Fraunhofer distance equation (Balanis, 2005; Volakis, 2007). Fraunhofer equation based on 9.4GHz and 16mm dipole antenna enabled a distance of 100cm to fulfill far-field conditions that are equivalent to open field environment. International Civil Aviation Organization has standardized and recommended minimum received signal strength in navaids designated operation area as -28dBmV/M and desired-to-undesired signal ratio of 20dB.

Whereas the atmospheric conditions in the field are dynamic and bound to affect the propagation of navaids signals, the environment in the laboratory was assumed constant. The effects of snow, clouds, rain, reflective ground and masses of water on navaids signals have been studied by Shah *et al.* (2008), Tromboni and Palmerin (2010), Biermann *et al.* (2008), Hueschen and Knox (1994) among others. The results of these studies will become significant when extrapolating laboratory experiment to field environment.

Whereas roofing materials could cause many other effects on navaids signals, only two effects were considered. Attenuation and reflection are the effects that were considered since they significantly alter the characteristics of microwaves and thus distort the intelligence in the navigation signals. For example, ILS intelligence is contained in the signal strength and radiation pattern. The principles of distance measuring equipment and radar are based on reflected signals. Variables considered were angle of incidence, state of polarization and transmission distance because the navigation signal is dynamic in aspects of direction, orientation and distance, all due to continuous motion of the aircraft.

The comparison between selected roofing materials based on navaids signal propagation was conducted in uniform environmental conditions. The materials considered were decra, steel, aluminum, plastic, clay and iron since they are commonly used around airports. Other materials such as concrete, wood, glass, paper and grass were not considered since they are rarely used on large scale.

CHAPTER 2
LITERATURE REVIEW

2.1 Propagation of Air Navigation Signals

According to Marcum (2002) the problem of monitoring the performance of the Instrument Landing System (ILS) has been investigated for a number of years. Both experimental and theoretical studies have yielded information about system performance, but the problem has not been completely solved. Major error sources contributing to ILS performance were identified as scattering from nearby reflective surfaces, and changes to the ground plane in the vicinity of the ILS as shown in Figure 2.1. Transmitter signal errors can affect the radiated antenna signals that form the ILS course-line. Reflective objects near the ILS produce multipath errors, which cause roughness, course bends, and scalloping in the approach region (Greenwell, 2000). ILS's critical areas are usually established to reduce multipath interference from objects such as structures, vehicles, and aircraft stationed on the ground.

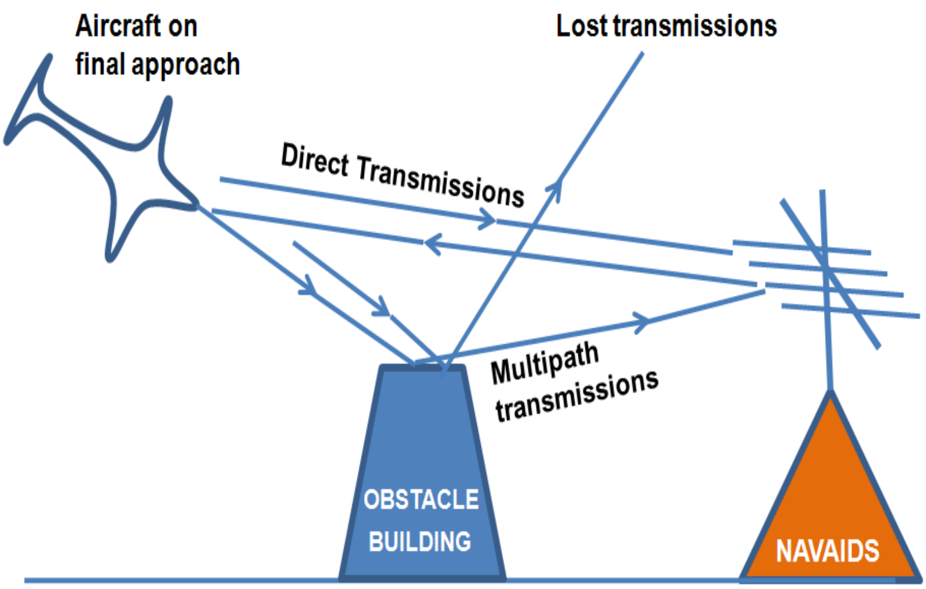

Figure 2.1: Multipath Effect of Buildings on Navaids Transmissions (Greenwell, 2000)

Delay of air navigation signals causes loss of intelligence in the propagation. Multipath occurs when part of transmitted Radio Frequency (RF) signal arrives at the receiving antenna with different delays. The delay is caused when the signal is bounced off stationary obstacles such as walls, floors, ceilings, desks, and moving objects such as people, machines and cars. The worst environments that create multipath errors are factories, car garages, and other buildings with a lot of metal surfaces (Chu and Kiang, 2004; Pu and Chung, 2008; Yarkoni and Blaunstein, 2006).

Navaids are radio communication systems used to provide navigation guidance to flights. The guidance includes direction, distance, lateral and inclination angles of the flight path. Navaids operate in Line of Sight (LOS) mode of propagation. LOS is the mode of propagation whereby the transmitter is able to 'see' the receiver in a straight line, in one direction and with no obstructions. The maximum radius for line of sight propagation is 100 km (Gupta, 2005). The intelligence of navaids is contained in signal strength, phase angle, delay, depth of modulation and radiation pattern. The LOS propagation caters for microwaves belonging to the radio band of VHF, UHF and SHF (300MHz to 30GHz) as defined in Table 2.1.

Table 2.1: Frequency Bands, Wavelengths and Radio Band Designations

Frequency	**Wave length**	**Radio band**	**Use**
30-300 Hz	10-1 Mm	ELF	
300-3000 Hz	1000-100k	ULF	
3-30 KHz	100-10 km	VLF	
30-300 KHz	10-1 km	LF	
300-3000 KHz	1000-100 m	MF	
3-30 MHz	100-10 m	HF	
30-300 MHz	10-1 m	VHF	VOR, VHF Radio
300-3000 MHz	100-10 cm	UHF	GP ILS, DME,
3-30 GHz	10-1 cm	SHF	Radar, Cell-phones
30-300 GHz	10-1 mm	EHF	

(CCK, 2008b)

Key

ELF -Extremely Low Frequency, UHF -Ultra Low Frequency, VLF -Very Low Frequency, LF -Low Frequency, MF -Medium Frequency, HF -High Frequency, VHF -Very High Frequency, UHF -Ultra High Frequency, SHF -Super High Frequency, EHF -Extra High Frequency.

2.1.1 Quality of Communication Links

According to Larpoulsen (1994) the quality of a radio-frequency communication link is a function of five parameters. First is the receiver sensitivity which is the minimum amount of signal power that must reach the receiver in order to decode the transmission. The sensitivity of a good receiver ranges from -75 dBm to -90 dBm. The second parameter is the background noise level in the band which is the minimum signal-to-noise ratio that will allow the receiver to extract a usable signal amidst the competing signals within the frequency band occupied by the desired signal. The third parameter is the transmitted signal level which is a measure of how much power the transmitter is able to deliver to its antenna. The fourth parameter determines how the transmitting and receiving antenna systems shape the signal in 3-dimensional space. The last parameter is a measure of dissipation of the signal as it travels through the atmosphere from the transmitter to the receiver.

2.1.2 Scattering of Radio Signals

Navigation signals scatter when they encounter obstacles in the line of sight. Scattering of the signal occurs when there are objects of comparable dimensions to the wavelength of the radiation in the medium of transmission. Scattering is particularly prevalent when there are rough and irregular surfaces present (Gupta, 2005; Kopp, 2000).

2.1.3 Attenuation

Attenuation is the reduction of signal strength during transmission. It is the opposite of amplification. It is measured in decibels (dB). During transmission, the signal gets attenuated. Attenuation is an inherent characteristic of Radio Frequency (RF) signal and is also very important in the design aspect. So it should be taken into consideration while designing and calculating the RSL (Receive Signal Level) of the RF signal between two stations. Attenuation is directly proportional to the frequency. That means that RF signal gets significantly attenuated at higher frequencies and there is less effect of attenuation at lower frequencies. This is partly because a shorter wave is more proportionately affected by absorption and path losses than longer waves over a similar distance (Gurung and Zhao, 2007).

Attenuation may be due to many effects, such as free-space loss, refraction, diffraction, reflection, coupling loss, and absorption. Attenuation is also influenced by terrain contours, environment, propagation medium, the distance between the transmitter and the receiver, and the height and location of antennas.

The signal radiated by a transmitter may also travel along many different paths to a receiver simultaneously; this effect is called multipath as shown in Figure 2.2. Multipath waves combine at the receiver antenna, resulting in a received signal that vary widely, depending on the distribution of the intensity and relative propagation time of the waves and bandwidth of the transmitted signal.

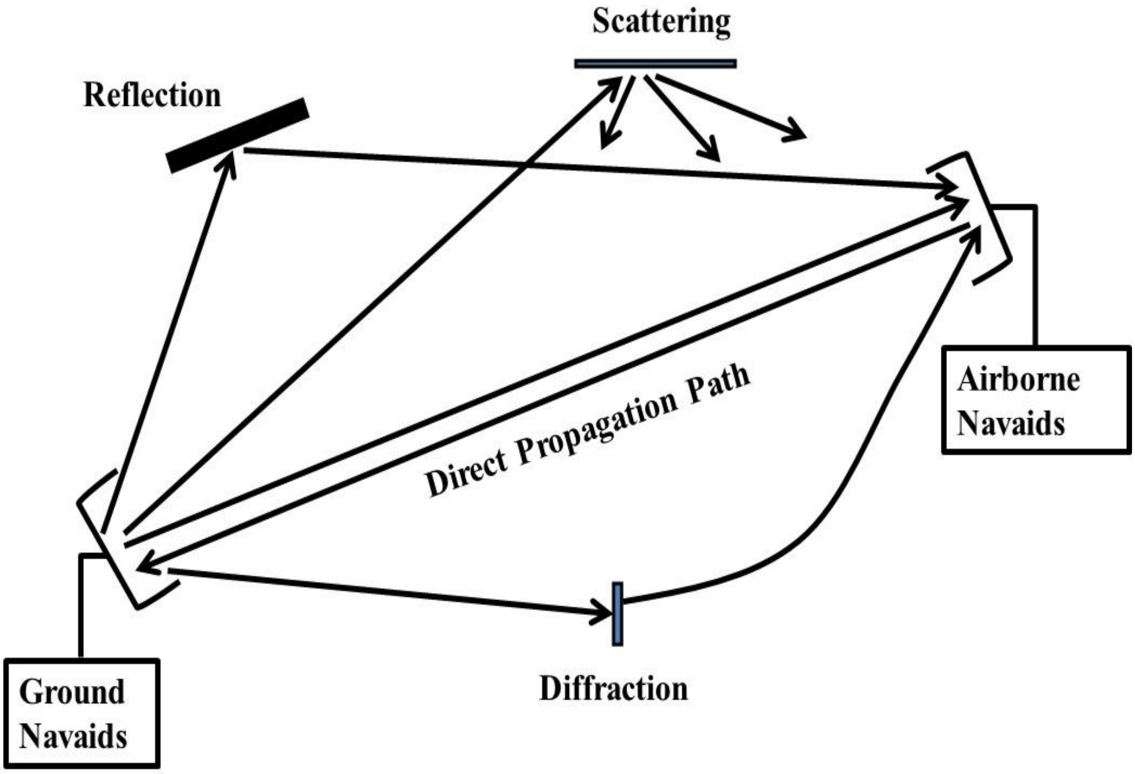

Figure 2.2: Effects of Obstacles and Multipath Propagation of Navaids Signals (Gupta, 2005)

Another contributing factor to attenuation is absorption. Absorption is the process where the intensity of a beam of electromagnetic radiation is attenuated when it passes through medium by conversion of the energy of the radiation to an equivalent amount of energy appearing within the medium. The radiant energy is converted into heat or some other form of molecular energy. A perfectly transparent medium permits the passage of a beam of radio wave without any change in intensity other than that caused by the spread or convergence of the beam, and the total radiant energy emergent from such a medium is equal to that which entered it. Emergent energy from an absorbing medium is less than that which enters and in the case of highly opaque medium the wave intensity is reduced practically to zero (Debus, 2005; Alam *et al.*, 2010).

2.1.4 RF Propagation and Path Loss Exponent

The RF signals emitted by antenna go through significant attenuation, even in free space before they reach intended recipient. The free space propagation loss is given by Friis formula in Equation 2.1 (Debus, 2005; Tsai, 2011).

$$L(dB) = 32.5 + 20\,LogF + 10\,nLogD \tag{2.1}$$

F is transmission frequency in MHz
D is distance in kilometers
n is path loss exponent

The parameter n is known as path loss exponent which is an indicator of how fast the signal attenuates with distance in a given environment. For free space propagation n is equal to 2. In a non-line of sight communication many other factors such as attenuation due to absorption, reflection and multipath come into this equation. If the type of materials and the exact amount of attenuation are known, these may be added to the propagation loss formula to calculate actual loss. In a mixed environment such as an indoor office, a different path loss exponent (n) may be used instead to approximate the path loss. For example, a value between 2.5 and 4 may be typical for indoor environment though the path loss exponent can be as high as 8 in some RF unfriendly environments. On the other hand, a tunnel may act as a waveguide, resulting in a path loss exponent less than 2 (Debus, 2005).

In practice a radio signal may encounter many objects in its transmission path and undergoes additional attenuation depending on the absorption characteristics of the objects. There are many types of objects including fixed mobile and transient objects that absorb RF energy and cause RF attenuation (Debus, 2005).

Table 2.2 shows the loss (or attenuation in dB) introduced by various objects and materials. Most of the attenuations are given as range of the actual value depending on the exact frequency of transmission and the thickness as well as specific types of materials used. Moreover, the number measured at different locations does not always agree as the measurement conditions may be different (Debus, 2005).

Table 2.2: Common Materials and Corresponding Attenuation in dB

Materials	F = 2.4GHz	F = 5GHz
Interior dry wall	3 – 4	3 – 5
Cubical wall	2 – 5	4 – 9
Wooden door	3 – 4	6 – 7
Brick walls	6 – 9	10 – 15
Concrete walls	9 – 18	15 - 30
Coated glass	13	20
Plain glass	2 – 3	6 – 8
Steel door	13 - 19	25 – 32

(Debus, 2005)

2.1.5 Regulations on Spectrum Utilization

K185 band is ranged from 9.3GHz – 9.5GHz (the frequency in this study was 9.4GHz) and its application is equivalent to K160 band (5150MHz – 5250MHz) as shown in Table 2.3. K185 and K160 bands are used for aeronautical radio navigation service, ground based radars and airborne weather radars (CCK, 2008b).

Table 2.3: Frequency Band, EIRP and PSD

Frequency Band MHz	Maximum EIRP power	Power Spectrum Density (PSD)
2400 – 2483	100mW	10mW/MHz
5150 – 5250	200mW	10mW/MHz
5470 – 5570	1W	50mW/MHz
5725 – 5775	200mW	10mW/MHz

(Adapted from CCK, 2008a)

2.1.6 Reflection

Reflection occurs when the radio wave is incident on a surface which has much larger dimensions than its wavelength. The propagated signal striking a surface will either be absorbed, reflected, transmitted or a combination of all. This reaction depends on the physical properties of the medium the signal is traversing, including surface geometry, texture, and material composition. The signal properties that influence the surface effects are the arriving incident angle, wavelength and polarization. The reflected waves follow the laws of reflection which state that the angle of reflection equals to the angle of incidence as shown in Figure 2.3. Depending on the material of the reflecting surface a portion of the signal may also be absorbed (Holland *et al.*, 2006; Gupta, 2005).

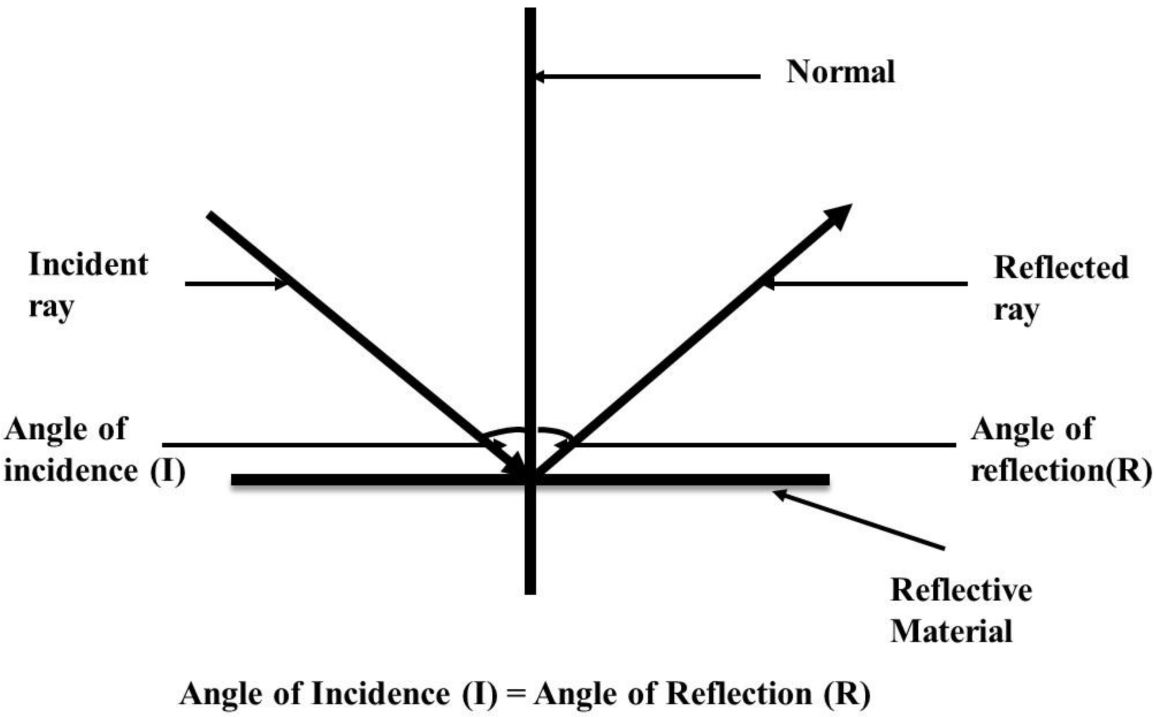

Figure 2.3: Relationship between Angle of Incidence and Angle of Reflection (Gupta, 2005)

2.1.7 Diffraction

Diffraction is the apparent bending of waves around small obstacles and spreading out of the waves past small openings. It occurs when the radio wave path between the transmitter and the receiver is obstructed by a surface that has sharp irregular edges. The radio signal impinging on the edge results in secondary waves which propagate in all directions around the edge as shown in Figure 2.4. The diffraction depends on the geometry of the object, the amplitude, phase, and polarization of the incident wave at the point of diffraction (Rappaport, 2003). Its effects are most pronounced where the wavelength is roughly similar to the dimensions of the diffracting object.

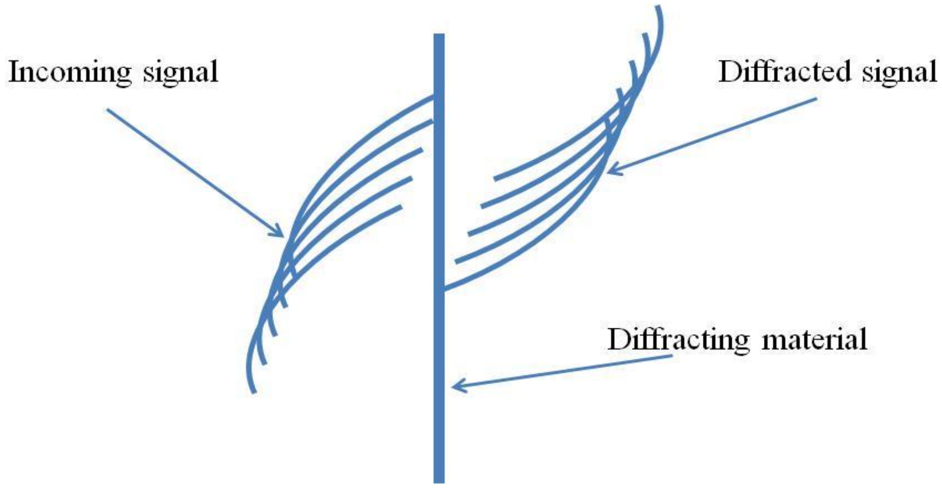

Figure 2.4: Diffraction of Signals
(Rappaport, 2003)

2.1.8 Radiation Patterns

The radiation pattern of an antenna is a plot of the relative field strength of the radio waves emitted by the antenna at different angles (Breidenbach and Kloza, 2007). It is typically represented by a three dimensional graph, or polar plots of the horizontal and vertical cross sections. The pattern of an ideal isotropic antenna, which radiates equally in all directions, would look like a sphere. Many non-directional antennas, such as monopoles and dipoles, emit equal power in all horizontal directions, with the power dropping off at higher and lower angles; this is an Omni-directional pattern and when plotted looks like a torus or donut. Equation 2.2 represents empirical formula for electric field strength distribution for radiation patterns of dipole antennas of given electrical lengths. Figure 2.5 shows radiation pattern.

$$e = E.\left| \frac{\cos\left(\frac{\pi l_{el}}{\lambda_o}\right)\sin(\varphi+\varphi_o) - \cos\left(\frac{\pi l_{el}}{\lambda_o}\right)}{\cos(\varphi+\varphi_o)} \right| \qquad (2.2)$$

Where;

e = electric field strength distribution

E = amplitude of field strength

l_{el}= electrical length

λ_o= free space wavelength

φ = polar angle

φ_o= reference angle

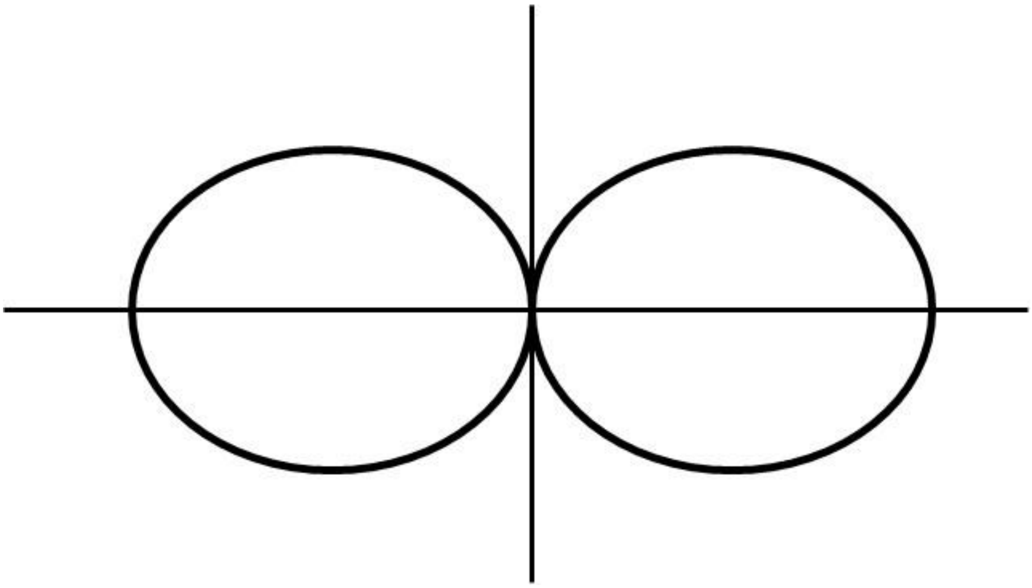

Figure 2.5: Radiation Pattern of Half-Wave Antenna
(Breidenbach and Kloza, 2007)

2.1.9 Polarization of Radio Antennas

The polarization of an antenna is the orientation of the electric field (E-plane) of the radio wave with respect to the Earth's surface and is determined by the physical structure of the antenna, orientation and excitation fed to it. It has something in common with antenna directionality; horizontal, vertical, and circular. Thus, a simple straight wire antenna will have one polarization when mounted vertically, and a different polarization when mounted horizontally (Figure 2.6). Electromagnetic wave polarization filters are structures which can be employed to act directly on the electromagnetic wave to filter out wave energy of an undesired polarization and to pass wave energy of a desired polarization (Breidenbach and Kloza, 2007; Sandiku, 2001; Hayt and Buck, 2003). Navaids equipment such as Instrument Landing System (ILS) and Doppler VHF Omni-directional Range (DVOR) are installed with horizontally polarized orientation whereas Distance Measuring Equipment (DME) and Secondary Surveillance Radar (SSR) are vertically polarized.

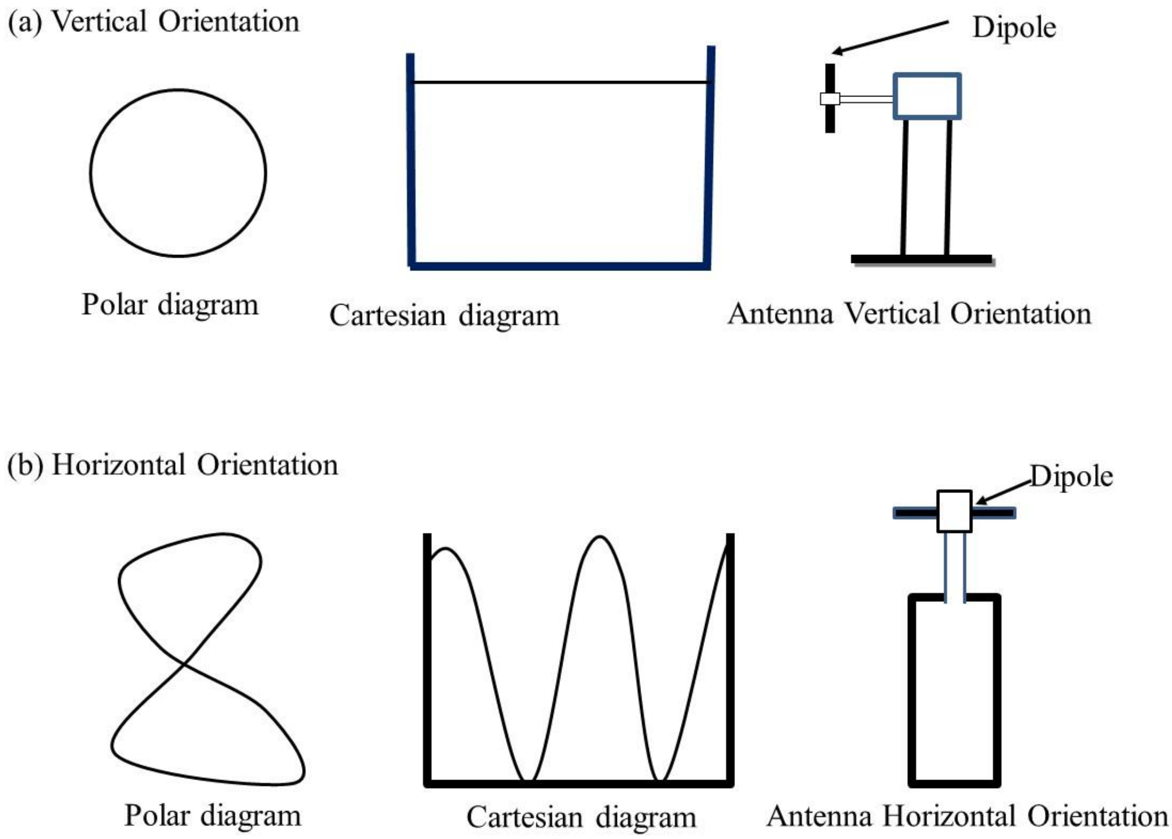

Figure 2.6: Free Space Polar Diagrams for λ/2 Antenna
(Breidenbach and Kloza, 2007)

Directional diagrams can be measured in horizontal or vertical mode. Usually the horizontal mode means a rotation of the test antenna in the electric or E-Plane. The vertical mode means a rotation of the test antenna in the magnetic or H-plane

2.1.10 Near-field and Far-field Distances

The near-field and far-field are regions of electromagnetic field around an object such as transmitting antennas. The near-field strength decreases with distance, whereas far-field strength decreases with the inverse square of distance (Balanis, 2005; Arokiamary, 2009).

While far-field is the region in which the field acts as normal electromagnetic radiation where it is dominated by electric dipole type electric or magnetic fields, the near-field is governed by multi-pole type fields which can be considered as collections of dipoles with fixed phase relationship. The boundary between the two regions depends on the dominant wavelength emitted by the source (Volakis, 2007; Bolomey and Gardiol, 2001).

Far-field carries a relatively uniform wave pattern, the far-field energy escapes to infinite distance i.e. it radiates. Near-field refers to regions such as near conductors and inside polarized media where propagation of electromagnetic waves is interfered with. The interaction with the media can cause energy to deflect back to source, in case of reactive near-field. The interaction with the medium can alternatively fail to return energy back to the source but cause a distortion in the electromagnetic wave (Rappaport, 2010; Singal, 2010).

According to Alexander (2011) near-field is that part of the radiated field that is below distances shorter than the Fraunhofer distance as defined in Equation 2.3 and Figure 2.7.

$$d \leq 2\frac{D^2}{\lambda} \tag{2.3}$$

Where;

D = longitudinal antenna diameter of transmitting source.

λ = wavelength

d = Fraunhofer distance

In both indoor and outdoor experiments, the distance between the source antenna and the receiver antenna must fulfill the far-field condition. Consequently, a far field distance must be maintained as defined in Equation 2.4 (Breidenbach and Kloza, 2007).

$$r_o \geq \frac{2(d_Q + d_t)^2}{\lambda_o} \tag{2.4}$$

Where;

r_o = distance between receiver and transmitter

λ_o = wavelength of the radiated wave

d_Q and d_t = largest dimensions in transverse (d_t) or longitudinal (d_Q) direction of the horn antenna

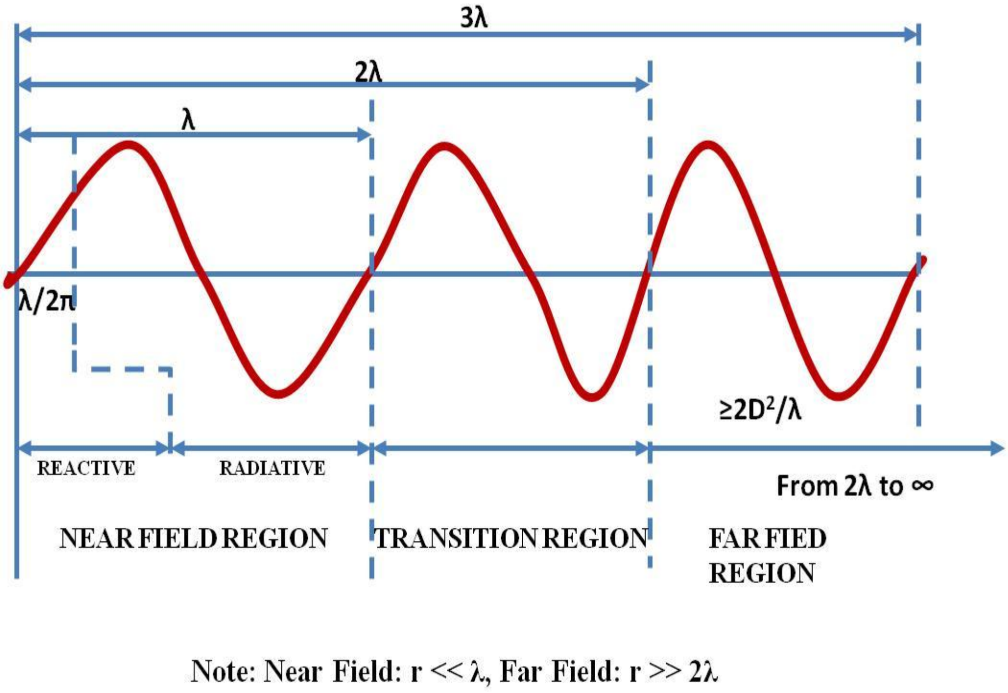

Figure 2.7: Near-Field and Far-Field Boundaries (Balanis, 2005)

When designing a far-field range the consideration is to simulate the operating environment of the test antenna as closely as possible. Far-field measurements can be performed on indoor and outdoor ranges. The selection of an appropriate test range is dependent on many factors such as: availability, access and cost of infrastructure suitable for quality measurements, weather, budget, security considerations, test frequency and aperture size, antenna handling requirements, pattern and gain measurement accuracy requirements (Balanis, 2005; Arokiamary, 2009).

Where the combination of the antenna aperture and the operating frequency permit, measurements can be made indoors - typically, in a special room that has been lined with anechoic material that is designed to be highly absorptive at the test frequencies. This anechoic material reduces reflections off the walls, floor, and ceiling that can combine with the main signal to distort the even illumination of the test aperture. The effects of the distortion can affect accurate gain and side lobe measurements (Volakis, 2007; Bolomey and Gardiol, 2001).

2.1.11 Variation of Signal Strength with Distance

According to Fette (2007), the range of line-of-sight signals, when there are no reflections from the earth or ionosphere, is a function of the dispersion of the waves from the transmitter antenna.

In the free-space case the signal strength decreases in inverse proportion to the distance away from the transmitter antenna. When the radiated power is known, the field strength, E is given by Equation 2.5.

$$E = \frac{\sqrt{(30 P_t} G_t)}{d} \qquad (2.5)$$

Where;

P_t = transmitted power,

G_t = the antenna gain,

d = the distance.

When P_t is in watts and *d* is in meters, *E* is in volts/meter.

To find the power at the receiver (P_r) when the power into the transmitter antenna is known, Friis formula is used as in Equation 2.6.

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2} \qquad (2.6)$$

Where;

G_t and G_r are the transmitter and receiver antenna gains, and λ is the wavelength.

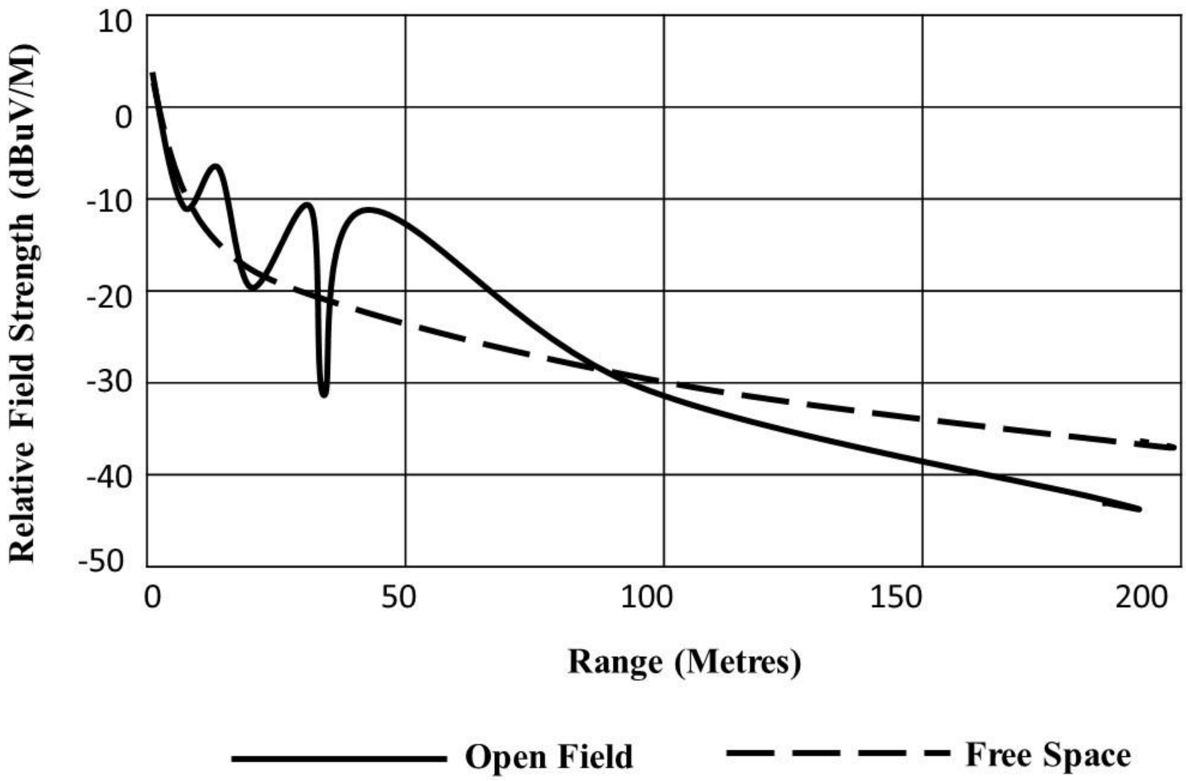

Figure 2.8: Field Strength Versus Range at 300 MHz
(Fette, 2007)

In both plots (Figure 2.8), signal strength is referenced to the free space field strength at a range of 3 meters. Up to a range of around 50 meters, there are several sharp depressions of field strength, but the signal strength is mostly higher than it would be in free space. The reason could be that at short distances reflections are augmenting the forward signal. Beyond 100 meters, signal strength decreases more rapidly than for the free space model. Whereas there is an inverse distance law for free space, in the open field beyond 100 meters the signal strength follows an inverse square law. Increasing the antenna heights extends the distance at which the inverse square law starts to take effect (Fette, 2007).

From the foregoing discussion, this research has compared the effects of selected roofing materials on radio signal propagation in open field environment. The analysis has generally confirmed that transmission distance and signal level are inversely proportional and have mixed proportionality at very short distances. However, the analysis goes further to show that the rate or the slope of proportionality will vary depending on the obstructions in the signal path.

For propagation over the horizon and based on recommendation ITU-R P.528 of the International Telecommunication Union (ITU), curves for path loss are specified and established as follows;

Table 2.4: Frequency Band and Path Loss per Nautical Mile

Frequency Band (MHz)	Path loss (dB) per Nautical Mile
108 – 137	0.5
960 – 1215	1.6
5030 – 5091	2.7

(ICAO, 2012)

2.2 Approach Flight Path

Approach flight path is the designated path of an aircraft when approaching an aerodrome to enable safe expeditious maneuver before landing or taking off. This is the period and stretch within which the aircraft is nearing the airport zone boundary under the guidance of Air Traffic Control (ATC) and navaids. The civil aviation approach flight area covers approximately 7 x7 square kilometers for international airports (Figure 2.9). Buildings in this area are restricted by way of controlling constructions, dumping and farming (ICAO, 2013a). ICAO (2006) and ICAO (2001) provide procedures for air navigation services particularly on aircraft operations within aerodromes and flight paths including clearance for obstructions and air traffic management.

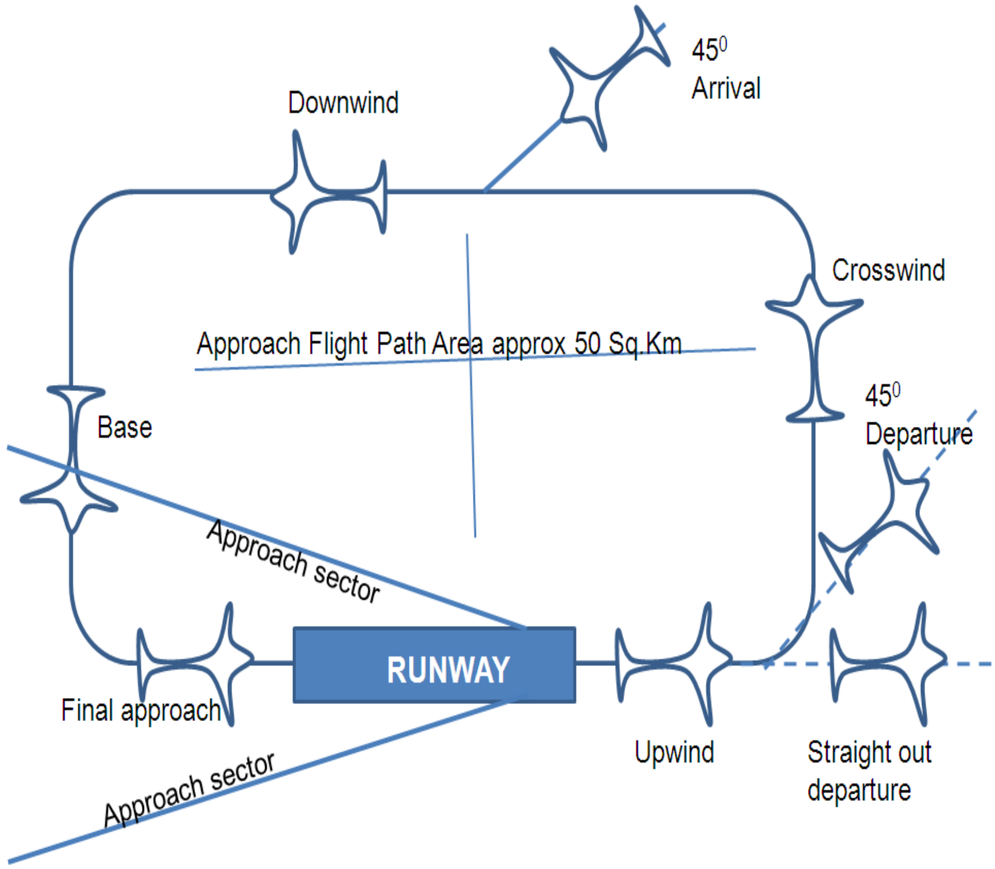

Figure 2.9: Typical Approach Flight Path for an International Airport (ICAO, 2003)

2.3 Radio Navigation Systems

The ability of the aircraft to navigate the air space expeditiously and safely by conforming to flight rules; and without fear of getting lost or endangering lives and property of those on board and on the ground is largely dependent on radio navigation systems.

Some radio navigation systems are airborne-based relying on the reception of trigger signals from one or more beacons on the ground. Others may be ground-based systems which require trigger transmissions from an aircraft. A third type of navaids is based on signals received from three or more satellites to enhance global positioning of aircrafts.

This research considered ground based navaids whose signals are likely to interact with obstacles such as roofing materials of structures around aerodromes. To illustrate the effects of this interaction, the study chose to investigate operations of three main navaids namely; Distance Measuring Equipment (DME), Instrument Landing System (ILS) and Very High Frequency Omni-directional Range (VOR) equipment.

2.3.1 Distance Measuring Equipment (DME)

DME uses basic radio telemetry to provide information on the distance between the aircraft and the ground station. It manipulates both the radio signal received from an on-board interrogator and the reply transmitted from the ground transponder. The principle is based on distance is equal to time multiplied by speed, where speed is the velocity of electromagnetic wave. The distance is determined by measuring the propagation delay of a radio frequency (RF) pulse that is emitted by the aircraft transmitter and returned at a different frequency by the ground station (Andreassen, 2008).

DME equipped (interrogator) aircraft transmits encoded RF pulse pairs to the ground beacon (transponder). The transponder replies with encoded pulse pairs to the interrogator. DME transponders transmit on a channel in the 962 to 1213 MHz range and receive on a corresponding channel between 1025 to 1150 MHz, where the two channels are 63 MHz apart (ICAO, 2010). This principle of measurement of distance is illustrated in Figure 2.10.

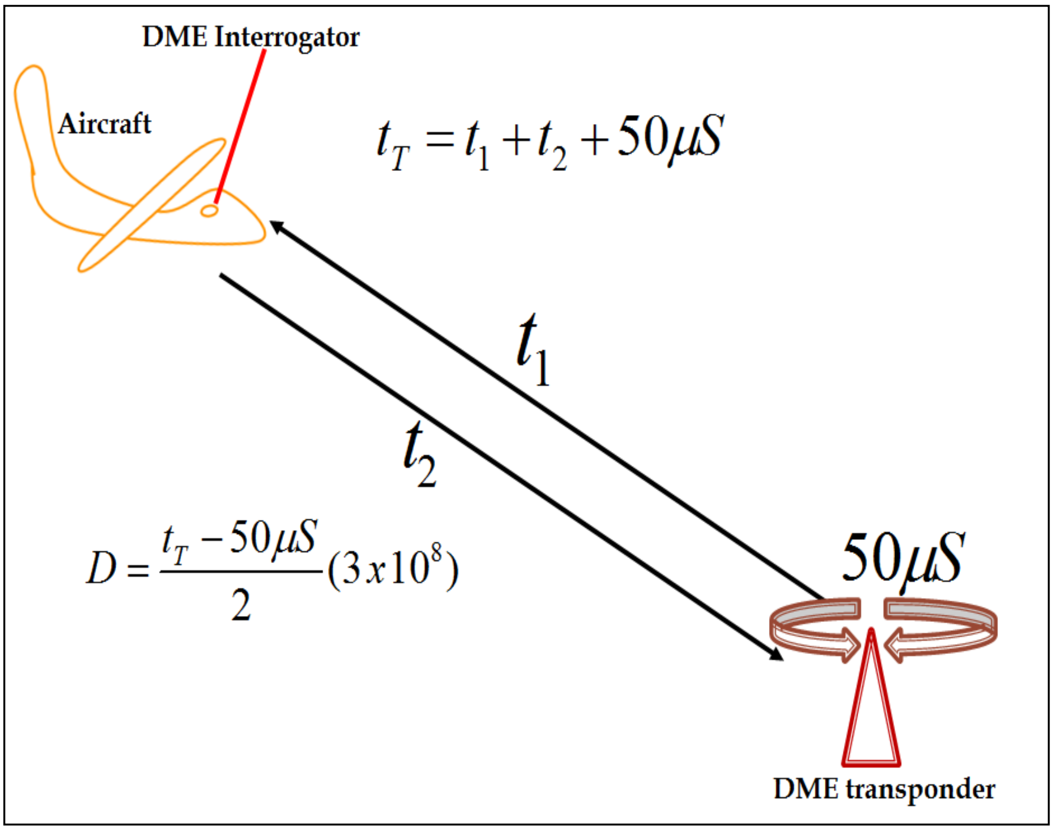

Figure 2.10: Basic Principle of DME

(Andreassen, 2008)

According to Andreassen (2008) measurement of distance based on radio frequency signals assumes free space propagation. However due to natural and artificial obstacles around airports, RF signals interact with this structures. This interaction is likely to result into attenuation and more particularly reflection. Figure 2.11 illustrates how reflection arising from the roof of a building can introduce errors in DME measurements.

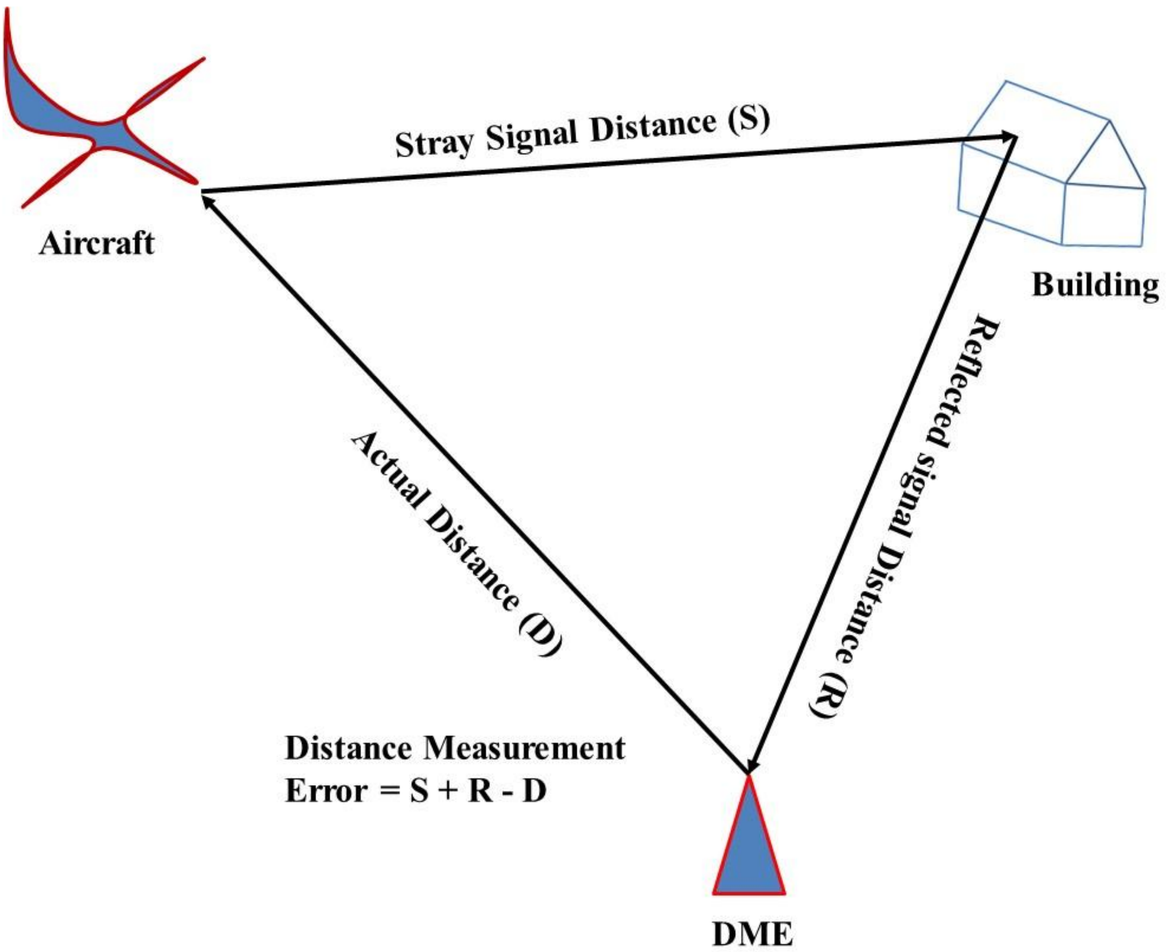

Figure 2.11: DME Distance Measurement Errors Caused by Reflection (Andreassen, 2008)

2.3.2 Instrument Landing System (ILS)

When an aircraft is about to make an approach and landing on an airport runway during bad weather conditions, there is need to radiate navigational information to carter for lost visibility (ICAO, 2010). Instrument Landing System (ILS) is used for this purpose. ILS is a ground-based instrument approach system that provides precision guidance to an aircraft approaching and landing on a runway, using a combination of radio signals, visual and aural indications to enable a safe landing during bad weather. ILS consists of two main independent sub-systems, one providing lateral guidance (localizer) and the other providing vertical guidance (glide path) to aircrafts approaching a runway. A modulation depth comparison of two radio signal beams radiated strategically from the localizer (LOC) and received by the ILS receiver in the aircraft provides lateral course-line information intended to coincide with runway center line, while a similar comparison from the glide path (GP) provides the slope information intended to coincide with inclination angle at the touch-down point of the runway (Andreassen, 2008).

The localizer transmitter operates within the frequency band of 108 to 112MHz with channel separation of 200KHz. Its antenna system is strategically designed and placed symmetrically around the centerline of the runway and approximately 300 metres behind the runway stop-end. Information about the position of an air craft is achieved by modulating the transmitted carrier with tone frequencies, 90Hz and 150Hz. The radiation pattern of the antenna system has such a form that 150Hz modulation is predominant on the right hand side of the course-line, seen in the approach direction while 90Hz modulation is predominant on the left side (Greenwell, 2000).

The two tone frequencies are amplitude modulated to a depth of 20% with tolerance of ±2% and harmonic distortion less than 10%. The course-line of a localizer is theoretically a straight line consisting of all points where the difference in depth of modulation (DDM) is equal to zero. The course-line is usually adjusted to coincide with the center-line of the runway. The receiving equipment of the localizer in the Air Craft (AC) is a cross-pointer instrument that reacts to the difference in depth of modulation between 90Hz and 150Hz dots (Figure 2.12).

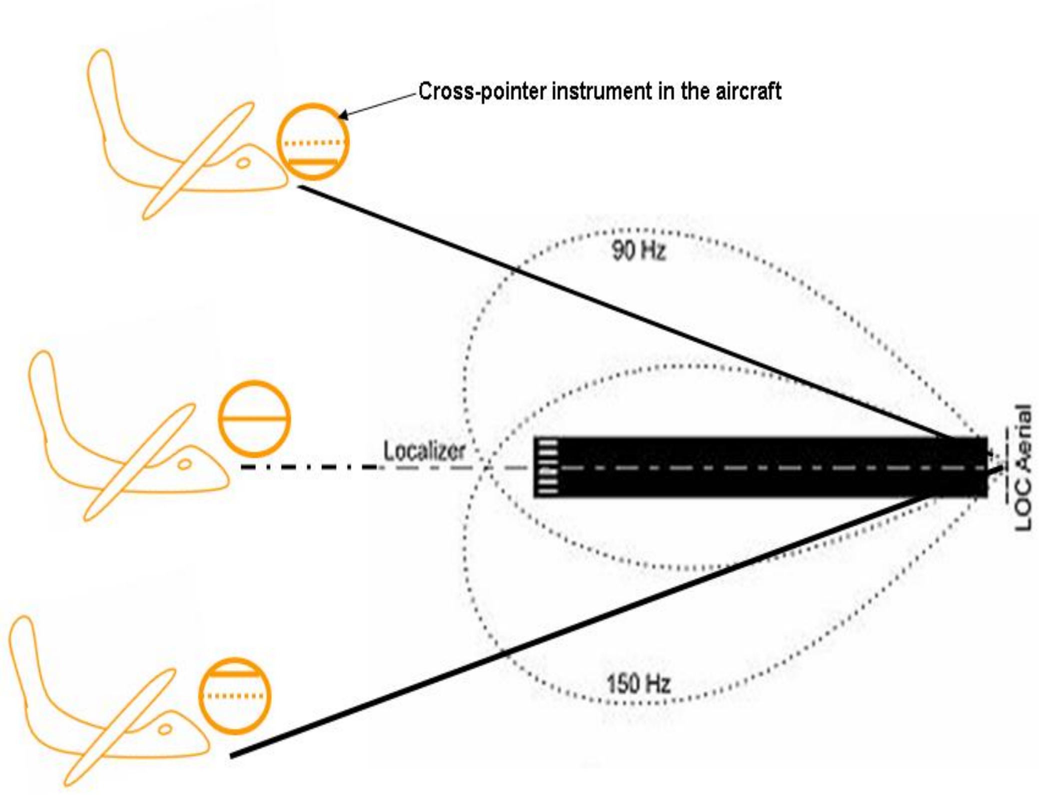

Figure 2.12: ILS Measurement of Lateral Displacement

(Greenwell, 2000)

The ILS principle is based on comparison of depths of modulation for two tones. These two tones 90Hz and 150Hz are modulated on the same carrier and form a signal called CSB (Carrier and Side Bands). This is done in the electronic part of the ground equipment. Further, the same tones are used for producing a combined sideband signal designated SBO (Side Bands Only). When the two Radio Frequency (RF) signals, CSB and SBO, are mixed in the near-field and far-field of the antenna, a modulation process called space modulation (SM) is obtained, causing the depth of modulation of CSB signal to be dependent on the amplitude and phase relationship between CSB and SBO in each point where they are mixed. By comparing depths of modulation after detection of the RF signals, the air craft receiver finds the magnitude and direction of the air craft's displacement from the desired course-line (Andreassen, 2008). The CSB and SBO signals can be expressed mathematically by Equations 2.7, 2.8 and 2.9 as follows (Andreassen, 2008);

$$E_{CSB} = E_c Cos\ 2\pi f_c t + E_{90} Sin\ 2\pi f_{90} t Cos\ 2\pi f_c t + E_{150} Sin\ 2\pi f_{150} t Cos\ 2\pi f_c t \tag{2.7}$$

$$E_{SBO\,90} = KSin\ 2\pi f_{90} t Cos\ (2\pi f_c t) \tag{2.8}$$

$$E_{SBO\,150} = KSin\ 2\pi f_{150} t Cos\ (2\pi f_c t) \tag{2.9}$$

Where;

E_{CSB}= Instantaneous voltage of carrier plus sideband components

E_{SBO90}= Instantaneous voltage of 90Hz sideband component

E_{SBO150}= Instantaneous voltage of 150Hz sideband component

K = Amplitude of each sideband

E_C= Amplitude of carrier signal

E_{90}= Amplitude of 90Hz signal

E_{150} = Amplitude of 150Hz signal

F_C= Frequency of the carrier signal

F_{90} = 90Hz

F_{150}= 150Hz

It must be noted that the mathematical expressions for radiated CSB and SBO signals in the far field can be altered if signal attenuation in space undergoes phase change and antenna characteristics are modified beyond tolerance. It thus means that components in CSB and SBO signals must be carefully observed and controlled to avoid deviations from nominal parameters. This research study has dwelt on finding out if roofing materials in aerodromes are obstacles that can destabilize these equations and cause errors in ILS Measurements (ICAO, 2010).

2.3.3 Very High Frequency Omni-directional Range Equipment (VOR)

The VOR (Very high frequency Omni-directional Range) automatically gives the pilot the direction of the aircraft with respect to magnetic north. The VOR system consists of one transmitting station on the ground and a VOR receiver in the air craft. The VOR ground stations are either situated on the air field or more often along the air ways in order to provide en-route navigation.

The VOR operates on principle that the phase difference between two signals can be employed as a means of determining azimuth (direction and bearing) if one of the signals maintain a fixed phase through 360 degrees (so that it may be used as a reference) and the phase of the other is made to vary as a direct function of azimuth. The phase difference between these two signals will indicate the azimuth of the aircraft with respect to the ground station. In practice the VOR determines direction of the aircraft from the VOR station by comparing the phase between a reference signal (REF) which is omnidirectional and a variable signal (VAR) which is a rotating figure of 8 (fig-8) as illustrated in Figure 2.13.

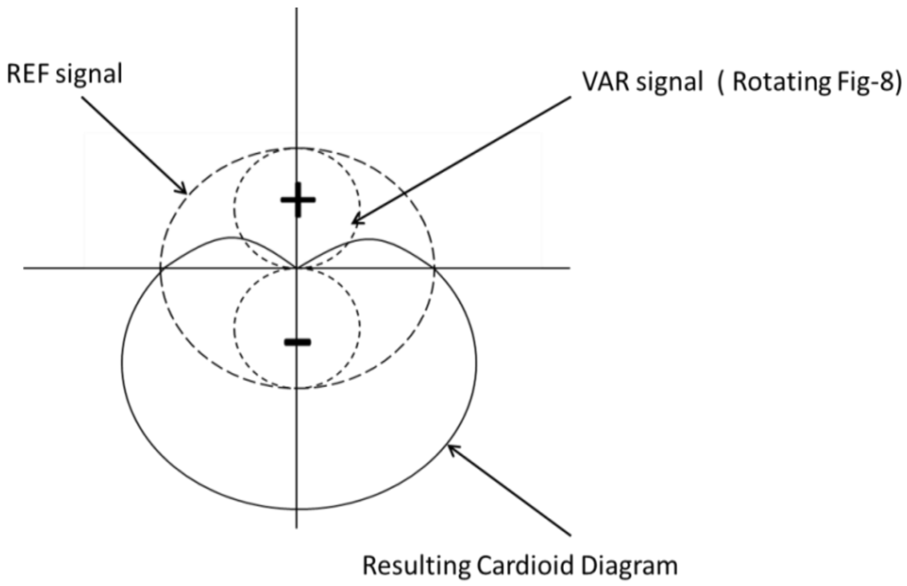

Figure 2.13: VOR Measurement of Azimuth
(Andreassen, 2008)

The conventional 30 Hz REF signal is on a 9960 Hz frequency modulated (FM) subcarrier. The amplitude modulated (AM) VAR signal is conventionally derived from a directional antenna array rotating electronically at 30 times per second (Selex Inc., 2009).

When the signal is received in the aircraft, the two 30 Hz signals are detected and then compared to determine the phase angle between them. The phase angle by which the AM signal lags the FM subcarrier signal is equal to the direction from the station to the aircraft, in degrees from local magnetic north, and is called the radial angle. The dip on the Cardioid will point to the correct bearing. (Figure 2.14)

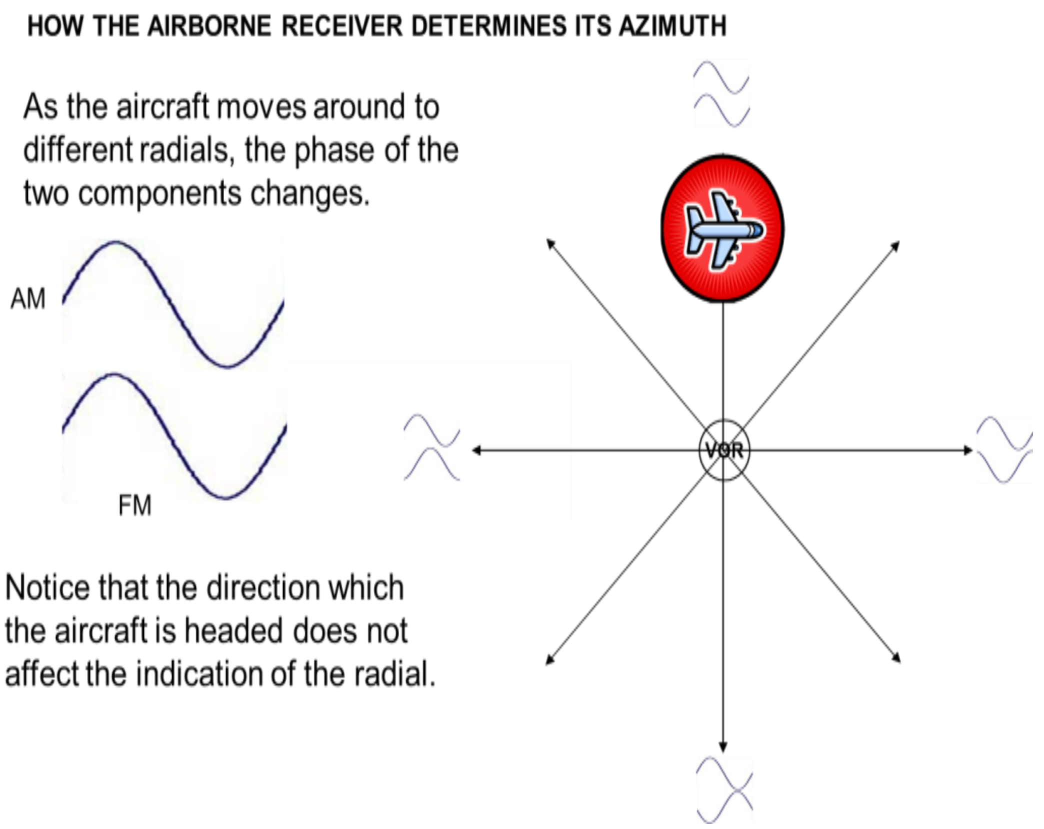

Figure 2.14: How the VOR Airborne Receiver Determines Radial Angle (Selex Inc., 2009)

The VOR is vulnerable to multi-path errors caused by poor terrain. This results into course roughness and scalloping that lead to measurement errors in the aircraft receiver (ICAO, 2010). Polarization errors also arise due to delicate balance between the predominant horizontal polarization and the unwanted vertical polarization that may arise due to electronic rotation of the antenna system. Any slight imbalance in wave polarization is likely to impact negatively on the accuracy of measuring instruments. This is one reason why this study chose to investigate effects of roofing materials on wave polarization.

2.3.4 Recommended Standards for Navaids Signals

ICAO (2010) notes that VOR polarization effect results from vertically polarized RF energy being radiated from the antenna system. It recommends that the presence of undesired vertical polarization should be checked.

The VOR antenna employs horizontal polarization with Omni-directional radiation pattern. Momentary deviations off the course due to roughness, scalloping or combinations thereof should not exceed 3 degrees from the average course. Designated operational coverage of en-route VOR should be 200NM (ICAO, 2010). The VOR minimum field strength to be protected throughout the designated operational coverage should be 39dBuV/M (90µV/M equivalent to -21dBmV/M) or power density of -107dBW/M^2 (ICAO, 2010).

ILS localizer and glide path uses signal input level from -104dBm to -18dBm.The minimum field strength to be protected throughout the ILS localizer front course is 32 dBµV/M (40 µV/M equivalent to -28dBmV/M) or power density of -114dBW/M^2. The ILS localizer signal is horizontally polarized. The localizer provides signals sufficient to allow satisfactory operation of a typical aircraft installation within the localizer and glide path coverage sectors. The localizer coverage sector extends from the centre of the localizer antenna system to distances of 25 NM within ±10° from the front course line; 17 NM between 10° and 35° from the front course line; 10 NM outside of ±35° if coverage is provided. The GP radial coverage is required to be at least 10NM. DME receiver sensitivity is set above -89dBm (ICAO, 2012).

International Civil Aviation Organization (ICAO, 2012) has specified that the minimum field strength for Very High Frequency (VHF) air-ground communication systems should be 75µV/M (-22dBmV/M) throughout the designated operational coverage; the desired-to-undesired (D/U) signal ratio should be 20 dB (ICAO, 2012).

2.4 Roofing Materials

Clay roof tiles are designed mainly to keep out rain, and are traditionally made from locally available materials such as clay. There are flat, concave or convex curved, s-shaped, semi-cylindrical and interlocking types. They minimize heat from the sun passing through to the inside (California Energy Commission, 2013). They absorb and attenuate sun rays. Their ability to reflect radio signals is minimal. However, they tend to cause more diffraction because of their shape and layout. A thickness of 22.5mm was used in the experiment.

Corrugated galvanized iron commonly abbreviated CGI is a building material composed of sheets of hot-dip galvanized mild iron, cold-rolled to produce a linear corrugated pattern in them. Iron sheets are generally reflective to radio waves depending on the layout and galvanization. Thickness of 0.55mm (gauge 26) was used.

Decra panels are pressure formed aluminum/zinc alloy coated steel with an acrylic bonded stone chip finish. The aluminum/zinc alloy coated steel provides superior corrosion resistance. The stone chip finish, manufactured for roofing use, resists fading and UV-ray penetration. Their effect on propagation of radio waves has been the centre of this study. Thickness of 0.55mm (gauge 26) was used.

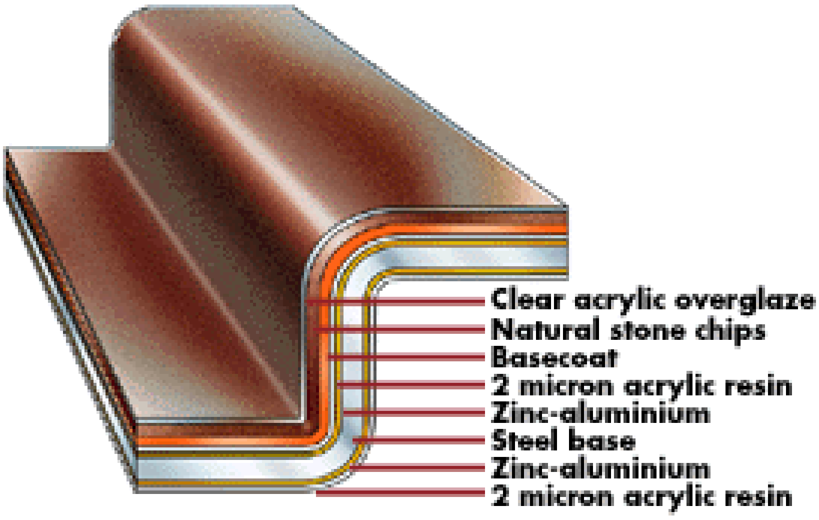

Figure 2.15: Composition of Decra Roofing Tiles
(California Energy Commission, 2013)

Steel roofing sheets or tiles are corrugated and galvanized coated with zinc resin or just plain. They have high performance in terms of strength and durability. They tend to reflect radio waves. Thickness of 0.55mm (gauge 26) was used.

Concrete roofing materials may be plain or reinforced with steel. They have high performance in terms of strength and durability. Concrete walls tend to attenuate microwave signal propagation due to absorption and reflection (Chomba *et al*., 2011a; Sandrolini *et al.*, 2007).

Plastic roofing materials are excellent corrosion resistant and are suitable for acid prone areas such as coastal regions. They have good absorption of noise effect than steel by about 30dB. It has very good sound and thermal insulation. Its reflectance and absorption of electromagnetic rays is not yet fully known. Thickness was 1.2mm.

Aluminum roofs are attractive, durable, energy-efficient, and increasingly affordable. In the past, aluminum was not a popular roofing material for cost reasons and because of concerns about the structural limitations of aluminum. Recent innovations have resolved the structural problems and decreased the cost of aluminum. Aluminum reflects radio waves depending on layout pitch angle and is normally used in fabrication of radio aerials mainly as reflector elements (Sandiku, 2001; Hayt and Buck 2003). A thickness of 0.55mm (gauge 26) was used.

2.5 Laboratory Equipment

The laboratory equipment includes assemblies of radio transmitter and receiver systems which comprise the Gunn oscillator, PIN modulator and horn antennas for assembling the transmitter. In addition, there were coaxial detectors, signal amplifiers and various antennas for assembling the receiver. A personal computer (PC) with CASSY LAB version 1.75 software and meters to provide presentation of measurements was among the facilitating equipment.

2.5.1. Gunn Oscillator

Gunn oscillators are widely used in the microwave to terahertz region. The Gunn oscillator uses a metallic coaxial cavity (in effect, a short length of co-axial cable) to provide the resonant effect which has been modeled as an LC circuit. Although it looks very different, the oscillator shares with a laser the use of a cavity (see Figure 2.16). The size of this cavity determines the time/phase delay which sets the resonant frequency (Breidenbach and Kloza, 2007).

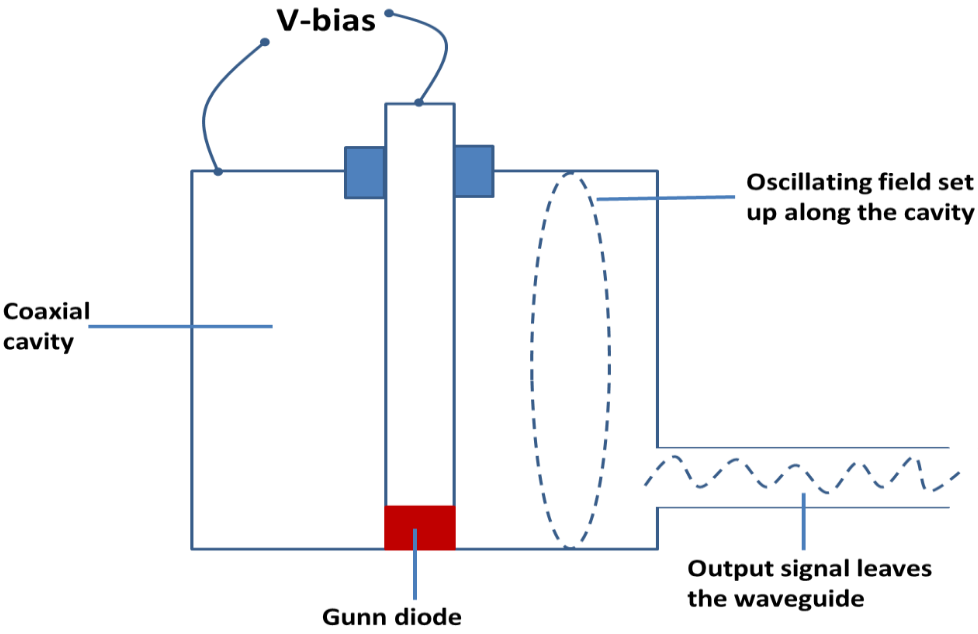

Figure 2.16: Operation of Gunn Oscillator

(Breidenbach and Kloza, 2007)

2.5.2. PIN Modulator

The PIN diode (has wide undoped **I**ntrinsic layer between **P** and **N** Layers) modulator circuit is an attenuator circuit in which the PIN diode is forward biased by the signal wave while the RF carrier wave is also present in the PIN diode. The forward biased resistance of the PIN diode is (relatively) slowly and continuously varied by the information signal waveform producing a continuous amplitude-modulated RF wave. RF carrier frequency retains its sinusoidal wave-form while the amplitude envelope varies at the modulation frequency (Breidenbach and Kloza, 2007).

2.6. Previous Studies

Extensive tests were conducted by the National Institute of Standards and Technology (NIST, 1997) of USA to show how various common building materials can shield electromagnetic fields. A wide range of materials and thicknesses were tested, such as bricks, concrete, lumber, drywall, plywood, glass and rebar. Pauli and Moldan (2008) from University of Bundeswehr in Germany tested additional building materials.

The tests were conducted for frequencies from 500 MHz to 8 GHz. This range covers emissions from cell phone towers, cordless phones, digital television, GPS, wireless smart meters, baby monitors and many other devices.

The reason NIST (1997) did these extensive tests was to prepare for future generations of wireless control systems at construction sites, as well as for tools to measure the thickness of walls. It was not to determine the effects of building materials on radio navigation signals.

Pauli and Moldan (2008) also found that whereas metallic shielding mostly reflects radio signals, non-metallic materials mostly absorb radio signals. This generalized result concurs with the findings of this study.

Marcum (2002) in his research found that one of the major sources of error contributing to Instrument Landing System (ILS) performance was identified as scattering from nearby reflective surfaces and changes to the ground plane in the vicinity of the ILS. Reflective objects near navaids produce multipath errors which cause roughness, course bends and scalloping in the approach region. He examined the effects of snow on the image-type glide path and derived a concise description of the conditions that cause the system to go out of designated tolerance. He designed a simple monitoring scheme that was to measure any change in image radiation from the glide path. Marcum (2002) established ILS critical areas to reduce multipath interference from objects such as building structures, vehicles and aircrafts parked on ground. The ILS critical areas were established as the region in front of each radio navigation antenna system where these objects are restricted.

Another research conducted by Cortesi *et al.* (2002) realized that the localizer equipment at Venice international airport experienced some problems that drove its signal out of tolerance. This problem was solved by means of an antenna recalibration plus flight checks, but no one was able to demonstrate if that problem was in any way related to construction of a new hangar within the airport area. This was realized in a demonstration, acting on a virtual model of reality, which was able to analyze multipath contribution of each airport structure separately from the other ones. Cortesi *et al.* (2002) conducted further research at Torino/Caselle international airport where electromagnetic model analysis was done by varying some elements such as airport infrastructure dimensions, the materials constituting the infrastructures and signal interaction with surrounding environment. The findings revealed that there were no significant changes in the VOR parameters. However, the DME system recorded significant changes in its parameters. In another experiment on radar at Lamezia airport it was realized that radiation pattern distortion was due to interaction with airport infrastructure and the radar coverage was affected by the presence of both site obstacles and terrain around the antenna location.

Singh (2003) conducted a laboratory experiment to observe interference, diffraction and absorption of microwaves. He set up a Gunn oscillator with the transmitter mounted on a protractor and a swivel. The receiver was mounted directly opposite the transmitter. He placed a screen with two openings in front of the transmitter horn. He recorded receiver readings at 2 degrees intervals for 60 degrees either side of the 90 degrees mark. He examined receiver power verses angle of incidence for double slit interference, and receiver power verses angle of incidence for single slit diffraction of diameter 0.03 m and 0.015 m respectively. His objective was to observe diffraction of waves and determine their wavelength.

Briginton (2010) explored both experimentally and numerically the microwave response of a square array of holes in a metal sheet. He investigated the electromagnetic interaction between metal surfaces and the resultant resonant transmission response. He examined dependence of angle of incidence, azimuth angle and wave polarization.

Gurung and Zhao (2007) illustrated with figures and graphs the characteristics of microwaves signal propagation in a medium. Various causes of attenuation such as rain, trees, structures, distance, snow, wind and fog were discussed.

Chomba *et al.* (2011a) and Chomba *et al.* (2011b) examined the signal attenuation level due to varying distances, concrete wall thickness, angle of incidence and number of floors from receiver to transmitter for signal propagated at 2.457GHz. It was found that signal attenuation levels increased as distance, wall thickness and number of floors was increased while signal attenuation levels reduced with increase of angle of incidence.

2.7. Knowledge Gaps

Just like this study, NIST (1997) and Pauli and Moldan (2008) found that metals are far superior as shielding materials. However, NIST did not test any roofing materials such as clay, decra, plastic, iron, steel or aluminum to determine their effects on radio signals.

The other six research works discussed interaction of microwaves with objects such as snow, concrete and metal. Marcum (2002) and Cortesi *et al*. (2002) studies dwelt on multipath errors caused by reflective and obstructive objects in the aerodrome. Singh (2003) and Briginton (2010) studied diffraction of microwaves while Gurung and Zhao (2007) examined attenuation. However, little research work was done to provide data on various roofing materials in terms of attenuation, reflection and diffraction of microwave signals especially in the aerodrome environment. No data was availed concerning the effects of roofing materials on radiation patterns of radio navigation systems.

Whereas, Chomba *et al.* (2011a) and Chomba *et al.* (2011b) provided vital findings on effects of angle of incidence and transmission distance respectively on microwave signals propagated through concrete walls, the research ignored comparison of concrete with roofing materials such as steel, iron, aluminum, clay and decra in terms of signal propagation. Most significantly, the research did not examine wave polarization and antenna orientation as some of the factors that affect signal propagation especially during reflection where angles of incidence are very critical. Similarly, no examination was done on radiation patterns of propagated signals despite the fact they are crucial in determining positions of reception in relation to signal strength. Further, the researcher chose to treat all independent variables one at a time yet naturally most of them occur concurrently. Hence, the combined effects of these variables on the propagated signal could not be conclusively established.

Therefore, this study was conducted to fill the knowledge gaps opened by previous studies. Effects of roofing materials and angle of incidence on navaids signal strength were studied together with effects of roofing materials on transmission distance and wave polarization. Also this study had technical advantages over previous studies. It applied use of specialized laboratory that assumed constant environmental conditions, provided portable radio equipment, RF absorbent materials and accurate computer measurements.

2.8 Conceptual Framework

The navaids signal originating from either ground or aircraft transponders is propagated into space. The maneuvering of the aircraft in space brings about variations in physical parameters of the propagation that include angle of incidence, state of polarization and transmission distance. This propagation encounters obstacles such as roofing materials whose effect may attenuate, reflect, diffract or vary radiation patterns of the transmitted signal. Such effects that alter the propagation parameters are bound to introduce errors in the signals received by navaids equipment as conceptualized in Figure 2.17

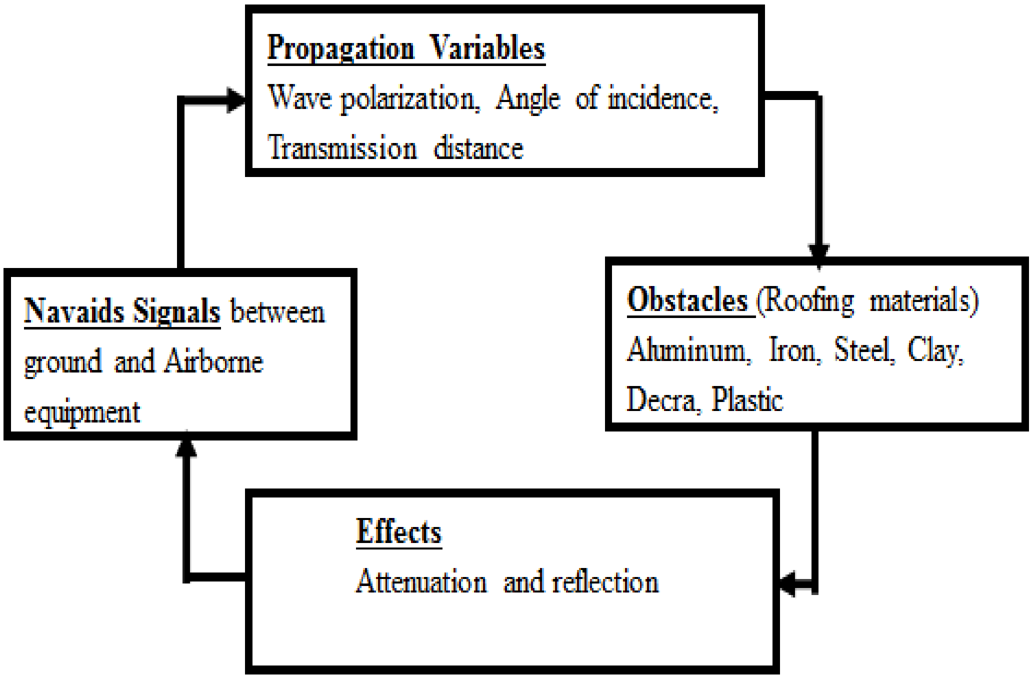

Figure 2.17: Conceptual Framework

CHAPTER 3
MATERIALS AND METHODS

3.1 Research Site and Instrumentation

3.1.1 Research Site

East African School of Aviation is one of the sixteen accredited ICAO training institutions in the world. Its laboratory was chosen for these experiments because it is strategically designed and equipped to serve as a research and development centre for aeronautical telecommunications and avionics.

3.1.2 Instrumentation

The equipment used for the study included the Gunn oscillator whose purpose was to generate microwave frequency tuned at 9.4 GHz. This translates to a wavelength (λ) of 32 mm and further translates to dipole aerial physical lengths of 8 mm ($\lambda/4$) and 16 mm ($\lambda/2$). These physical lengths were easily handled in a laboratory environment. Thus a choice of 9.4 GHz was the strategy to comfortably manage the experiment in a laboratory. A PIN (Positive Intrinsic Negative) diode was used to modulate 10mW microwave signal before transmission. Included was also an 18dB gain horn antenna to radiate the microwave signals from the transmitter. A set of microwave absorbers were used to absorb stray microwave signals. The absorbers were placed around the equipment in an enclosure to shield against electromagnetic wave leakage.

A rotating antenna platform calibrated in polar deviations and designed for automatic rotation was used to enable a 360^0 rotation of radiation pattern. Different test antennas were mounted on this platform. Test antennas included dipole antennas whose characteristic impedance was 50 ohms. Dipole orientation was varied between vertical and horizontal polarization whereas helix antenna was used for circularly polarized waves. Two coaxial cables of length 2 metres and two stand rods of height 345mm were also used in the interconnect.

A Personal Computer (PC) with Windows XP was loaded with CASSY LAB version 1.75 software to record and store radiation patterns, angular positions and signal levels in millivolts. A Coaxial detector in the receiver equipment was used to detect the microwave signal and provide equivalent direct voltage measurements. Sets of coaxial cables and microwave accessories were used to interconnect transmitter, receiver and PC as presented in Figure 3.1 to Figure 3.8.

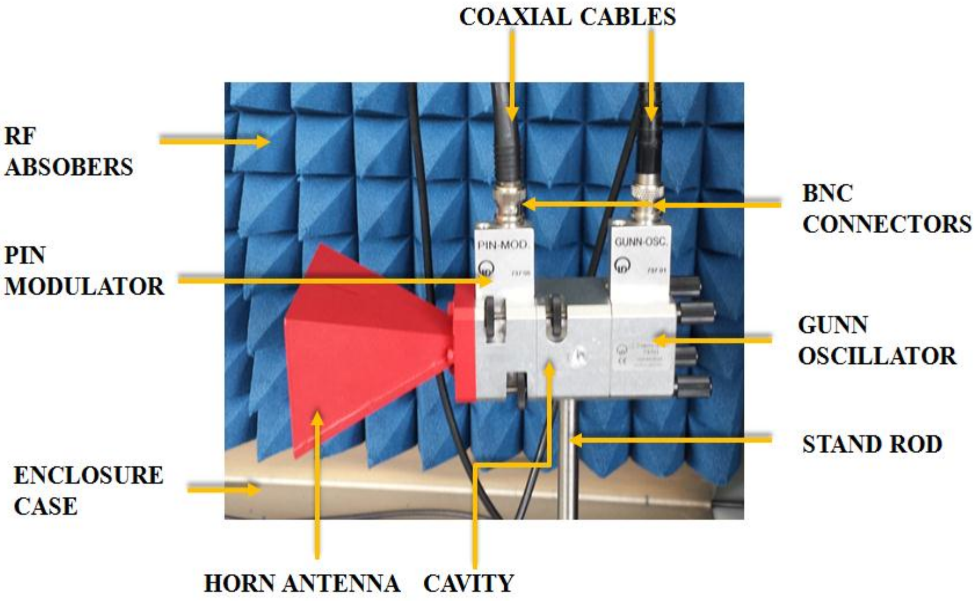

Figure 3.1: Transmitting Equipment Assembly

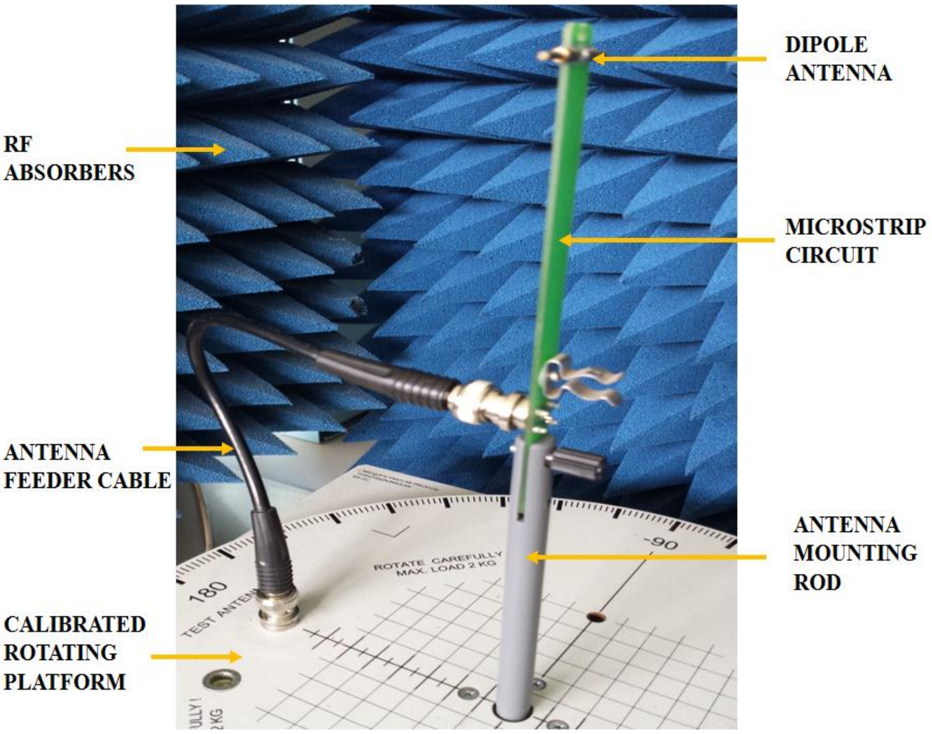

Figure 3.2: Receiving Equipment Assembly for Horizontal Dipole Antenna

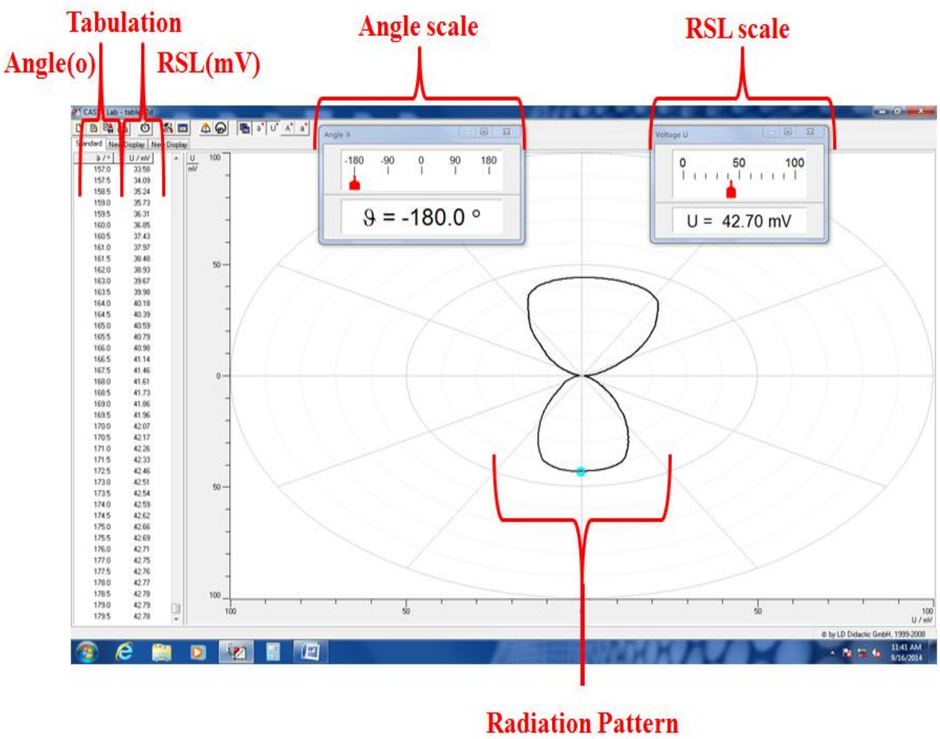

Figure 3.3: Computer Screen Print for Horizontal Dipole in E-plane

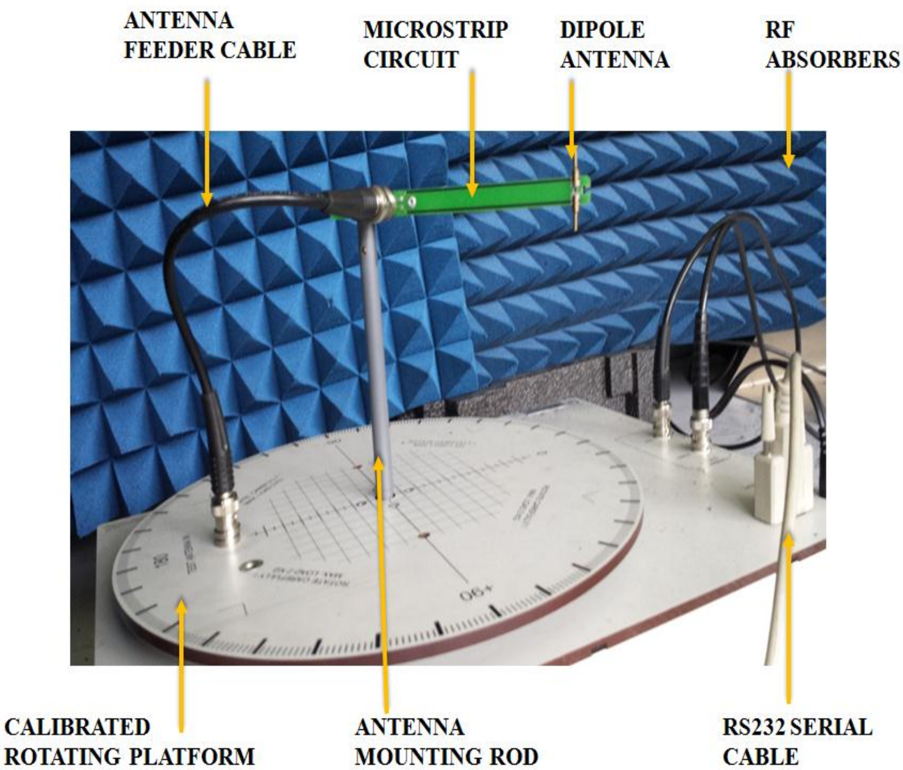

Figure 3.4: Receiving Equipment Assembly for Vertical Dipole Antenna

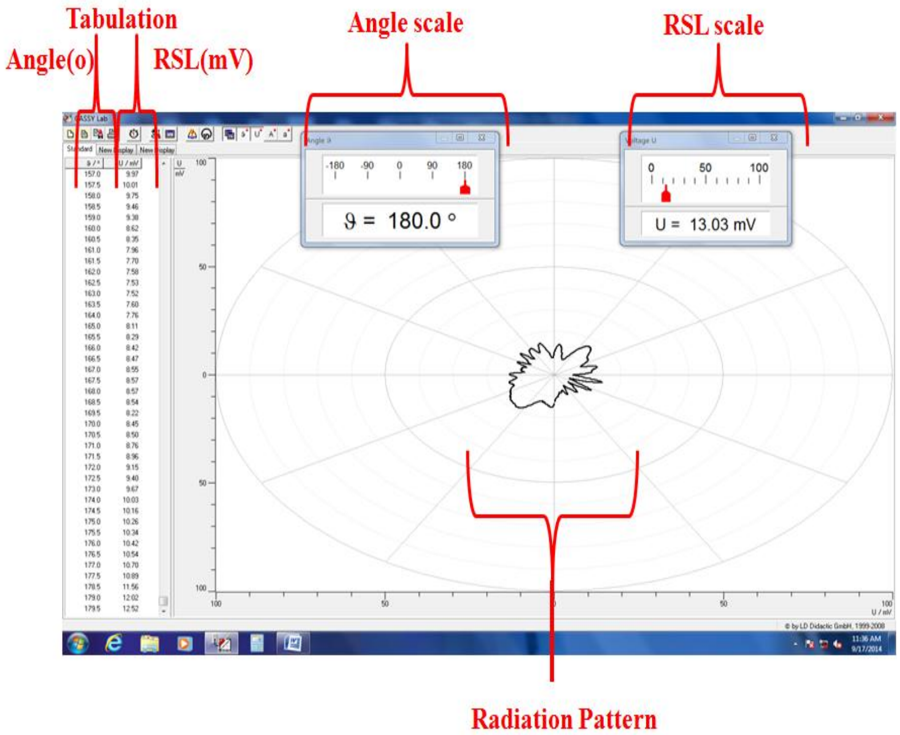

Figure 3.5: Computer Screen Print for Vertical Dipole in E-plane

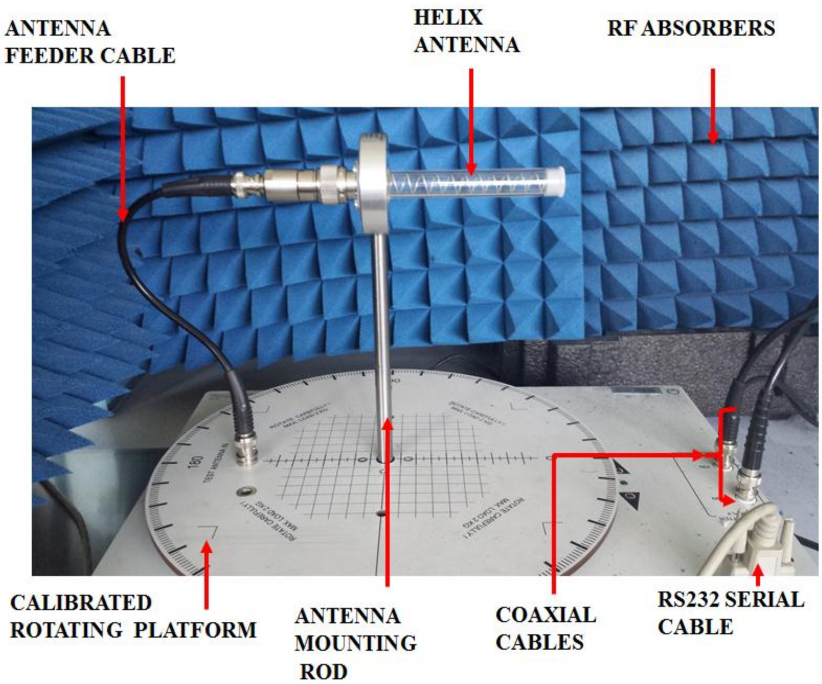

Figure 3.6: Receiving Equipment Assembly for Circular Helix Antenna

Figure 3.7: Computer Screen Print for Circular Helix Antenna

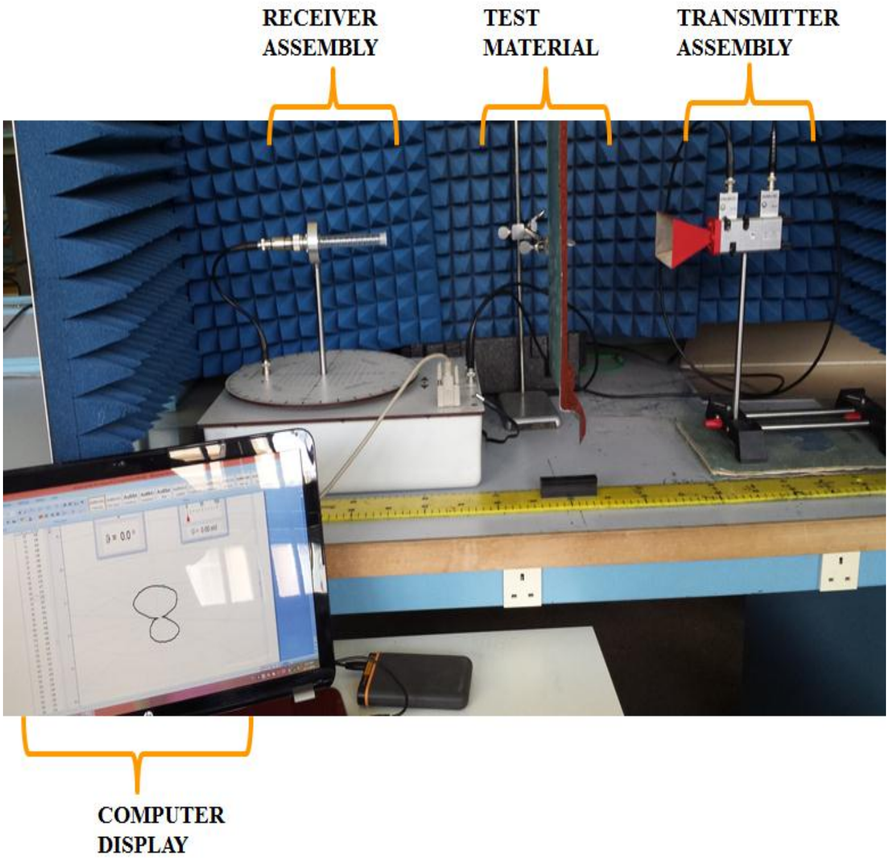

Figure 3.8: Interconnection of Receiving and Transmitting Equipment

3.1.3 Measurements and Error Control

The axis of symmetry of the test antenna and the centre of the rotary plate were put in line. The antenna was inserted in the central mounting of the rotary plate as a general fulfillment of a 360^0 uniform motion.

The main lobe of the test antenna was located at 0° in the radiation pattern diagram to enable its main-beam direction point into the 0° direction and aligned with the transmitting antenna (Figure 3.9). This meant that its back looked over to the exiting source antenna. The reason for this lies in the nature of the process that enables main-beam direction to be measured in one run instead of being divided into two halves. Environmental influences on the system thus have less effect on the important region of the main lobe (Breidenbach and Kloza, 2007).

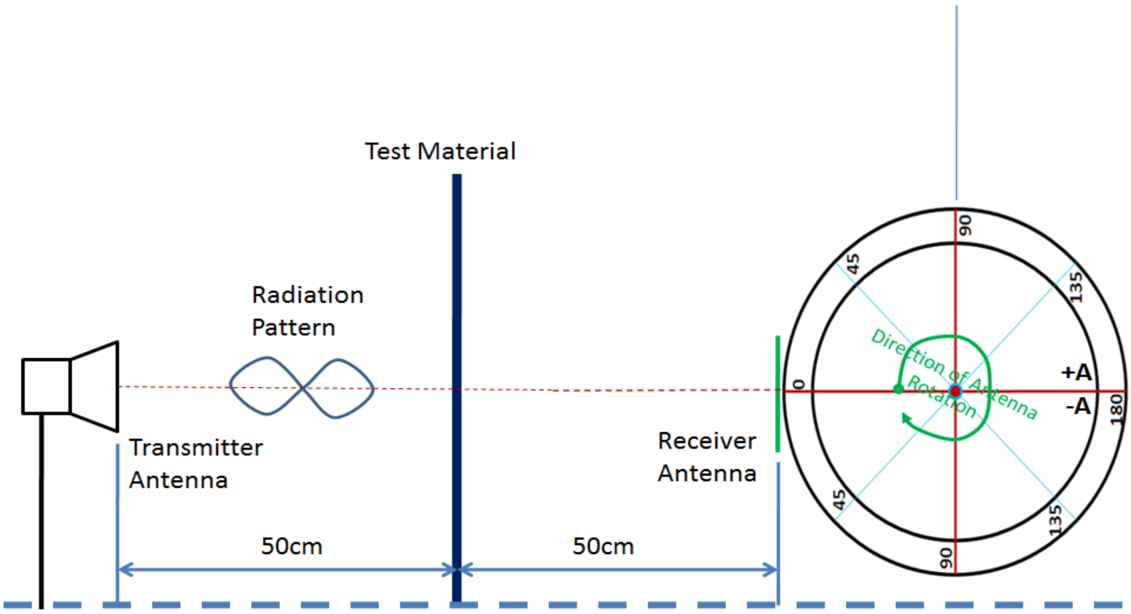

Figure 3.9: Alignment of Measuring Equipment

The actual antenna signal (A) from the detector could not be measured directly. Only the voltage drop (U) generated by the detector current at the measuring amplifier was measurable. In general, U is not proportional to A but instead:

$$U \approx A^m \tag{3.1}$$

Where m describes the detector characteristics and depends on the power of incoming microwaves. In low power range m ≈ 2 so that U ≈ A^2.

Preliminary experiments had shown that the assumed square behavior only applies at very low microwave powers or received voltages where U < 5 mV. However, the antenna measurement system made it possible to enter other detector characteristics. The selected detector characteristics were checked and a variable attenuator was introduced which enabled the antenna signal in front of the detector to be attenuated in a well-controlled way to handle voltage drops of up to 50mV.

3.1.4 Far-field and Near-field Condition Tests

The test antenna was a dipole of half-wave length (λo/2) which had a physical length of 16mm. The wavelength (λo) of the radiated wave was 32mm. The mean distance between the source antenna and the test antenna was set at various distances i.e. 100cm, 60cm and 30cm. Maximum transverse measurement (d_t) of radiating horn antenna was 100mm and the longitudinal measurement (d_Q) of the receiving antenna was 16mm. Therefore the far-field condition was checked by determining the minimum distance (r_o) required to fulfill condition given by Equation 3.2 referred to as Fraunhofer equation for far-field conditions (Breidenbach and Kloza, 2005)

$$r_o \geq \frac{2(d_Q + d_t)^2}{\lambda_o} \tag{3.2}$$

Hence $r_o \geq$ 841mm = 84.1cm

It was therefore shown that far-field conditions were fulfilled for test distance of 100cm. However, near-field conditions were tested for distances of 60cm and 30cm using the condition set by Equation 3.3 referred to as Fraunhofer distance equation for near-field conditions (Alexander, 2011)

$$d \leq 2\frac{D^2}{\lambda} \tag{3.3}$$

Where;

D = longitudinal antenna diameter of transmitter = 100mm

λ = wavelength = 16mm

Hence $d \leq 625\ mm$ = 62.5cm

It was shown that 30cm distance fulfilled near-field conditions. However, 60cm distance was found to be in the transition between near-field and far-field.

3.2 Measurement of Effects of Roofing Materials and Angle of Incidence

When a radio signal was transmitted via roofing materials only a small part of it was captured by the receiving antenna (Figure 3.10). The rest was attenuated. This attenuation was as a result of reflection, absorption and free space losses among other losses. The experiment considered reflected signal to be that which was picked by the receiving antenna positioned behind the transmitting antenna (Figure 3.11). Thus loses due absorption and free space losses were separated from reflection losses. The desired-to- undesired signal ratio was used as a measure of signal strength for signals transmitted via various roofing materials. The desired signal which was the received signal level in the propagation path was compared with the undesired signal which was the received signal level in the reflective path. Therefore, two experiments were conducted. The first was to determine mean received signal levels for roofing materials in the propagation path and the second was to determine mean received signal level for roofing materials in the reflective path.

3.2.1 Measurement of Received Signal Level in the Propagation Path

The experiment was set up as in Figure 3.10. Distance between the transmitter and the receiver was kept at 100 cm and the antenna orientation was maintained for horizontal polarization. The test materials were inserted one after the other at the center between the receiver and the transmitter. Reference measurements (Ref) were recorded at instants when there was no material between the transmitter and the receiver. The material variation began from decra, aluminum, iron, clay, steel to plastic. The angle of incidence was automatically varied from -180 degrees to +180 degrees at intervals of 0.5 degrees. For every material, three repetitions were performed and mean values noted as shown in appendix A. The propagated received signal levels (PRSL) were captured by the computer system. A sample of means was manually recorded from 0 – 180 degrees in steps of 15 degrees as presented in Table 4.1.

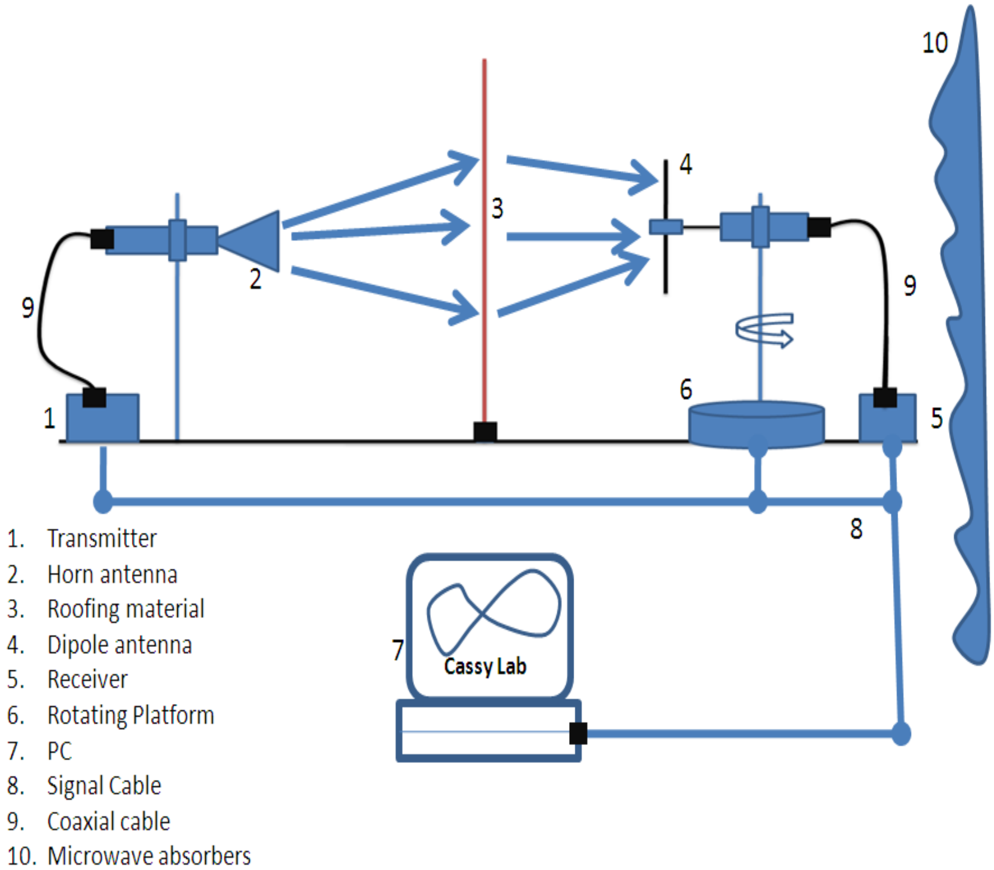

Figure 3.10: Measurement of Received Signal Level in the Propagation Path

3.2.2 Measurement of Received Signal Strength in the Reflective Path

The equipment was set up as in Figure 3.11 and Figure 3.12. The distance between the receiver and the test materials was kept at 100 cm. The receiver antenna orientation was maintained at horizontal polarization. The transmitter was fixed at the centre between the receiver and the test materials. The transmitter beam was focused to the test materials. The material variation began from decra, aluminum, iron, clay, steel to plastic. The angle of incidence was varied by automatic rotation of the receiver antenna from -180 degrees to +180 degrees at intervals of 0.5 degrees. Reflections from the test materials were picked up by the receiver. For every material three repetitions were performed and mean values noted as shown in appendix A. The reflected received signal levels (RRSL) were captured by the computer system. A sample of means was manually recorded from 0 – 180 degrees in steps of 15 degrees as presented in Table 4.5. The radiation patterns were as shown in Figure 3.13.

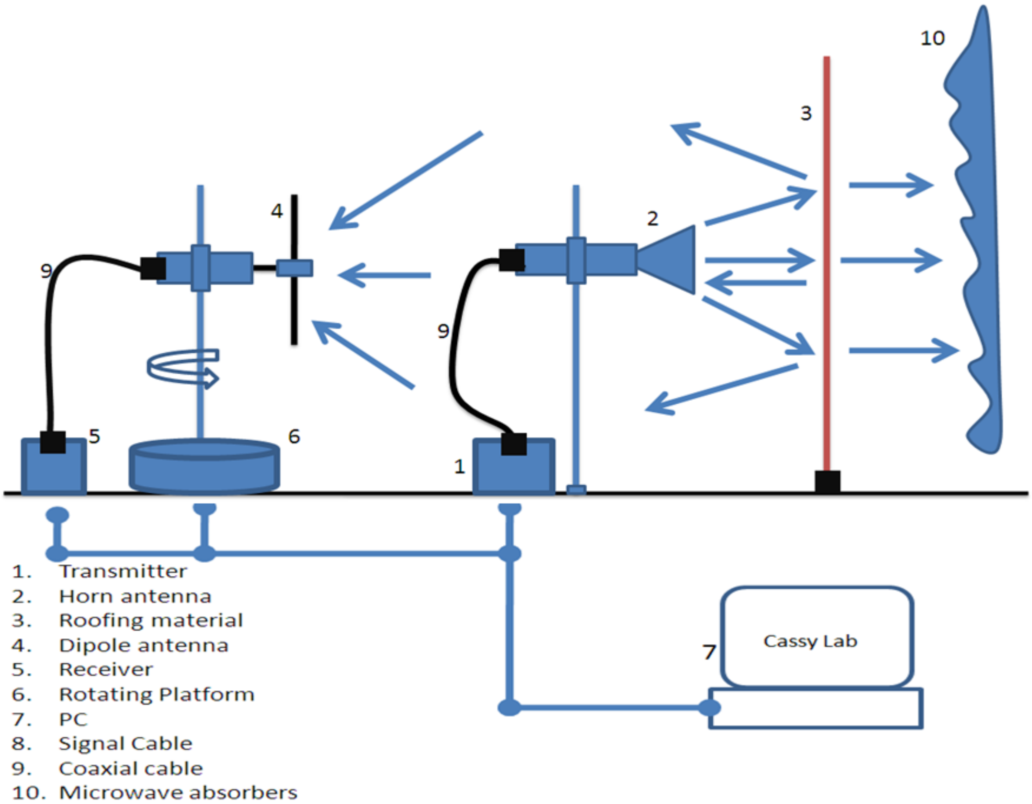

Figure 3.11: Measurement of Received Signal Level in the Reflective Path

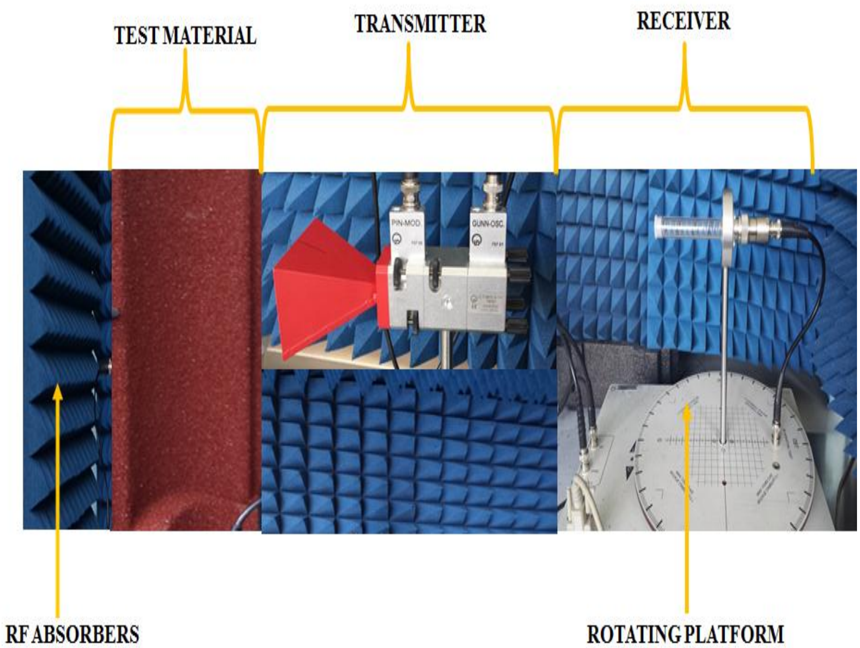

Figure 3.12: Measurement of Reflected Signal Level

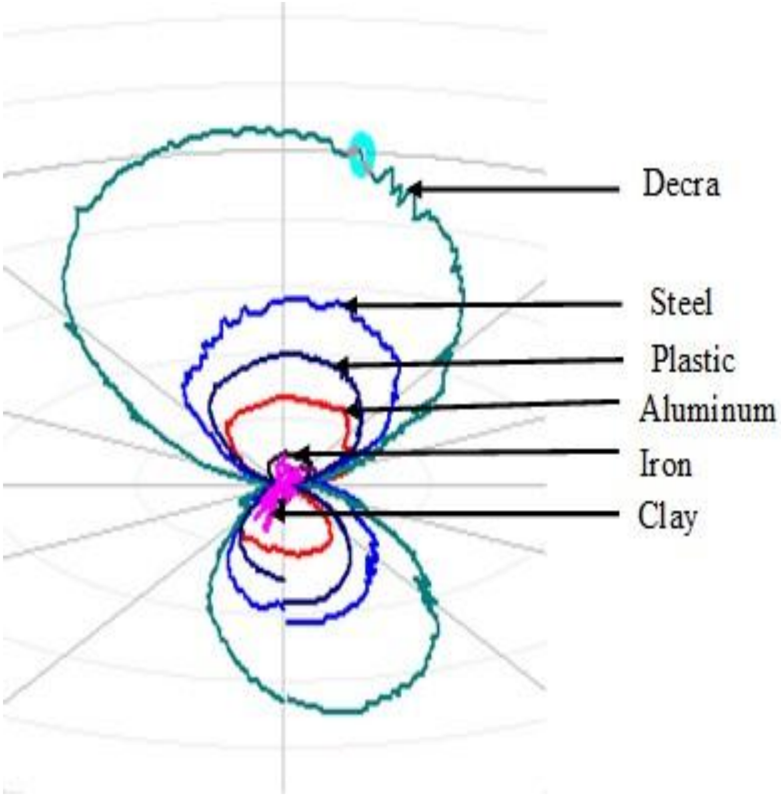

Figure 3.13: Radiation Patterns Resulting from Reflection

3.3. Measurement of Effects of Roofing Materials on Transmission Distance

The experiment was set up as in Figure 3.10 and Figure 3.14. Distance between the transmitter and the receiver was varied from 30 to 100 cm and the antenna orientation was maintained for horizontal polarization. The test materials were inserted one after the other at the centre between the receiver and the transmitter. The material variation began from decra, aluminum, iron, clay, steel to plastic. The angle of incidence was automatically varied from -180 degrees to +180 degrees at intervals of 0.5 degrees. The propagated received signal level was captured by the receiving antenna and processed by the computer system. A sample was recorded in steps of 15 degrees from 0 to 180 degrees as indicated in appendix B. The mean received signal level was calculated for each material at three different distances and recorded in Table 4.8.

Figure 3.14: Measurement of Transmission Distance

3.5 Measurement of Effects of Roofing Materials on Wave Polarization

The purpose was to determine whether roofing materials can alter wave polarization of propagated radio signals. The experiment was set up as in Figure 3.9. Distance between the transmitter and the receiver was fixed at 100 cm and the antenna orientation was varied from vertical, horizontal to circular polarization. The test materials were inserted one after the other at the centre between the receiver and the transmitter. The material variation began from decra, aluminum, iron, clay, steel to plastic. The angle of incidence was varied from -180 degrees to +180 degrees at intervals of 0.5 degrees. The propagated received signal level was captured by the computer system. A sample was recorded in steps of 15 degrees from 0 to 180 degrees as presented in Table 4.9 and appendix C.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Effects of Roofing Materials and Angle of Incidence on Signal Strength

In order to measure navaids signal strength, two experiments were conducted. The first was to determine Propagated Received Signal Level (PRSL) which was the signal received in the transmission path and the second was to determine Reflected Received Signal Level (RRSL) which was the received signal in the reflective path. The ratio of PRSL to RRSL is a measure of desired-to-undesired (D/U) signal ratio which is an equivalent measure of signal strength (ICAO, 2012).

The results of effects of roofing materials and angle of incidence on navaids signal strength was presented in three steps. First was the treatment of roofing materials on propagated received signal level ignoring effect of angle of incidence. Second was the treatment of angle of incidence on propagated received signal level ignoring effect of roofing materials. Third was the combined treatment of roofing materials and angle of incidence on propagated received signal level.

Table 4.1 shows propagated received signal levels (PRSL) which are mean values of the received signal level captured by the receiver in the transmission path for various materials at varying angles. Reference (Ref) column represents the signal captured when there was free space between the transmitter and the receiver.

Table 4.1: Propagated Received Signal Levels

Propagated Received Signal Level in mV Distance (D) = 100 cm; Polarization = Horizontal								
Materials	**Ref**	**Decra**	**Aluminum**	**Iron**	**Clay**	**Steel**	**Plastic**	**Mean**
Angle(A^o)								
0	8.08	0.10	2.39	4.69	4.72	1.21	4.91	**3.73**
15	6.60	0.09	2.50	3.91	3.93	0.88	3.70	**3.01**
30	3.88	0.12	1.94	2.52	2.87	0.16	1.55	**1.86**
45	1.37	0.12	1.30	1.39	1.19	0.40	0.25	**0.86**
60	0.67	0.09	0.59	0.64	0.67	0.24	0.04	**0.42**
75	0.32	0.07	0.20	0.30	0.51	0.06	0.02	**0.21**
90	0.08	0.05	0.11	0.32	0.30	0.02	0.09	**0.14**
105	0.41	0.03	0.03	0.42	0.13	0.09	0.37	**0.21**
120	1.02	0.06	0.00	0.61	0.17	0.22	0.78	**0.49**
135	2.54	0.01	0.08	0.96	0.52	0.53	1.67	**0.90**
150	4.80	0.12	0.45	2.41	1.36	0.98	3.07	**1.88**
165	7.63	0.11	1.10	3.30	2.98	1.55	4.74	**3.06**
180	7.63	0.06	1.54	3.62	3.42	1.32	4.86	**3.21**
Mean	**3.46**	**0.08**	**0.94**	**1.93**	**1.75**	**0.59**	**2.00**	

4.1.1 Effects of Roofing Materials on Propagated Received Signal Level

The mean values of PRSL per a material were tabulated alongside the type of material without factoring effect of angle of incidence, as shown in Table 4.2 and plotted in Figure 4.1.

Table 4.2: Effects of Roofing Materials in the Transmission Path

Materials	**Decra**	**Steel**	**Aluminum**	**Clay**	**Iron**	**Plastic**
Mean PRSL (mV)	0.08	0.59	0.94	1.75	1.93	2.00
Ref (mV)	3.46	3.46	3.46	3.46	3.46	3.46
PRSL(%)	2.31	17.1	27.2	50.6	55.8	57.8
Attenuation(%)	97.7	82.9	72.8	49.4	44.2	42.2

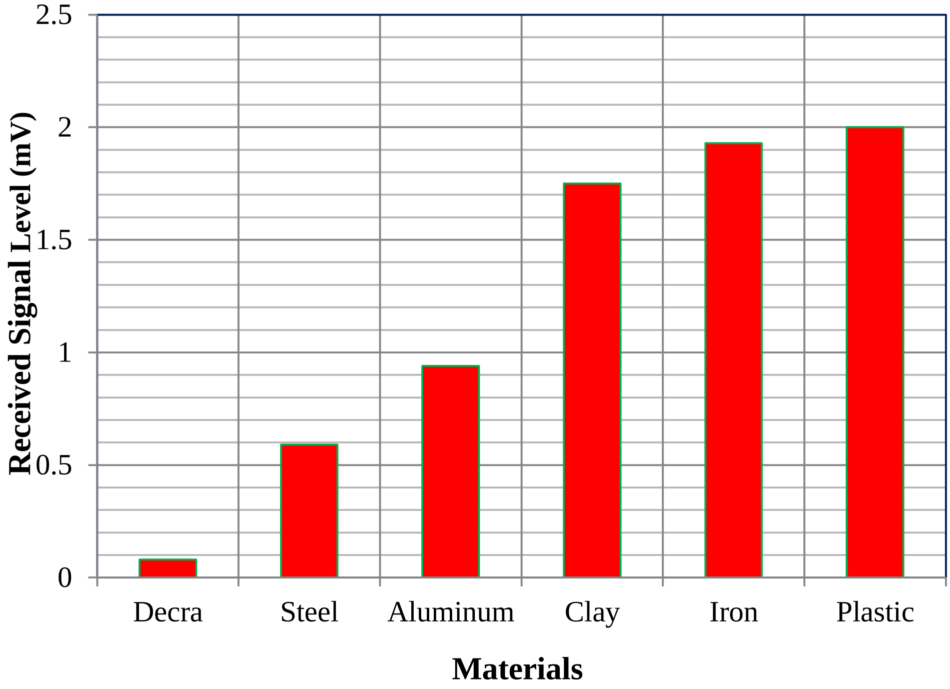

Figure 4.1: Effects of Roofing Materials in the Transmission Path

The trends from Figure 4.1 show that decra has the least propagated received signal level. Therefore, decra is the material that offers highest attenuation. Plastic exhibits highest propagated received signal level and therefore it offers lowest attenuation. It was shown that received signal strength increases in the order; decra, steel, aluminum, clay, iron and plastic. However, statistical analyses using single factor ANOVA and t-test revealed that there was no significant difference between clay, iron and plastic. Further it was shown that there was no significant difference between steel and aluminum. Decra was found to be uniquely different from the rest of the materials. Table A-14 to Table A-17 in appendix A provides statistical analyses that compared effects of roofing materials in the transmission path.

4.1.2 Effects of Angle of Incidence on Propagated Received Signal Level

The mean values of propagated received signal level per angle were tabulated alongside the angle of incidence without factoring effect of roofing materials, as shown in Table 4.3 and plotted in Figure 4.2. The tabulated range of angle of incidence was 0 to 90 degrees which was a mirror duplicate of 90 to 180 degrees range as presented by Figure A-3 in appendix A. Therefore, the mean values for the two ranges were approximately similar.

Table 4.3: Effects of Angle of Incidence in the Transmission Path

Angle of Incidence (deg)	0	15	30	45	60	75	90
Mean PRSL(mV)	3.73	3.01	1.86	0.86	0.42	0.21	0.14

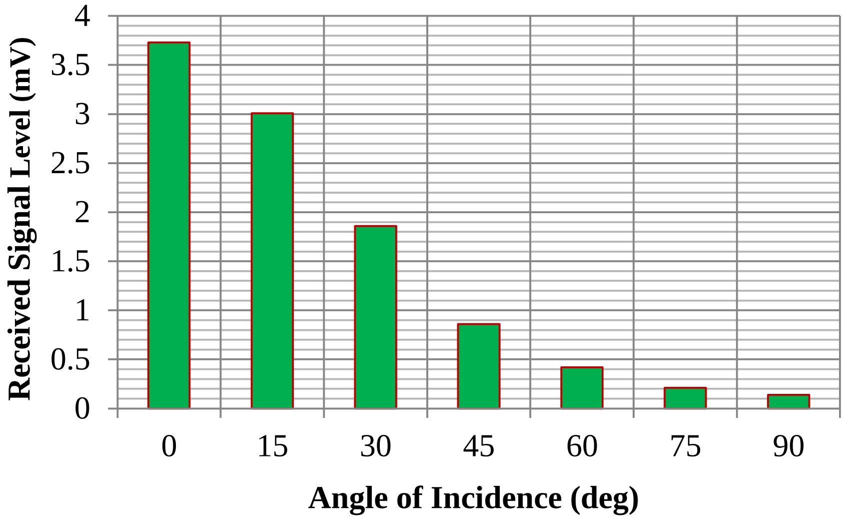

Figure 4.2: Effects of Angle of Incidence in the Transmission Path

The trends from Figure 4.2 show that at an angle of 0 degrees the propagated received signal level is maximum. Angle of 90 degrees exhibits lowest propagated received signal level. Therefore, received signal level decreases with increase in angle of incidence.

4.1.3 Interaction of Roofing Materials and Angle of Incidence

The combined effect of roofing materials and angle of incidence in the transmission path was considered. The purpose was to determine whether there was an interaction between the two independent variables; roofing material and angle of incidence. It was shown that the effects of roofing materials differed depending on the angle of incidence and therefore there was an interaction effect between roofing material and angle of incidence as shown by Table 4.4 and Figure 4.3.

Table 4.4: Interaction of Roofing Materials and Angle of Incidence

	Propagated Received Signal Level (mV)					
Roofing Materials	**Decra**	**Steel**	**Aluminum**	**Clay**	**Iron**	**Plastic**
Angle of incidence						
0	0.10	1.21	2.39	4.72	4.69	4.91
15	0.09	0.88	2.50	3.93	3.91	3.70
30	0.12	0.16	1.94	2.87	2.52	1.55
45	0.12	0.40	1.30	1.19	1.39	0.25
60	0.09	0.24	0.59	0.67	0.64	0.04
75	0.07	0.06	0.20	0.51	0.30	0.02
90	0.05	0.24	0.11	0.30	0.32	0.09

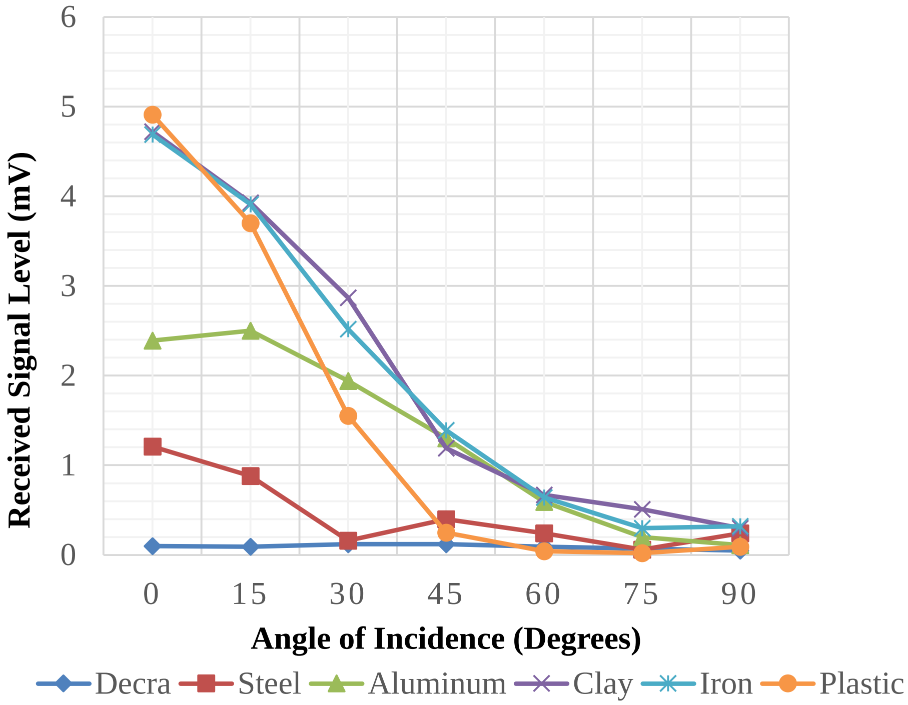

Figure 4.3: Effect of Roofing Material and Angle of Incidence

4.1.4 Reflected Received Signal Level

Table 4.5 shows Reflected Received Signal Levels (RRSL) which are mean values of the received signal level captured by the receiver antenna in the reflective path on various materials at varying angles.

Table 4.5: Reflected Received Signal Levels

Reflected Received Signal Level in mV Distance (D) = 100 cm; Polarization = Horizontal								
Materials	**Ref**	**Decra**	**Aluminum**	**Iron**	**Clay**	**Steel**	**Plastic**	**Mean**
Angle(A^o)								
0	8.08	5.27	1.28	0.45	0.16	2.78	1.95	**2.85**
15	6.60	4.06	1.23	0.40	0.25	2.35	1.70	**2.37**
30	3.88	2.21	0.99	0.36	0.26	1.56	1.05	**1.47**
45	1.37	1.14	0.65	0.26	0.28	0.82	0.59	**0.73**
60	0.67	0.53	0.39	0.16	0.26	0.40	0.27	**0.38**
75	0.32	0.12	0.31	0.13	0.15	0.14	0.10	**0.18**
90	0.08	0.12	0.16	0.07	0.08	0.24	0.03	**0.11**
105	0.41	0.27	0.17	0.04	0.03	0.37	0.01	**0.18**
120	1.02	0.57	0.09	0.04	0.02	0.55	0.11	**0.34**
135	2.54	1.05	0.15	0.04	0.01	0.70	0.38	**0.69**
150	4.80	2.08	0.6	0.08	0.02	1.26	0.84	**1.38**
165	7.63	3.09	1.01	0.17	0.07	1.87	1.51	**2.19**
180	7.63	3.18	1.03	0.25	0.12	2.05	1.77	**2.29**
Mean	**3.46**	**1.82**	**0.62**	**0.19**	**0.13**	**1.16**	**0.79**	

The mean values of Reflected Received Signal Level per a material were tabulated alongside the type of material without factoring effect of angle of incidence, as shown in Table 4.6 and plotted in Figure 4.4.

Table 4.6: Effects of Roofing Materials in the Reflective Path

Roofing Materials	Decra	Steel	Plastic	Aluminum	Iron	Clay
Mean RRSL (mV)	1.82	1.16	0.79	0.62	0.19	0.13
Ref (mV)	3.46	3.46	3.46	3.46	3.46	3.46
RRSL(%)	52.6	33.5	22.8	17.9	5.49	3.76

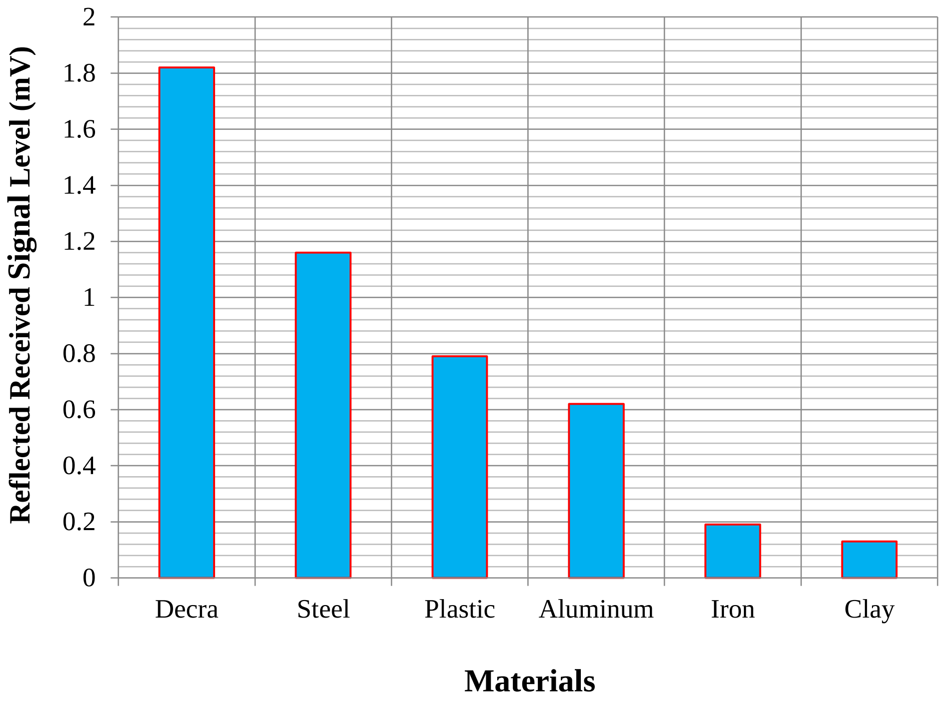

Figure 4.4: Effects of Roofing Materials in the Reflective Path

Table 4.6 and Figure 4.4 show that decra is the most reflective roofing material followed by steel, plastic, aluminum, iron and clay respectively. However, statistical analysis in appendix A shows that there is no significant difference between decra, steel and plastic. Iron and clay have no significant difference. Aluminum differs from all the rest.

4.1.5 Desired-to-Undesired Signal Ratio

Desired-to-Undesired (D/U) signal ratio was determined by dividing propagated received signal level (PRSL) by reflected received signal level (RRSL) as presented in Table 4.7 and Figure 4.5.

Table 4.7: Desired to Undesired Signal Ratio

	PRSL	RRSL	D/U	D/U (dB)
Decra	0.08	1.82	0.04	-27.1
Steel	0.59	1.16	0.51	-5.87
Aluminum	0.94	0.62	1.52	3.61
Clay	1.75	0.13	13.5	22.6
Iron	1.93	0.19	10.2	20.1
Plastic	2.00	0.79	2.53	8.07

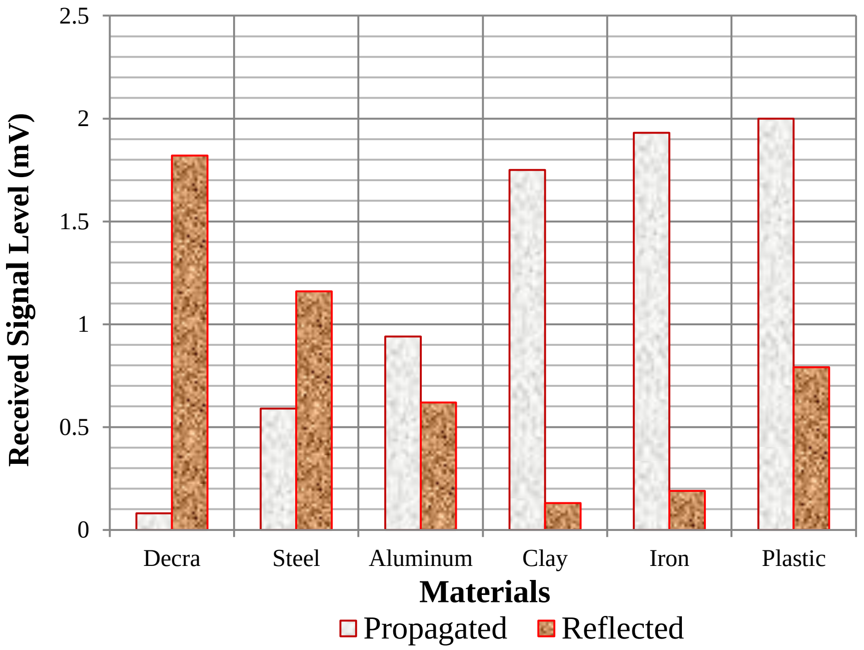

Figure 4.5: Comparison of Transmission and Reflective Paths

The D/U ratio is a measure of signal strength of the propagated received signal (desired) compared with signal strength of the undesired signal from the same frequency component (Iwao and Kuwabara, 2009). The desired signal is one that reaches the receiver where it may be decoded. Decoding the undesired signal may introduce multipath errors in the measurement of distance and signal strength. The higher the Desired-to-Undesired (D//U) signal ratio the better the media since it shows that there is more signal in the transmission path than in the reflective path and therefore better signal strength (Maxson, 2005). International Civil Aviation Organization has specified that the minimum D/U signal ratio should be 20dB in the designated operational coverage area of navaids (ICAO, 2012).

Figure 4.6 shows desired-to-undesired signal ratio compared to ICAO recommended minimum value of 20dB. Steel, aluminum and plastic have D/U ratios below 20dB and therefore their effect on signal strength is outside acceptable limits. Clay and iron have D/U ratios of 22.6dB and 20.1dB respectively which put them above the recommended minimum value and therefore their effect on signal strength is within acceptable limits. Decra with a D/U ratio of -27dB is much below the recommended minimum standard. This means that decra roofing material has the worst effects on navaids signal strength. This is due to high reflectance (52.6%) and high attenuation (97.7%) which make decra unsuitable for use in flight paths. This finding enhances Marcum (2002) argument that reflective obstructions should be prohibited in navaids critical areas.

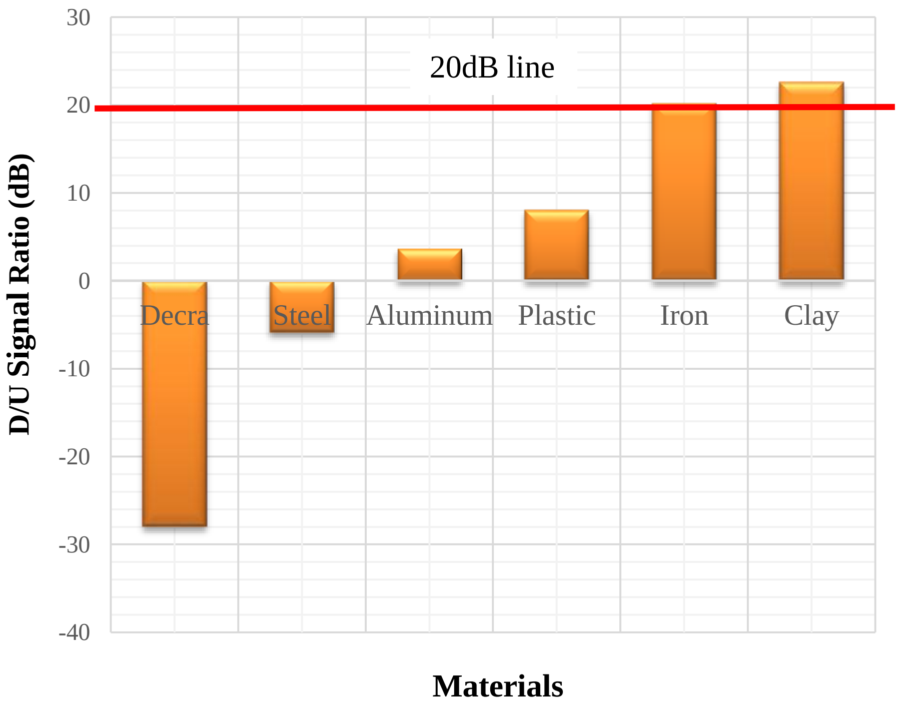

Figure 4.6: D/U Signal Ratio Compared to Recommended Standard

The D/U signal ratio for angles of incidence was also considered and the trend was plotted in Figure A-4 of appendix A. It was shown that as the angle of incidence was varied from 0 to 90 degrees, the D/U ratio decreased and therefore the signal strength decreased. This outcome reciprocates the findings of Chomba (2011a) who found that signal attenuation in concrete walls decreases with increase in angle of incidence.

4.2 Effects of Roofing Materials on Navaids Transmission Distance

Table 4.8 shows that the aggregated mean signal strength decreases with distance spontaneously. In plastic and clay, the decrease is rapid. However, in iron and aluminum, signal strength increases with distance. In steel and decra, signal strength is apparently constant for the three considered distances as shown in Figure 4.7.

Table 4.8: Effects of Roofing Materials on Transmission Distance

Mean Received Signal Level (mV)				
Polarization (P) = Horizontal				
Distance(cm)	**30**	**60**	**100**	**Mean**
Materials				
Decra	0.05	0.04	0.08	**0.06**
Aluminum	0.13	0.23	0.94	**0.43**
Iron	0.25	0.08	1.93	**0.75**
Clay	23.2	2.87	1.75	**9.27**
Steel	1.33	1.65	0.59	**1.19**
Plastic	21.2	9.30	2.00	**10.8**
Mean	**7.69**	**2.36**	**1.22**	

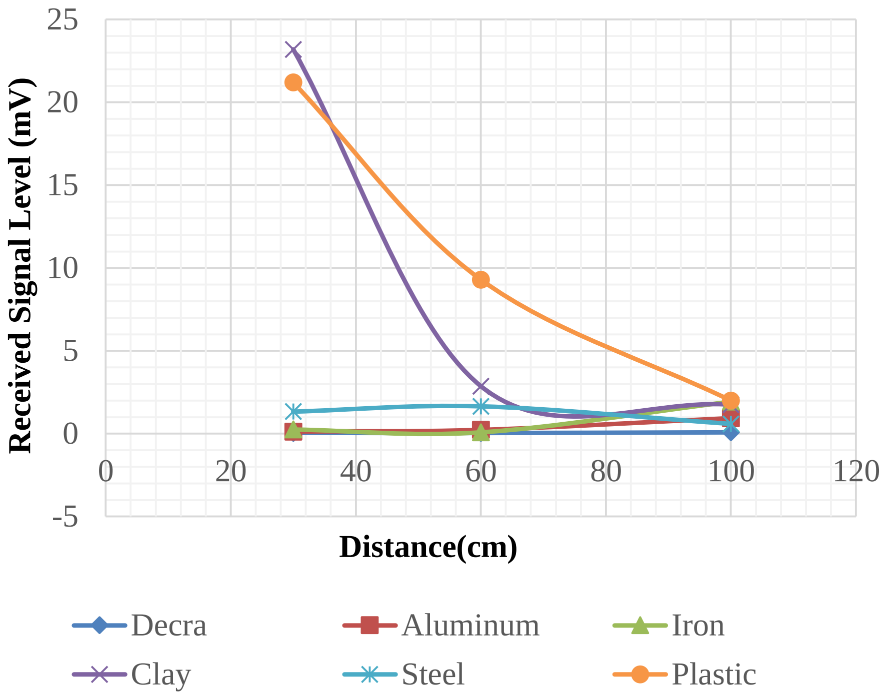

Figure 4.7: Received Signal Level and Transmission Distance

MS Excel was used to analyze the correlation (r) between signal strength in various roofing materials and transmission distance. Statistical analysis in appendix B showed that decra (r = +0.775), aluminum (r = +0.947) and iron (r = +0.866) offered positive correlation which meant that the signal via these materials increased with distance. However, clay (r = -0.848), steel (r = -0.738) and plastic (r = -0.976) offered negative correlation which meant that the signal via these materials decreased with distance. This finding concurs with Chomba (2011b) who found that received signal level via concrete walls decreased with increase in transmission distance. Generally, the mean (r = -0.905) correlation showed that signal level via roofing materials decreased with increase in distance. These correlations were plotted in Figure 4.8.

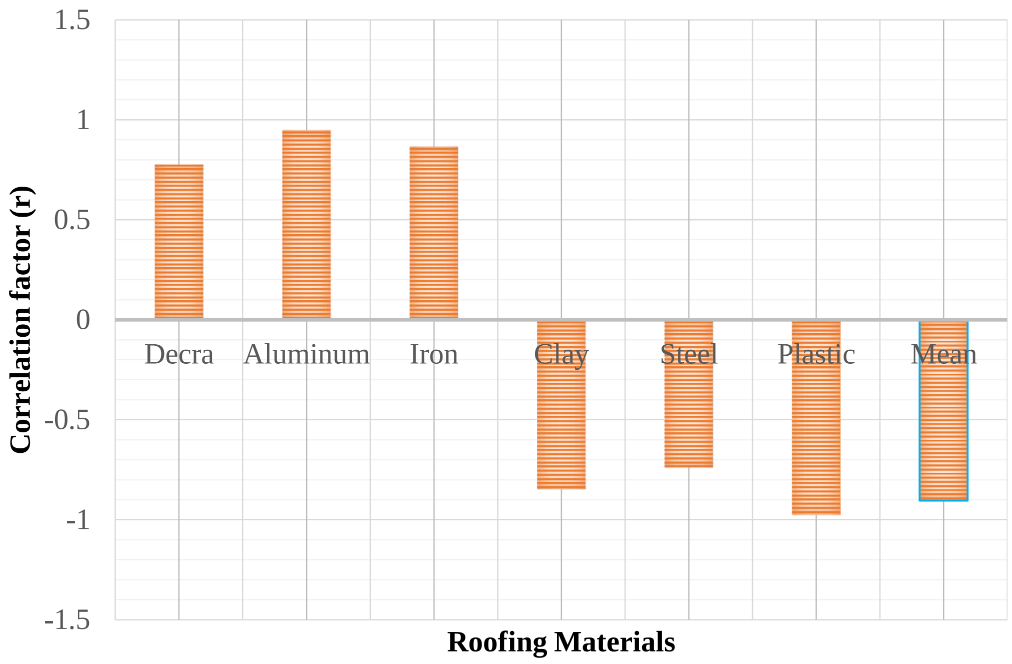

Figure 4.8: Correlation of Distance and Received Signal Level

4.3 Effects of Roofing Materials on Navaids Wave Polarization

The effect of roofing materials on navaids wave polarization was considered as shown in Table 4.9 and Figure 4.9.

Table 4.9: Effects of Roofing Materials on Navaids Wave Polarization

Mean Received Signal Levels (mv)				
Distance = 100cm, assume effects of Angle = constant				
Polarization	**Horizontal**	**Vertical**	**Circular**	**Mean**
Materials				
Plastic	2.00	8.48	4.09	**4.86**
Clay	1.75	7.24	2.79	**3.73**
Iron	1.93	2.18	1.21	**1.78**
Aluminum	0.94	0.85	1.26	**1.02**
Steel	0.59	0.87	0.51	**0.66**
Decra	0.08	0.28	0.19	**0.18**
Mean	**1.22**	**3.32**	**1.68**	

Plastic materials provide highest received signal level for all types of polarization. Steel and decra provide the lowest received signal level irrespective of the mode of polarization.

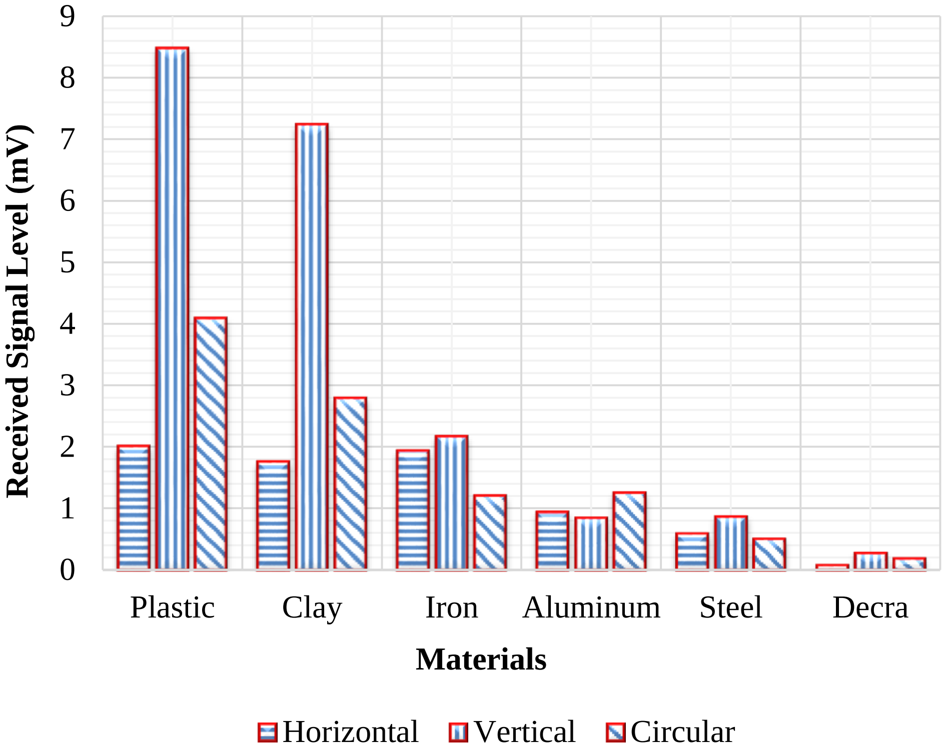

Figure 4.9: Effect of Roofing Materials on Navaids Wave polarization

Statistical analysis in appendix C shows that Fcrit> F and $0.05<p<0.95$ is true for polarization factor, therefore there is no significant difference between types of polarization. This result means that the presence of roofing materials in the transmission path did not have significant effect on wave polarization. This result concurs with Briginton (2010) who found that solid materials had no effect on wave polarization but metallic materials with array of holes could alter the wave polarization. He further examined dependence of angle of incidence and wave polarization

4.4 Discussions

The findings of this study concur with Laws of Kenya Civil Aviation Act No. 21 (2013) on restriction of structures around designated operational areas of aerodromes and flight paths. It also concurs with ICAO (2013a) on civil aviation security regulations for protection of airports, aircrafts and navigation facilities. This concurrency means that highly reflective roofing materials are significant hazards to air transport. According to Pauli and Moldan (2008), metals offer higher reflectance to radio signals than non-metallic materials which offer higher absorption. This study generally concurs that metals reflect more than non-metals. The findings show that decra, steel and aluminum are the most reflective. Plastic, iron and clay are least reflective. Decra is a metal alloy coated with stone dust. A closer look shows that there are shinny metallic pigments in the coating which probably makes it more reflective than aluminum. Iron sheets used in roofing are galvanized (CGI) which probably makes them less reflective than plastic which appears polished and shiny. These two factors make a difference in reflectance trend.

Decra roofing material offered a strong reflected signal (52.6%) resulting into highest attenuation (97.7%). Such a strong reflected signal could find its way into the transmission path and cause significant interference on the forward signal strength (Selex Inc., 2009). International Civil Aviation Organization has specified that the minimum Desired-to-Undesired (D/U) signal ratio should be 20 dB for air-ground communication systems (ICAO, 2012). Clay and iron offered D/U ratios that were above this recommended minimum and therefore their effect to signal strength was within acceptable limits. Steel, aluminum and plastic had D/U ratios below 20dB and therefore their effect on signal strength is outside acceptable limits. Decra exhibited the worst D/U ratio and therefore is not suitable for use in aerodrome areas.

It was shown that as the angle of incidence was varied from 0 to 90 degrees, the D/U ratio decreased and therefore the signal strength decreased. This outcome reciprocates the findings of Chomba (2011a) who found that signal attenuation in concrete walls decreased with increase in angle of incidence.

The study also found that effects of roofing materials on transmission distance varied depending on selected material. Signal strength via plastic, clay and steel materials decreased with increase in distance as that via aluminum, decra and iron increased with increase in distance. However, the overall effect of roofing materials on transmission distance was that of negative correlation. This finding concurs with Chomba (2011b) who found that received signal level via concrete walls decreased with increase in transmission distance.

Further, the study found that the selected roofing materials had no significant effect on wave polarization. It meant that roofing materials had little effect on radiation patterns and therefore radiation patterns cannot be altered by the presence of roofing materials in the propagation path. This result concurs with Briginton (2010) who found that unperforated materials had no effect on wave polarization but metallic materials perforated with array of holes could alter wave polarization.

These experiments were conducted in an enclosed area with minimal environmental interference. The apparatus was enclosed in radio frequency (RF) absorbent material to damp used RF wave and neutralize stray capacitances. Isolation of the environment was attained by sealing the edges of the RF absorbents thus minimizing the window for other equipment in the laboratory to cause interference.

The study required that the transmission signal be constant in all the experiments but closer examination revealed that there was a small difference between the signal at the start and at the end of experiments, the significance of this difference was not determined but was minimized via use of repetitions and average values.

Generally, the calibration data for the receiver and transmitter was not readily available however critical performance checks were conducted as per the technical manuals and error margins of 2.2% and 1.5% were realized for the receiver and transmitter respectively. These errors were assumed negligible.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

It has been shown that the effect of roofing materials on navaids signal strength was significant depending on selected roofing material. The effect of roofing materials on navaids transmission distance depended on the obstructing material. Roofing materials had no significant effect on navaids wave polarization

The effect of roofing materials and angle of incidence on navaids signal strength was compared with ICAO recommended values. Received signal level decreased with increase in angle of incidence from 0 to 90 degrees. The desired-to-undesired signal ratios of clay and iron were above the ICAO recommended minimum value of 20dB. This meant that clay and iron had no significant effects on navaids signal propagation unlike decra, steel, aluminum and plastic which showed significant negative effects on signal strength. The study established that decra had the worst effects on signal strength due to its high reflectance and strong attenuation. This finding means that decra is unsuitable for roofing applications around airports.

Effects of roofing materials on transmission distance varied depending on the selected material. It also depended on whether the operation was in the near-field or far-field regions. The relationship between roofing materials and transmission distance was determined by the correlation factor r. The navaids signal via plastic, clay and steel roofing materials decreased with increase in distance while that via decra, aluminum and iron increased with increase in distance. The aggregated result was that navaids signal via roofing materials decreased with increase in distance.

Effect of roofing materials on navaids wave polarization was compared for horizontal, vertical and circular modes. Despite the differences in received signal levels, statistical analyses revealed that there was no significant difference between the three modes of wave polarization and therefore roofing materials had no significant effect on antenna radiation patterns.

5.2 Recommendations

From the results and conclusions, the following recommendations have been suggested;

1) Building and aviation industries should develop a compromise roofing material that has little effect on flight navigation. The use of decra as a roofing material around airports and flight paths should be restricted. Whereas clay and iron have shown to be better than the rest, there is room to improve them.
2) The angle at which roofs are inclined should be designed to minimize reflections. It has been shown that reflection and generally attenuation depend on the angle of inclination of roofing material; this angle can be improved during construction so as to minimize reflections.
3) Relationship between type of roofing material and transmission distance need to be studied further so as to explain why there is a mix of positive and negative correlation.
4) Further studies should be directed in conducting experiments in open fields and factoring in sources of variability arising from the environment so as to actualize the true scenario of flight navigation.
5) Similar studies should be conducted on roofing materials other than those considered in this research.

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APPENDICES

Appendix A

Roofing Materials and Angle of Incidence

Table A-1: No Obstacle Raw Readings (Ref)

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	7.75	8.13	8.36	**8.08**
15	6.31	6.50	7.00	**6.60**
30	3.41	4.08	4.14	**3.88**
45	1.28	1.34	1.49	**1.37**
60	0.63	0.63	0.75	**0.67**
75	0.32	0.32	0.31	**0.32**
90	0.12	0.08	0.05	**0.08**
105	0.42	0.42	0.38	**0.41**
120	1.05	1.02	0.99	**1.02**
135	2.47	2.57	2.58	**2.54**
150	4.62	4.91	4.86	**4.80**
165	7.32	7.65	7.91	**7.63**
180	7.40	7.63	7.86	**7.63**

Table A-2: Iron Raw Readings in Transmission Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	4.96	4.50	4.61	**4.69**
15	4.08	3.76	3.90	**3.91**
30	2.51	2.46	2.59	**2.52**
45	1.33	1.40	1.44	**1.39**
60	0.67	0.62	0.64	**0.64**
75	0.28	0.30	0.33	**0.30**
90	0.33	0.33	0.31	**0.32**
105	0.43	0.43	0.39	**0.42**
120	0.64	0.6	0.59	**0.61**
135	1.10	0.87	0.91	**0.96**
150	2.40	1.99	2.04	**2.41**
165	3.59	3.06	3.25	**3.30**
180	3.64	3.61	3.61	**3.62**

Table A-3: Aluminum Readings in Transmission path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	2.39	2.40	2.38	**2.39**
15	2.54	2.48	2.47	**2.50**
30	2.02	1.91	1.89	**1.94**
45	1.40	1.25	1.25	**1.30**
60	0.62	0.59	0.56	**0.59**
75	0.22	0.19	0.20	**0.20**
90	0.13	0.10	0.10	**0.11**
105	0.03	0.03	0.02	**0.03**
120	0.00	0.00	0.00	**0.00**
135	0.07	0.09	0.09	**0.08**
150	0.37	0.48	0.46	**0.45**
165	1.10	1.11	1.09	**1.10**
180	1.57	1.54	1.51	**1.54**

Table A-4: Steel Raw Readings in Transmission Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	1.21	1.22	1.20	**1.21**
15	0.80	0.90	0.95	**0.88**
30	0.16	0.18	0.15	**0.16**
45	0.39	0.39	0.42	**0.40**
60	0.24	0.26	0.22	**0.24**
75	0.07	0.07	0.05	**0.06**
90	0.02	0.02	0.03	**0.02**
105	0.09	0.07	0.10	**0.09**
120	0.22	0.24	0.20	**0.22**
135	0.50	0.50	0.60	**0.53**
150	1.10	0.95	0.90	**0.98**
165	1.54	1.59	1.53	**1.55**
180	1.31	1.33	1.32	**1.32**

Table A-5: Clay Raw Readings in Transmission Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	4.70	4.68	4.77	**4.72**
15	3.93	3.90	3.97	**3.93**
30	2.85	2.92	2.83	**2.87**
45	1.19	1.19	1.20	**1.19**
60	0.67	0.69	0.66	**0.67**
75	0.51	0.52	0.50	**0.51**
90	0.30	0.32	0.28	**0.30**
105	0.13	0.16	0.11	**0.13**
120	0.16	0.20	0.15	**0.17**
135	0.52	0.52	0.52	**0.52**
150	1.37	1.34	1.36	**1.36**
165	2.98	2.97	3.00	**2.98**
180	3.42	3.41	3.42	**3.42**

Table A-6: Decra Raw Readings in Transmission Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	0.10	0.10	0.10	**0.10**
15	0.09	0.08	0.09	**0.09**
30	0.12	0.11	0.12	**0.12**
45	0.12	0.12	0.12	**0.12**
60	0.09	0.08	0.09	**0.09**
75	0.07	0.07	0.06	**0.07**
90	0.05	0.05	0.05	**0.05**
105	0.03	0.02	0.03	**0.03**
120	0.06	0.06	0.05	**0.06**
135	0.01	0.01	0.01	**0.01**
150	0.12	0.12	0.11	**0.12**
165	0.11	0.11	0.12	**0.11**
180	0.06	0.05	0.06	**0.06**

Table A-7: Plastic Raw Readings in Transmission Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	4.91	4.92	4.90	**4.91**
15	3.71	3.69	3.70	**3.70**
30	1.56	1.55	1.55	**1.55**
45	0.25	0.26	0.25	**0.25**
60	0.04	0.03	0.05	**0.04**
75	0.02	0.02	0.03	**0.02**
90	0.09	0.09	0.10	**0.09**
105	0.37	0.39	0.34	**0.37**
120	0.77	0.79	0.77	**0.78**
135	1.69	1.64	1.73	**1.67**
150	3.08	3.10	3.04	**3.07**
165	4.74	4.74	4.75	**4.74**
180	4.86	4.88	4.84	**4.86**

Table A-8: Iron Raw Readings in Reflective Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	0.45	0.44	0.45	**0.45**
15	0.40	0.39	0.41	**0.40**
30	0.36	0.36	0.36	**0.36**
45	0.25	0.25	0.27	**0.26**
60	0.17	0.16	0.16	**0.16**
75	0.12	0.14	0.13	**0.13**
90	0.07	0.08	0.06	**0.07**
105	0.04	0.03	0.05	**0.04**
120	0.04	0.04	0.04	**0.04**
135	0.04	0.04	0.04	**0.04**
150	0.07	0.08	0.09	**0.08**
165	0.17	0.17	0.18	**0.17**
180	0.26	0.24	0.25	**0.25**

Table A-9: Aluminum Raw Readings in Reflective Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	1.29	1.27	1.30	**1.28**
15	1.23	1.22	1.25	**1.23**
30	0.86	1.05	1.07	**0.99**
45	0.65	0.65	0.66	**0.65**
60	0.38	0.39	0.40	**0.39**
75	0.31	0.30	0.32	**0.31**
90	0.15	0.15	0.17	**0.16**
105	0.17	0.17	0.18	**0.17**
120	0.09	0.09	0.08	**0.09**
135	0.15	0.15	0.16	**0.15**
150	0.59	0.59	0.61	**0.60**
165	1.00	1.02	1.02	**1.01**
180	1.03	1.04	1.02	**1.03**

Table A-10: Steel Raw Readings in Reflective Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	2.78	2.74	2.82	**2.78**
15	2.35	2.36	2.33	**2.35**
30	1.55	1.58	1.54	**1.56**
45	0.82	0.82	0.83	**0.82**
60	0.40	0.41	0.39	**0.40**
75	0.14	0.15	0.12	**0.14**
90	0.24	0.25	0.23	**0.24**
105	0.36	0.36	0.38	**0.37**
120	0.54	0.54	0.56	**0.55**
135	0.70	0.68	0.72	**0.70**
150	1.26	1.27	1.26	**1.26**
165	1.87	1.88	1.86	**1.87**
180	2.06	2.05	2.05	**2.05**

Table A-11: Clay Raw Readings in Reflective Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	0.16	0.16	0.16	**0.16**
15	0.24	0.25	0.25	**0.25**
30	0.27	0.28	0.26	**0.26**
45	0.29	0.28	0.27	**0.28**
60	0.26	0.26	0.27	**0.26**
75	0.15	0.15	0.14	**0.15**
90	0.08	0.09	0.07	**0.08**
105	0.03	0.03	0.02	**0.03**
120	0.01	0.01	0.04	**0.02**
135	0.00	0.00	0.00	**0.00**
150	0.02	0.02	0.03	**0.02**
165	0.07	0.08	0.06	**0.07**
180	0.11	0.11	0.13	**0.12**

Table A-12: Decra Raw Readings in Reflective Path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	5.26	5.27	5.29	**5.27**
15	4.06	4.04	4.08	**4.06**
30	2.21	2.20	2.22	**2.21**
45	1.14	1.14	1.13	**1.14**
60	0.53	0.53	0.54	**0.53**
75	0.11	0.12	0.13	**0.12**
90	0.12	0.11	0.13	**0.12**
105	0.27	0.27	0.28	**0.27**
120	0.57	0.57	0.56	**0.57**
135	1.06	1.04	1.05	**1.05**
150	2.07	2.07	2.09	**2.08**
165	3.08	3.09	3.10	**3.09**
180	3.18	3.18	3.19	**3.18**

Table A-13: Plastic raw readings in reflective path

	Received Signal Level (RSL) in mV			
Repetitions	**1**	**2**	**3**	**Mean**
Angle				
0	1.94	1.96	1.95	**1.95**
15	1.69	1.70	1.72	**1.70**
30	1.05	1.06	1.05	**1.05**
45	0.58	0.59	0.61	**0.59**
60	0.27	0.27	0.28	**0.27**
75	0.10	0.11	0.10	**0.10**
90	0.03	0.03	0.04	**0.03**
105	0.01	0.01	0.01	**0.01**
120	0.11	0.12	0.10	**0.11**
135	0.37	0.37	0.40	**0.38**
150	0.84	0.84	0.85	**0.84**
165	1.51	1.53	1.50	**1.51**
180	1.76	1.78	1.77	**1.77**

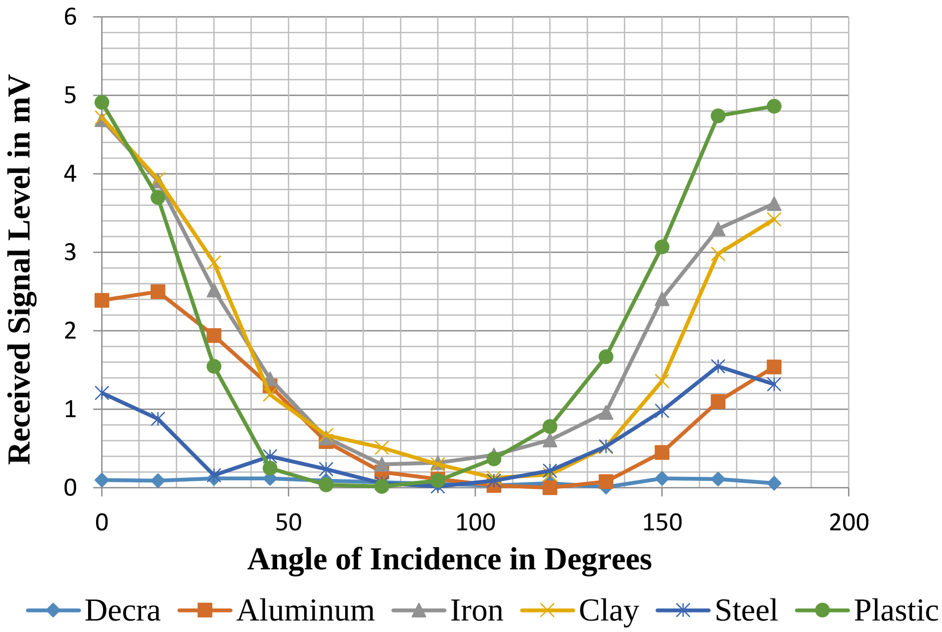

Figure A-1: Received Signal Level Vs Angle of Incidence

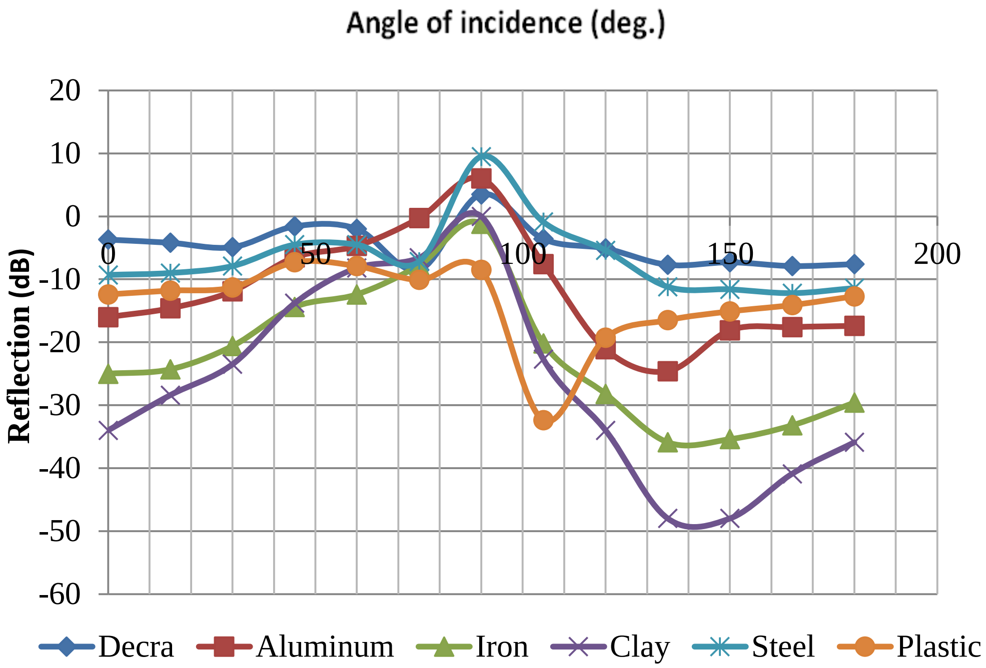

Figure A-2: Variation of Reflection and Angle of Incidence

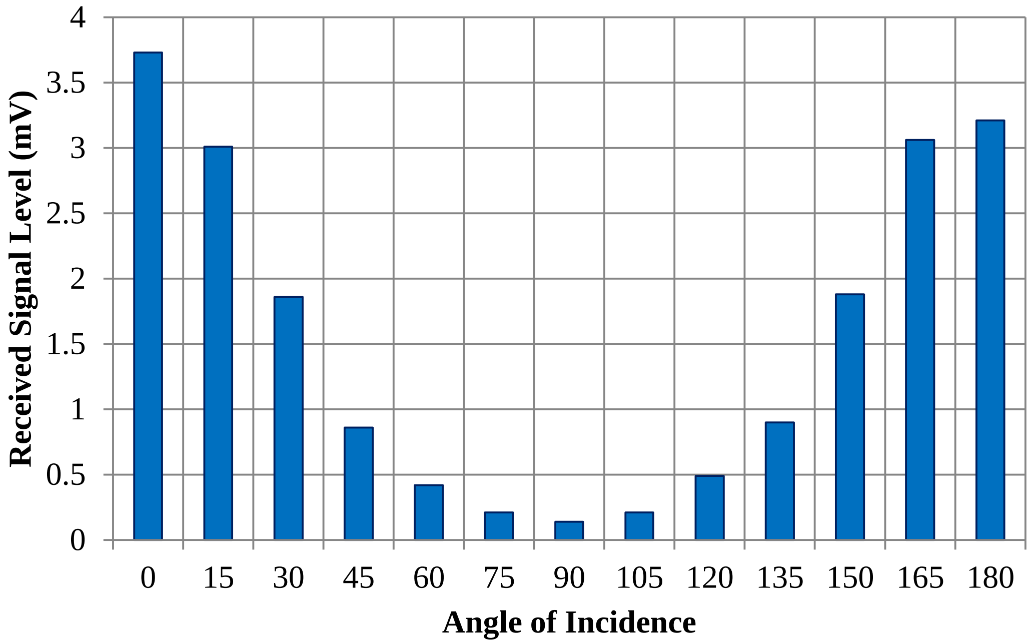

Figure A-3: Mean Received Signal Level per Angle of Incidence

Table A-13A: Desired-to-Undesired Ratio for Angles of Incidence

Angle	PRSL	RRSL	D/U	D/U (dB)
0	3.73	2.85	1.31	2.35
15	3.01	2.37	1.27	2.08
30	1.86	1.47	1.27	2.08
45	0.86	0.73	1.18	1.44
60	0.42	0.38	1.11	0.91
75	0.21	0.18	1.17	1.36
90	0.14	0.11	1.27	2.08
105	0.21	0.18	1.17	1.36
120	0.49	0.34	1.44	3.17
135	0.90	0.69	1.30	2.28
150	1.88	1.38	1.36	2.67
165	3.06	2.19	1.40	2.92
180	3.21	2.29	1.40	2.92

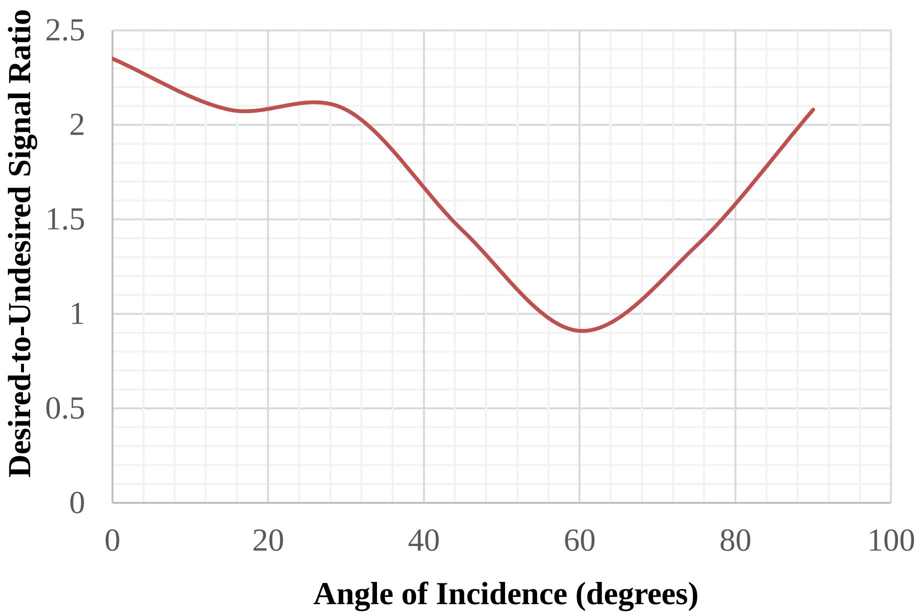

Figure A-4: Desired-to-Undesired Signal Ratio for Angles of Incidence

Table A-14: Comparison of Roofing Materials by MS Excel ANOVA: Single Factor

SUMMARY

Groups	**Count**	**Sum**	**Average**	**Variance**
Decra	7	13.45	1.921	4.151
steel	7	8.290	1.184	1.129
Plastic	7	5.690	0.813	0.600
Aluminum	7	5.010	0.716	0.207
Iron	7	1.830	0.261	0.021
Clay	7	1.440	0.206	0.006

ANOVA

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	14.28	5	2.857	2.803	0.031	2.477
Within Groups	36.69	36	1.019			
Total	50.97	41				

Table A-15: Comparison of Iron and Aluminum using t-Test: Two-Sample Assuming Unequal Variances

	Iron	**Clay**
Mean	0.261	0.206
Variance	0.021	0.006
Observations	7	7
Hypothesized Mean Differ	0	
df	9	
t Stat	0.894	
P(T<=t) one-tail	0.197	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.395	
t Critical two-tail	2.262	

Deduction: tcrit>t stat; there is no significant difference between iron and clay but aluminum differs from the rest.

Appendix B

Navaids Transmission Distance

Table B-1: Aluminum Readings for Transmission Distance

	Received Signal Level (RSL) in mV			
Distance	**30cm**	**60cm**	**100cm**	**Mean**
Angle				
0	0.03	0.79	2.39	**1.07**
15	0.01	0.45	2.50	**0.99**
30	0.05	0.19	1.94	**0.73**
45	0.10	0.05	1.30	**0.48**
60	0.02	0.04	0.59	**0.23**
75	0.06	0.08	0.20	**0.11**
90	0.12	0.05	0.11	**0.09**
105	0.13	0.06	0.03	**0.07**
120	0.15	0.08	0.00	**0.08**
135	0.07	0.17	0.08	**0.11**
150	0.07	0.39	0.48	**0.31**
165	0.30	0.39	1.10	**0.60**
180	0.58	0.23	1.54	**0.78**
Mean	**0.13**	**0.23**	**0.94**	

Table B-2: Iron Readings for Transmission Distance

	Received Signal Level (RSL) in mV			
Distance	**30cm**	**60cm**	**100cm**	**Mean**
Angle				
0	0.44	0.03	4.69	**1.72**
15	0.57	0.03	3.91	**1.50**
30	0.41	0.00	2.52	**0.98**
45	0.35	0.01	1.39	**0.58**
60	0.39	0.00	0.64	**0.34**
75	0.20	0.00	0.30	**0.17**
90	0.08	0.04	0.32	**0.15**
105	0.05	0.05	0.42	**0.17**
120	0.03	0.19	0.61	**0.28**
135	0.02	0.12	0.96	**0.37**
150	0.15	0.16	2.41	**0.91**
165	0.29	0.21	3.30	**1.27**
180	0.22	0.22	3.62	**1.35**
Mean	**0.25**	**0.08**	**1.93**	

Table B-3: Steel Readings for Transmission Distance

	Received Signal Level (RSL) in mV			
Distance	**30cm**	**60cm**	**100cm**	**Mean**
Angle				
0	3.05	4.08	1.21	**2.78**
15	2.97	4.17	0.88	**2.67**
30	2.00	3.13	0.16	**1.76**
45	1.19	1.55	0.40	**1.05**
60	0.70	0.83	0.24	**0.59**
75	0.29	0.34	0.06	**0.23**
90	0.17	0.04	0.02	**0.08**
105	0.13	0.01	0.09	**0.08**
120	0.26	0.15	0.22	**0.21**
135	0.61	0.51	0.53	**0.55**
150	1.31	1.27	0.98	**1.19**
165	2.16	2.34	1.55	**2.02**
180	2.40	2.97	1.32	**2.23**
Mean	**1.33**	**1.65**	**0.59**	

Table B-4: Clay Readings for Transmission Distance

	Received Signal Level (RSL) in mV			
Distance	**30cm**	**60cm**	**100cm**	**Mean**
Angle				
0	44.08	8.660	4.730	**19.16**
15	43.83	8.490	3.930	**18.75**
30	41.00	5.100	2.870	**16.32**
45	28.26	2.720	1.190	**10.72**
60	13.66	1.040	0.670	**5.120**
75	5.190	0.590	0.510	**2.100**
90	1.420	0.310	0.300	**0.680**
105	1.170	0.150	0.130	**0.480**
120	3.730	0.020	0.170	**1.310**
135	10.66	0.160	0.520	**3.780**
150	25.27	1.440	1.360	**9.360**
165	40.59	3.520	2.980	**15.70**
180	42.78	5.140	3.42	**17.11**
Mean	**23.20**	**2.870**	**1.750**	

Table B-5: Decra Readings for Transmission Distance

	Received Signal Level (RSL) in mV			
Distance	**30cm**	**60cm**	**100cm**	**Mean**
Angle				
0	0.05	0.09	0.10	**0.05**
15	0.07	0.07	0.09	**0.08**
30	0.12	0.04	0.12	**0.09**
45	0.17	0.02	0.12	**0.10**
60	0.11	0.01	0.09	**0.07**
75	0.04	0.01	0.07	**0.04**
90	0.02	0.02	0.05	**0.03**
105	0.02	0.03	0.03	**0.03**
120	0.02	0.06	0.06	**0.02**
135	0.02	0.06	0.01	**0.03**
150	0.01	0.05	0.12	**0.06**
165	0.02	0.05	0.11	**0.06**
180	0.03	0.04	0.06	**0.04**
Mean	**0.05**	**0.04**	**0.08**	

Table B-6: Plastic Readings for Transmission Distance

	Received Signal Level (RSL) in mV			
Distance	**30cm**	**60cm**	**100cm**	**Mean**
Angle				
0	43.73	23.35	4.910	**24.00**
15	43.20	20.12	3.700	**22.34**
30	35.80	13.20	1.550	**16.85**
45	21.23	6.060	0.250	**9.180**
60	10.76	3.500	0.040	**4.770**
75	4.750	1.780	0.020	**2.180**
90	1.240	0.380	0.090	**0.570**
105	0.950	0.240	0.370	**0.520**
120	2.170	1.000	0.780	**1.320**
135	8.040	4.150	1.670	**4.620**
150	24.11	10.84	3.070	**12.67**
165	38.89	17.64	4.740	**20.42**
180	41.08	18.67	4.860	**21.54**
Mean	**21.23**	**9.300**	**2.000**	

Table B-7: Statistical correlation (r) of roofing materials and transmission distance MS Excel correlation factor (r)

	Distance	Decra	Aluminum	Iron	Clay	Steel	Plastic	Mean
Distance	1							
Decra	0.775	1						
Aluminum	0.947	0.937	1					
Iron	0.866	0.987	0.980	1				
Clay	-0.848	-0.321	-0.631	-0.468	1			
Steel	-0.738	-0.998	-0.916	-0.977	0.268	1		
Plastic	-0.976	-0.618	-0.854	-0.736	0.943	0.574	1	
Mean	-0.905	-0.432	-0.719	-0.570	0.993	0.381	0.976	1

Appendix C

Navaids Wave Polarization

Table C-1: Raw mean data for horizontal polarization test

Received signal Level (mV) Polarization = Horizontal, Distance = 100cm							
Angle	**0**	**15**	**30**	**45**	**60**	**75**	**90**
Materials							
Ref	8.08	6.6	3.88	1.37	0.67	0.32	0.08
Iron	4.69	3.91	2.52	1.39	0.64	0.30	0.32
Clay	4.72	3.93	2.87	1.19	0.67	0.51	0.30
Plastic	4.91	3.70	1.55	0.25	0.04	0.02	0.09
Aluminum	2.39	2.50	1.94	1.30	0.59	0.20	0.11
Steel	1.21	0.88	0.16	0.40	0.24	0.06	0.02
Decra	0.10	0.09	0.12	0.12	0.09	0.07	0.05
Mean	**3.73**	**3.09**	**1.86**	**0.86**	**0.42**	**0.21**	**0.14**

Angle	**105**	**120**	**135**	**150**	**165**	**180**	**Mean**
Materials							
Ref	0.41	1.02	2.54	4.80	7.63	7.63	**3.46**
Iron	0.42	0.61	0.96	2.41	3.30	3.62	**1.93**
Clay	0.13	0.17	0.52	1.36	2.98	3.42	**1.75**
Plastic	0.37	0.78	1.67	3.07	4.74	4.85	**2.00**
Aluminum	0.03	0.00	0.08	0.45	1.10	1.54	**0.94**
Steel	0.09	0.22	0.53	0.98	1.55	1.32	**0.59**
Decra	0.03	0.06	0.01	0.12	0.11	0.06	**0.08**
Mean	**0.21**	**0.41**	**0.90**	**1.88**	**3.06**	**3.21**	

Table C-2: Raw mean data for vertical polarization test

Received signal Level (mV)							
Polarization = Vertical, Distance = 100cm							
Angle	**0**	**15**	**30**	**45**	**60**	**75**	**90**
Materials							
None	10.2	8.50	13.0	14.1	10.1	12.9	6.13
Iron	1.17	1.08	0.58	1.35	2.10	3.48	2.71
Clay	0.97	1.31	7.55	16.9	16.4	14.3	2.73
Plastic	8.68	5.26	9.56	9.76	5.90	7.42	4.33
Aluminum	0.12	0.17	1.74	4.87	1.00	0.12	0.38
Steel	0.31	0.51	0.17	2.15	2.05	0.30	0.30
Decra	0.04	0.16	0.13	0.36	0.10	0.17	0.23
Mean	**3.07**	**2.43**	**4.68**	**7.16**	**5.38**	**5.53**	**2.4**

Angle	**105**	**120**	**135**	**150**	**165**	**180**	**Mean**
Materials							
None	14.3	9.96	7.98	6.19	8.11	12.5	**10.4**
Iron	3.11	1.85	1.57	1.87	3.38	4.05	**2.18**
Clay	4.10	4.94	4.58	3.20	4.28	12.9	**7.24**
Plastic	9.24	12.2	10.1	7.28	8.62	11.9	**8.48**
Aluminum	0.34	0.13	0.27	0.47	0.46	0.96	**0.85**
Steel	0.72	0.27	0.50	0.89	1.24	1.89	**0.87**
Decra	0.40	0.28	0.77	0.52	0.32	0.13	**0.28**
Mean	**4.60**	**4.23**	**3.68**	**2.92**	**3.77**	**6.34**	

Table C-3: Raw mean data for circular polarization test

Received signal Level (mV) Polarization = Circular, Distance = 100cm							
Angle	**0**	**15**	**30**	**45**	**60**	**75**	**90**
Materials							
Ref	0.51	0.09	0.29	0.64	0.70	1.47	1.98
Iron	0.07	0.00	0.02	0.06	0.06	0.14	0.33
Clay	0.11	0.00	0.04	0.13	0.13	0.33	0.33
Plastic	0.31	0.11	0.12	0.47	0.54	1.08	1.40
Aluminum	0.06	0.03	0.02	0.00	0.02	0.09	0.08
Steel	0.01	0.00	0.02	0.02	0.08	0.08	0.09
Decra	0.00	0.00	0.00	0.00	0.05	0.05	0.04
Mean	**0.15**	**0.03**	**0.07**	**0.19**	**0.23**	**0.46**	**0.61**

Angle	**105**	**120**	**135**	**150**	**165**	**180**	**Mean**
Materials							
Ref	2.35	1.19	8.40	5.62	23.9	21.2	**5.26**
Iron	0.28	0.61	1.52	2.73	5.39	4.54	**1.21**
Clay	0.77	0.07	1.93	2.37	14.3	15.8	**2.79**
Plastic	2.91	0.33	6.87	3.87	20.4	14.8	**4.09**
Aluminum	0.32	0.65	1.01	1.82	4.21	8.09	**1.26**
Steel	0.51	0.01	0.83	1.89	2.61	0.42	**0.51**
Decra	0.05	0.08	0.18	0.61	0.85	0.51	**0.19**
Mean	**1.03**	**0.42**	**2.96**	**2.70**	**10.23**	**9.33**	

Table C-4: Statistical comparison of modes of polarization using MS Excel

ANOVA: Two-Factor Without Replication

SUMMARY	Count	Sum	Average	Variance
Plastic	3	14.57	4.856667	10.93843
Clay	3	11.78	3.926667	8.504033
Iron	3	5.32	1.773333	0.253633
Aluminum	3	3.05	1.016667	0.046433
Steel	3	1.97	0.656667	0.035733
Decra	3	0.55	0.183333	0.010033
Horizontal	6	7.29	1.215	0.63363
Vertical	6	19.9	3.316667	12.92731
Circular	6	10.05	1.675	2.20527

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Materials	53.9	5	10.8	4.32	0.023	3.33
Polarization	14.6	2	7.32	2.94	0.099	4.10
Error	24.9	10	2.49			
Total	93.5	17				

Deduction: Fcrit for polarization columns is greater than F, and P value is within the range 0.05 and 0.95 thus there is no significant difference between the three modes of polarization. It means that the effect of roofing materials on polarization was insignificant.

Appendix D

Research Letters and Approvals

D-1: Request for Study Leave

--------------------------- Original Message ----------------------------
Subject: STUDY LEAVE
From: "bmuli" <bmuli@kcaa.or.ke>
Date: Thu, January 17, 2013 7:22 pm
To: romusonga@kcaa.or.ke
Cc: mombasamia@kcaa.or.ke
srangar@kcaa.or.ke
rkimathi@kcaa.or.ke

Dear Robert,
How are you and the new year?

Your application for study leave without pay to enable you complete your Masters degree was considered by the Training and Development Committee in its meeting held on 9th October 2012 and approved with effect from 1st December 2012 up to and including 30th November 2013.

On reporting on duty after the expiry of the study leave, you will be expected to report with duly signed letter of completion from the college.

By a copy of this email, the Chief Human Resource Officer in charge of salaries is requested to stop your salary for the period stated.

Finally have a good study environment and wish you success.

B. S. K. Muli
Human Resource Officer (Training & Development)
KENYA CIVIL AVIATION AUTHORITY

D-2: MSc Research Proposal Approval

EGERTON UNIVERSITY

Tel: Pilot: 254-51-2217620
254-51-2217877
254-51-2217631
Dir. line/Fax: 254-51-2217847

P.O. Box 536 – 20115
Egerton, Njoro, Kenya
Email: bpgs@egerton.ac.ke
www.egerton.ac.ke

OFFICE OF THE DIRECTOR GRADUATE SCHOOL

BM12/2074/08 18^Th^ January, 2013

Omusonga Robert Jere
Department of AGEN
P. O Box 536,
EGERTON

Dear Mr. Jere

RE: MSc RESEARCH PROPOSAL APPROVAL 7^TH^ NOVEMBER 2012

This is to inform you that the Board of Post graduate Studies in its meetings held 7^TH^ **NOVEMBER 2012**considered and Approved your research proposal entitled: "***Effects of Selected Roofing Materials on Air Navigation Signal Propagation***". With the following corrections;

- Revise the Title "Air Traffic"
- Update WorkPlan
- Use Graduate School guidelines

Two copies of the corrected proposal together with certificate of correction form should be forwarded to graduate school not later than thirty days from the date of this letter.

Yours sincerely,

J G Kamau
FOR DIRECTOR, BOARD OF POSTGRADUATE STUDIES

C.c. Dean (FET)
Dr. D.M. Nyaaga Supervisor
Dr. J.M. Githeko Supervisor

Egerton University ISO 9001:2008 Certified

D-3: Submission of final Proposal and Commencement of data collection

EGERTON UNIVERSITY

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254-51-2217631
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P.O. Box 536 - 20115
Egerton, Njoro, Kenya
Email: bpgs@egerton.ac.ke
www.egerton.ac.ke

OFFICE OF THE DIRECTOR GRADUATE SCHOOL

Ref:.....BM12/2074/08

Date: 3rd September, 2013

Mr. Robert J. Omusonga
Dept. of IEEN
Egerton University
P. O. Box 536
EGERTON

Dear Mr. Omusonga

RE: CORRECTED PROPOSAL

This is to acknowledge receipt of two copies of your corrected proposal, entitled entitled **"Effects of Selected Roofing Materials on Air Navigation Signal Propagation."**

You are now at liberty to commence your fieldwork.

Please note, you are expected to publish at least one paper in an international peer-reviewed journal before final examination (oral defense) of your Masters thesis.

Thank you.

Yours sincerely,

Prof. M.A. Okiror
DIRECTOR, BOARD OF POSTGRADUATE STUDIES

c.c. Supervisors
COD, IEEN
Dean, FET
Admissions

MAO/vk

Egerton University is ISO 9001:2008 Certified

D-4: Completion of Data collection

Robert Jere Omusonga,

P.O. Box 93939-80100,

Tel: 0721856563,

MOMBASA.

25th SEPT 2014

The Director,

Board of Post Graduate Studies,

Egerton University,

P.O Box 536-20115,

EGERTON.

Thro'

Supervisors:

Prof. Nyaanga D.M.

Prof. Githeko J.M.

Dear Sir,

RE: COMPLETION OF DATA COLLECTION

S/No. BM12/2074/08

This is to inform you that I completed field work and data collection for my Master's thesis entitled **"effects of selected roofing materials on air navigation signal propagation".**

Attached please find copies of raw data that I intent to start analyzing under the guidance of my research supervisors. Thank you for your continued support.

Yours faithfully,

R. J. Omusonga

D-5: Invitation for Oral Defense of Thesis

EGERTON UNIVERSITY
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P. O. Box 536-20115,
EGERTON, KENYA

FACULTY OF ENGINEERING AND TECHNOLOGY
MEMORANDUM

FROM: FET POSTGRADUATE CHAIR
REF: EU/ FET/REFERENCE
DATE: 18th November, 2015

To ALL FET Academic Staff and Postgraduate Students

RE: MSc Thesis Oral Defence

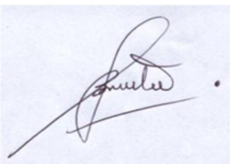
You are invited to attend a Faculty MSc Final Oral Thesis Defence on **Tuesday 24th November 2015** in the FET Boardroom starting from **9.30AM**.

The details of the MSc candidate are:

1. Name: **Robert Jere Omusonga**,
   Reg. No. **BM12/2074/08**
   Title of MSc Thesis: "***Effects of selected Roofing Materials on Air Navigation Signal Propagation***"
   Time: **9.30 AM**
   Supervisors:
   1. Prof. D.M. Nyaanga
   2. Prof. J.M. Githeko

Kindly plan to attend and be punctual. Your continued support and contribution in assessing our postgraduate students is highly appreciated.

Thanks,



Prof. Dr.-Ing. Benedict M. Mutua, PhD, Rer.Nat.

CHAIR, FET POSTGRADUATE COMMITTEE

Copy to: DEAN, FET
COD-AGEN, COD-CEEN, COD-ECEN, COD-IEEN

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D-6: Results of Oral Defense

EGERTON UNIVERSITY
Tel:+254 51 2217891/2
www.egerton.ac.ke

P. O. Box 536-20115,
EGERTON, KENYA

FACULTY OF ENGINEERING AND TECHNOLOGY
MEMORANDUM

FROM: FET POSTGRADUATE CHAIR
REF: EU/ FET/REFERENCE
DATE: 24th November, 2015

Director-General,
Kenya Civil Aviation Authority,
P.O. Box 30163-00100,
Nairobi.
Dear Sir,

RE: MSc Thesis Oral Defence by Robert Jere Omusonga

This is to confirm that Robert Jere Omusonga, Reg. No. BM12/2074/08 who is a student in the Faculty of Engineering and Technology, Egerton University ***successfully*** defended his MSc Thesis on **24th November 2015**. However, he needs some time to do some corrections so that he can submit the final Thesis for graduation.

Thanks,

CHAIRMAN DEPARTMENT OF AGRICULTURAL ENGINEERING
EGERTON UNIVERSITY
P.O. Box 536-20115
EGERTON

Prof. Dr.-Ing. Benedict M. Mutua, PhD, Rer.Nat.
CHAIR, FET POSTGRADUATE COMMITTEE

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Appendix E
List of Published Papers

E-1: Published papers

Omusonga, R. J., Nyaanga, D. M. Githeko, J. M. and Chomba, B. K. (2015). Effects of roofing materials and angle of incidence on navaids signal strength. *Industrial Engineering Letters Vol. 5 No. 5 pp. 137 – 151, May 2015*. International Institute of Science Technology and Engineering. www.iiste.org

Omusonga, R. J. (2015). Impact of choice of roofing materials on navaids wave polarization. *Innovative Systems Design and Engineering Vol. 6 No.5 pp. 104 – 113, May 2015.* International Institute of Science Technology and Engineering. www.iiste.org

Omusonga, R. J. (2015). Comparison of effects of various roofing materials on navaids transmission distance. *International Journal of Engineering and Advanced Technology Studies Vol. 3 No. 2 pp. 1 – 16, June 2015*. European Centre for Research and Development. www.eajournals.org

E-2: Conference paper

Omusonga, R. J., Nyaanga, D. M., Githeko, J. M. and Chomba, B. K. (2015). Effects of selected roofing materials on air navigation signal strength. *Kabarak University 5^Th^ Annual International Conference. Symposium S2015-A, 14^th^ - 17^th^ July 2015.* Kabarak University, Nakuru Kenya. www.eserver.kabarak.ac.ke/index.php/conf05/conf05/paper/view/309