



**CHARACTERIZATION OF THE MULTIPATH ENVIRONMENT OF
THE GLOBAL NAVIGATION SATELLITE SYSTEM
RECEIVERS OVER UGANDA**

BY

BABIREKERE HELLEN

BU/GS19/MSP/2

**A RESEARCH DISSERTATION SUBMITTED TO THE DIRECTORATE OF
GRADUATE STUDIES, RESEARCH AND INNOVATIONS IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD
OF DEGREE OF MASTER OF SCIENCE IN PHYSICS
OF BUSITEMA UNIVERSITY**

OCTOBER , 2024

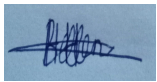
Declaration

I, the undersigned, affirm that this research dissertation is entirely my own work and has not been previously submitted to any academic institution for any award. Where other sources of information have been used, they have been acknowledged.

BABIREKERE HELLEN

BU/GS19/MSP/2

Signature:

A small, square, blue-tinted image showing a handwritten signature in dark ink. The signature is stylized and appears to be 'B. Hellen'.

Date: 21/11/2024

Approval

This research dissertation is presented in partial fulfillment for the award of degree of Master of Science in Physics of Busitema University, with the endorsement of the designated academic supervisors:

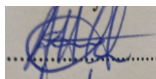
1. Dr. Andima Geoffrey

Department of Physics

Faculty of Science and Education

Busitema University

Signature:



Date: 22/11/2024

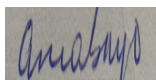
2. Assoc. Prof. Amabayo Emirant Bertillas

Department of Physics

Faculty of Science and Education

Busitema University

Signature:



Date: 22/11/2024

Dedication

This dissertation is dedicated to Bishop Owalu Joseph Anthony, my parents; Mrs. Mukama Ever and Mr. Mukama Anthony, and my sister Mrs. Tamale Justine.

Acknowledgement

First and foremost, I express gratitude to the Almighty God for blessing me with the invaluable gift of life, wisdom, good health, and supportive relatives.

I offer heartfelt appreciation to my supervisors, Dr. Andima Geoffrey and Assoc. Prof. Amabayo Emirant Bertillas, for their support, guidance, mentorship, moral assistance, and enrichment throughout my university studies. May God generously bless them in return. Similarly, I express my gratitude to all my lecturers for their educational, moral, and intellectual support throughout my course.

I would also like to express my heartfelt gratitude to the Eastern Africa Network for Women in Basic Sciences for their financial assistance, which played a crucial role in my successful completion of the university course.

I acknowledge Makerere University and Mbarara University of Science and Technology for providing the scintillation data used in the study. I thank the Crustal Dynamics Data Information System (CDDIS) for providing the IGS data that was downloaded.

I must express my gratitude to my parents, Mr. Mukama Anthony and Mrs. Mukama Ever, for their unwavering support, love, moral guidance, and financial assistance throughout my journey. I ask for God's blessings upon them, granting them long life and the opportunity to witness my success in life.

Special appreciation goes to all my classmates and coursemates; Waibi Rogers, Murami John Bosco and Mbayo Peter for proofreading my work and giving me helpful feedback. I extend my sincere appreciation to everyone who has provided me with advise and motivation to complete my studies, including my family, friends and colleagues.

Table of Contents

Declaration	i
Approval	ii
Dedication	iii
Acknowledgement	iv
Table of Contents	v
List of Figures	viii
List of Tables	ix
List of Acroynms and Abbreviations	x
Abstract	xii
Chapter 1: Introduction	1
1.1 Background	1
1.2 Statement of the Problem	3
1.3 Aim of the study	3
1.4 Objectives	3
1.5 Scope of study	4
1.6 Significance	4
Chapter 2: Literature Review	5
2.1 The Earth's Atmosphere	5
2.1.1 Earth's Atmospheric Layers	5
2.1.2 Troposphere	5
2.1.3 Mesosphere	8
2.1.4 Thermosphere	8
2.1.5 Exosphere	9
2.2 Ionosphere	10
2.2.1 Importance of the ionosphere	10
2.2.2 Production of the ionosphere	11

2.2.3	The structure of the ionosphere	11
2.2.4	Ionospheric Irregularities	14
2.2.5	Ionospheric Scintillation	16
2.2.6	Scintillation Proxy	19
2.3	Multipath	19
2.3.1	Multipath effects	21
2.3.2	Multipath mitigation	22
Chapter 3:	Materials and Methods	24
3.1	Data sources	24
3.2	Data processing	25
3.2.1	IGS Data	25
3.2.2	SCINDA Data	25
3.3	Methods used to analyze the data	26
3.3.1	Determination of obstacle structures in the vicinity of GNSS receivers .	26
3.3.2	Determination of signals that are affected by multipath	26
3.3.3	Determination of the azimuth dependent elevation threshold	27
Chapter 4:	Results and Discussion	29
4.1	Determination of the obstacle structures in the vicinity of the GNSS receivers .	29
4.2	Determination of signals affected by multipath	31
4.2.1	Variation of S4 with time for Mbarara–SCINDA	36
4.2.2	Variation of S4proxy with time for Mbarara-GPS	37
4.2.3	Variation of S4 with time for Makerere–SCINDA	37
4.2.4	Variation of S4proxy with time for Entebbe–GPS	39
4.2.5	Variation of S4proxy with time for Mt. Baker–GPS	40
4.3	Determination of the azimuth dependent elevation threshold	42
4.3.1	Occurrence percentage and mean occurrence of $S4 > 0.2$	42
4.3.2	Curve fitted on points with high and regular scintillations	46
4.3.3	Varying and fixed elevation threshold	49
Chapter 5:	Conclusions and Recommendations	52
5.1	Conclusion.	52

5.2 Recommendations for future research.	53
References	54

List of Figures

2.1	Earth's atmospheric layers	6
2.2	The structure of the ionosphere	12
2.3	The Multipath phenomenon	20
2.4	The Multipath effect	21
2.5	The GNSS receiver in an open place	22
3.1	Map of Uganda showing SCINDA and GPS receivers.	24
4.1	Variation of Azimuth with Elevation.	30
4.2	Diurnal variation of S4, S4proxy and elevation with time	32
4.3	Monthly variability of occurrence of amplitude scintillation over Mbarara in 2014.	34
4.4	Diurnal variation of S4, S4proxy and elevation with time	35
4.5	Variation of S4 with time for Mbarara—SCINDA for PRN 31.	36
4.6	Variation of S4proxy with time for Mbarara—GPS for PRN 22.	38
4.7	Variation of S4 with time for Makerere—SCINDA for PRN 18.	39
4.8	Variation of S4proxy with time for Entebbe—GPS (2011) for PRN 25.	40
4.9	Variation of S4proxy with time for Mt. Baker—GPS (2010) for PRN 18.	41
4.10	Occurrence percentage and mean occurrence of scintillations > 0.2	43
4.11	Curve fitted on the points with high and regular scintillation occurrence for both SCINDA and GPS receivers in Uganda.	47
4.12	Varying and fixed elevation threshold.	49

List of Tables

3.1	Location of SCINDA and GPS receiver stations in Uganda	25
4.1	Comparison between Varying and Fixed elevation threshold	50

List of Acroynms and Abbreviations

ADET	Azimuth Dependent Elevation Threshold
CDDIS	Crustal Dynamics Data Information System
C/NO	Carrier-to-Noise Ratio
DOD	Department of Defense
DOY	Day Of the Year
EIA	Equatorial Ionization Anomaly
Elv	Elevation
EPBs	Equatorial Plasma Bubbles
Es	Sporadic E
GIS	Geographical Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GW	Gravity Waves
HF	High Frequency
IGS	International GNSS service
LT	Local Time
NASA	National Aeronautics and Space Administration
PRE	Pre-Reversal enhancement
PRN	Pseudo-Random Number
PVT	Positioning, Velocity and Timing
RF	Radio Frequency
RINEX	Receiver INdependent EXchange
RTI	Rayleigh Taylor Instability
SCINDA	Scintillation Network Decision Aid
SNR	Signal to Noise Ratio
S4	Amplitude Scintillation Index
TEC	Total Electron Content

TIDs	Travelling Ionospheric Disturbances
TV	Television
USA	United States of America
UT	Universal Time
UV	UltraViolet
VHF	Very High Frequency

Abstract

Errors in the data tracked by the Global Navigation Satellite System (GNSS) receiver consist of errors from the satellites, errors from the propagation medium such as the ionosphere and multiple signal paths surrounding it, known as the multipath errors. Some efforts to curb multipath were made such as setting a fixed elevation cutoff for the receivers and placement of receivers in an open environment. However, this does not cater for the different heights of the obstacles in the receiver environment implying that a fixed cutoff elevation cannot be set for such environment. In addition, placement of receivers in an open environment may not be possible most especially in cities where there are many buildings and yet data from such places is also needed for ionospheric studies. Therefore, in this study the possibility of a variable elevation cutoff for each receiver environment in Uganda was investigated. Potential sources of multipath were first identified for the different receivers in Uganda. The results show that there exists a stationary object at an azimuth of 0° – 30° , 70° – 110° , 240° – 300° and 330° – 350° from Mbarara–GPS receiver. This object can block satellite signals as far as 20° elevation. Similarly for the case of the receiver at Entebbe, stationary objects exist at an azimuth of 0° – 20° and 220° – 330° . The stationary structures can obstruct satellite signals at an elevation of 0° – 20° . Basing on the variation of elevation against azimuth, obstacles at Mbarara–SCINDA exist at azimuth angles of 0° – 20° and 340° – 360° . For this receiver, the satellite paths were not visible at elevation angles of 10° – 20° . The receiver at Makerere has stationary obstacles at azimuth angles of 0° – 20° and 340° – 360° , as observed from the variation of elevation against azimuth for this receiver. The satellite signals were obstructed at elevation angles of 10° – 20° . Likewise, the receiver at Mt. Baker has obstacles at 0° – 140° azimuth. At elevation angles of 0° – 20° , the satellite signals were obstructed. Amplitude scintillation together with the S4proxy were used to identify multipath events in space and time. Before using the S4proxy, it was validated against amplitude scintillation from collocated receivers. The results show that majority of the scintillation events occurred between 18:00 Universal Time (UT) and 22:00 UT during the selected days of the year. These scintillations occurred during post sunset because they were initiated by the Rayleigh Taylor Instability (RTI) mechanism. This mechanism occurs when light plasma supports dense plasma.

The mechanism occurs in the F layer of the ionosphere. It is during post sunset that the bottomside of the F layer contains light plasma while the topside of the F layer contains denser plasma. This is because during that time, the ionosphere is high enough to overcome recombination of ions and electrons, thus making the topside F layer denser than the bottomside. When light plasma supports dense plasma, it becomes unstable, which makes the dense plasma to sink into it, while the light plasma to drift upwards. This creates a fluctuation in the electron density in the ionosphere, which causes ionospheric scintillations. The days considered in this study were selected on the basis that they had high scintillation occurrence for both amplitude scintillation and the S4proxy. The seasonal pattern reveals higher likelihood of occurrence of both amplitude scintillation and the proxy in the equinox months. The S4proxy highly correlate with the amplitude scintillation, with a correlation coefficient ranging between 0.8323 and 0.9312. The S4proxy was then used to characterise the environment of the receivers where scintillation monitors were not available. Multipath events were identified on the different satellite links. These events varied from one receiver to another, suggesting differences in the characteristics of the environment of the various receivers. The scintillation events around MBAR receiver were observed by satellite number 22 and took place between 5:00 UT and 6:00 UT on the DOY; 002, 003, 004, 005 and 006. Satellite number 22 was selected because it was in view for all the five consecutive days that were selected for the above receiver. The PRN 18 observed scintillation events near MAK occurring between 2:00 UT and 3:00 UT, spanning from Day of Year 041 to 045. Between Days of Year 003 and 007, PRN 25 detected scintillation events near EBBE from 2:00 UT to 4:00 UT. Similarly, PRN 18 observed scintillation events near BAKC on days 017 through 021 of the year. Satellite number 31 detected scintillation events near the MBA receiver from DOY 289 to 293 between 5:00 and 10:00 UT. These scintillations were observed by only one satellite at each station simply because that particular satellite was in view for all the five consecutive days that were selected for the scintillation occurrence. Amplitude scintillation was then mapped on an azimuth– elevation space to identify elevation threshold for each azimuth. The azimuth–elevation threshold values were then modeled using splines. The model was then used to determine the varying elevation threshold for each receiver. Comparing the varying elevation threshold with the fixed elevation threshold, more data was obtained using the varying elevation threshold and the quantity of that data varied from one receiver to another.

Chapter One

Introduction

1.1 Background

The Global Navigation Satellite System (GNSS) denotes the constellation of satellites transmitting positioning, navigation, and timing data from the satellites in space to GNSS receivers. The receivers then use this data to determine location ([Hofmann-Wellenhof et al., 2007](#)). The GNSS provides precise location information using the trilateration system. This system uses signals from multiple satellites to calculate the exact position of a receiver by measuring the time it takes for signals to travel from the satellites to the receiver ([Kumar et al., 2021](#)). In addition, the GNSS provides precise time information based on atomic clocks on the satellites. The accurate time provided by GNSS is used in applications such as telecommunications, financial transactions, and power grid management ([Xie et al., 2021](#)). [Ferreira et al. \(2020\)](#) says that the GNSS enables users to plan routes and provide real-time guidance for navigating from one location to another. The GNSS receivers calculate distances to satellites by measuring the time it takes for signals to travel from the satellites to the receiver. This time, multiplied by the speed of light, gives the distance ([Langley et al., 2017](#)). To determine the receiver's position, the system solves equations based on the distances from several satellites. These distances form spheres around each satellite, and the position is found where these spheres intersect ([Panchuk et al., 2018](#)). However, the GNSS is not perfect in its services because of the Constellation Satellite Error, the Signal Reception Error and the Propagation Error around the receiver known as the multipath error ([Karaim et al., 2018](#)). The phenomenon that involves the Global Positioning System (GPS) signal from the satellite reaching the receiver through various pathways, caused by reflections from nearby objects such as buildings, mountains and trees is known as multipath ([Braasch, 2017](#)). According to [Hunegnaw and Teferle \(2022\)](#), multipath is defined as an electromagnetic signal that reaches an antenna via an indirect route, resulting from the diffraction and reflection of the signal by nearby objects or surfaces in the antenna's vicinity. The primary factor contributing to multipath effects is the

proximity of the antenna to reflective structures, with its impact being more noticeable when the signal originates from a satellite at a low elevation angle (Granger and Simpson, 2008). Multipath effects are widely acknowledged as major error sources that compromise the precision of GNSS signals for navigation and positioning tasks. Teunissen (2020) says that the reflected signals travel a longer path compared to the direct signal. This added distance introduces extra time delay. Since GNSS receivers calculate position based on the time it takes for the signal to travel from the satellite to the receiver, this extra delay leads to inaccurate distance measurements and thus incorrect positioning. Additionally, the multipath signals diminish the reliability of GNSS data utilized in ionospheric research (Tang et al., 2021). Multipath causes the receiver to detect a combination of direct and reflected signals, which can distort the time of arrival measurements. For ionospheric studies, accurate time measurements are crucial for determining the total electron content (TEC) and other ionospheric parameters. Multipath errors introduce additional delays and distortions that can lead to incorrect TEC estimations (Gifford et al., 2020). Multipath errors also contribute to GNSS timing errors. Jin et al. (2014) stresses that GNSS timing relies on precise distance measurements between the satellite and the receiver. When a signal is reflected off a surface before reaching the receiver, it travels a longer path compared to the direct signal. This extra distance introduces an additional delay. Since GNSS receivers use the travel time of the signal to calculate the distance to the satellite, this increased delay results in an incorrect distance measurement, which skews the timing calculations. Multipath also causes errors in GNSS navigation measurements by introducing additional delays and interference into the signal, leading to inaccurate distance and position calculations. The reflected signals alter the time measurements used for distance estimation, which impacts the overall accuracy of the navigation system (De Paz et al., 2013). Multipath errors can also result in cycle slips, loss of satellite lock, or reduced accuracy in determining position (Bharadwaj and Vidyarthi, 2020). To mitigate the multipath effect, the antenna is positioned away from nearby objects whenever feasible (Aditya et al., 2018). Usually, conservative fixed-elevation thresholds ranging from 15° to 30° are employed to discard signals originating from low elevation angles. Nonetheless, these fixed-elevation masks fail to account for the specific environmental conditions surrounding a particular receiver antenna, such as the different heights of the obstacles. Utilizing a fixed-elevation cutoff angle results in the exclusion of valuable data linked to non-multipath signals and might not

eliminate all multipath errors originating from structures with elevation angles exceeding the fixed cutoff angle ([Atilaw, 2015](#)).

1.2 Statement of the Problem

Distortion of signals in the vicinity of the GNSS receiver due to multipath degrades the quality of data captured by the receiver. The reflected signals can cause interference with the direct signals, leading to errors in the calculated position. The scattered signals in the receiver environment may travel longer paths than the direct signals, introducing additional delay, which leads to errors in the timing. For ionospheric studies, accurate time measurements are crucial for determining ionospheric parameters such as TEC. The error in timing can lead to incorrect estimation of ionospheric parameters. Quality data need to be based on data that doesnot include signals that are scattered by stationary structures in the receiver environment. A fixed elevation cutoff has always been set for the receivers. However, this doesnot cater for the different heights of obstacles. In case it is used, corrupt data may be tracked by the receiver in the event that the obstacle has a higher elevation angle compared with the fixed elevation and at times useful data is eliminated by the receiver software when the fixed elevation is much higher than the elevation of the obstacles. Therefore, characterizing the receiver environment is paramount to improving the quality of the GNSS data. Basing on the obstacles present and their height, an azimuth dependent elevation threshold model for each receiver was determined in order to remove all the signals scattered by stationary obstacles in the receiver environment.

1.3 Aim of the study

To characterize the multipath environment of the GNSS receivers over Uganda.

1.4 Objectives

This study was guided by the following objectives:

- To determine the stationary objects that exist in the vicinity of the receiver.

- To determine signals that are affected by multipath.
- To determine a varying elevation threshold for each receiver.

1.5 Scope of study

The study took place in Uganda and focused on characterizing the multipath environment using the International Global Navigation Satellite System Service (IGS) receivers and Scintillation Network Decision Aid (SCINDA) receivers in the country for the years of 2010, 2011 and 2014.

1.6 Significance

The ionospheric data will help in space weather monitoring. Since the ionosphere interacts with solar wind and other space weather phenomena such as geomagnetic storms, monitoring ionospheric data helps in understanding and predicting space weather events that can affect satellites, communication systems and power grids on earth. The ionospheric data will help in ionospheric modelling. The ionosphere can affect observations in radio astronomy by causing signal distortion. Accurate ionospheric models and data helps in correcting these distortions and improving the quality of astronomical observations. The ionospheric data will help in undertaking scientific research about the ionosphere. Since the ionosphere is a complex and dynamic layer of the atmosphere, studying about it helps scientists to understand ionospheric dynamics, processes and their interaction with the solar system. Ionospheric data will be used to correct errors in the GPS signals, thus improving the precision of navigation systems. Accurate ionospheric data will help in predicting and mitigating ionospheric effects such as scintillations thus ensuring reliable communication.

Chapter Two

Literature Review

2.1 The Earth's Atmosphere

The Earth's atmosphere comprises a narrow swath of air delineated by various layers determined by temperature ([Ustin and Middleton, 2021](#)). Without this shielding layer, life on Earth would be impossible, as it shields us from the heat and radiation emitted by the sun and contains the air essential for breathing. While oxygen is essential for life on Earth, it is not the predominant element in our atmosphere. The earth's atmosphere is composed of approximately 78% nitrogen, 21% oxygen, 0.93% Argon, 0.04% carbon dioxide, neon, helium, methane, krypton, ozone, hydrogen and water vapor ([Huddart and Stott, 2020](#)). Although the proportion of most gases remains consistent at low altitudes, the atmospheric pressure decreases as altitude increases ([Grocott et al., 2009](#)). Atmospheric pressure decreases with altitude primarily due to the decreasing density of air molecules as you move higher in the atmosphere. This decrease occurs because the weight of the air above decreases with altitude, resulting in lower pressure exerted on objects at higher elevations.

2.1.1 Earth's Atmospheric Layers

The Earth's atmosphere is segmented into distinct layers, delineated by variations in temperature corresponding to changes in altitude. The boundaries between the layers are not rigidly defined and may exhibit some degree of variation ([Schubert et al., 2001](#)).

2.1.2 Troposphere

The troposphere represents Earth's lowest atmospheric layer. It begins from the Earth's surface and extends up to approximately 18 kilometers, a range that varies based on factors such as latitude, longitude, and seasons ([Mohanakumar, 2008](#)). It holds 75% of the total mass of the



Figure 2.1: Earth's atmospheric layers
Adapted from <https://www.dreamstime.com/earth-atmosphere>

Earth's atmosphere and 99% of the total mass of water vapor, making it the primary location for most weather phenomena (Barry and Chorley, 2009). In the troposphere, temperature typically decreases as altitude rises due to the predominant heating mechanism, which involves energy transfer from the Earth's surface. Typically, the warmest part of the troposphere is found at its lowest section (Fueglistaler et al., 2009). The troposphere's density surpasses that of all its atmospheric layers above it due to the greater atmospheric weight exerted on it, resulting in its most significant compression (Hocking et al., 2016). Vertical mixing plays a crucial role in the troposphere. The decline in temperature with altitude follows a predictable pattern because the air near the surface is warmed, becoming lighter, while the air higher up cools towards space, becoming denser (Wallace and Hobbs, 2006). Vertical mixing refers to the process by which air, heat, moisture, and other atmospheric properties are mixed vertically within the troposphere, the lowest layer of Earth's atmosphere. This mixing occurs due to various factors

such as convection, turbulence, and mechanical mixing caused by atmospheric processes like wind shear. It plays a significant role in redistributing heat, moisture, and pollutants throughout the troposphere, influencing weather patterns, atmospheric stability, and air quality (Haynes, 1999). The troposphere, the layer where we reside, encompasses all the air we breathe and the clouds that adorn the sky. The tropopause, situated at the upper boundary of the troposphere, serves as the functional dividing line between the troposphere and the stratosphere. At the equator, this layer is found at an altitude of 18 km, while at the poles, it occurs at only 8 km above the surface (Mohanakumar, 2008). Due to the tropopause being an inversion layer where air temperature rises with altitude, the temperature at the tropopause remains consistent, resulting in the highest concentration of nitrogen within this layer (Birner et al., 2006). The stratosphere stretches from above the troposphere to approximately 50 kilometers in altitude. Beyond the tropopause, temperatures ascend with altitude (Mohanakumar, 2008). The temperature rise with altitude stems from the absorption of the Sun's ultraviolet (UV) radiation by the ozone layer. Roughly 10% of the atmospheric mass resides in the stratosphere (Sen Mandi and Sen Mandi, 2016). The temperature elevation observed with altitude in the stratosphere occurs due to solar heating, whereby ultraviolet radiation within the wavelength range of 0.200 to 0.242 micrometers dissociates diatomic oxygen (O_2). The consequent bonding of individual oxygen atoms to O_2 results in the formation of ozone (O_3) (Ramaswamy et al., 2001). Radiation of high frequency, such as X-rays, ultraviolet, and gamma rays, poses harm to living tissues. This has the potential to induce the transformation of cells into cancerous ones. Absence of ozone in the stratosphere would result in sunlight's UV radiation harming all living organisms on Earth. Due to its low water vapor content, the stratosphere is characterized by very dry air, resulting in a scarcity of clouds within this region (Williamson et al., 2019). Commercial airplanes fly within the stratosphere to evade the turbulence typically found in the troposphere. Hence, the stratosphere exhibits a consistent temperature pattern, whereby temperatures rise with altitude owing to the ozone layer's presence. This layer absorbs and disperses UV radiation from the Sun, acting as a protective barrier for life on our planet (Sharman et al., 2012).

2.1.3 Mesosphere

This refers to the upper atmospheric region located approximately 50 to 80 kilometers above Earth's surface ([Allen, 2009](#)). Being at high altitudes, the mesosphere contains thin air that is not suitable for human breathing. The atmosphere of this layer consists of oxygen, nitrogen, and carbondioxide, all mixed together rather than stratified according to their respective masses ([Palmer, 2017](#)). The mesosphere stands as the chilliest realm within Earth's atmosphere, boasting exceedingly low temperatures plummeting to as cold as -100°C at its upper limit. Its notable characteristic is the decline in temperature as altitude increases. This occurs because the stratosphere serves as the heat source. The extremely limited water vapor found at the uppermost part of the mesosphere gives rise to noctilucent clouds, the highest clouds in Earth's atmosphere ([Gadsden, 1998](#)). When space rocks descend toward Earth, it is within the mesosphere that they incinerate. If any space rocks manage to breach the mesosphere and hit Earth's surface, they are referred to as meteorites upon impact. The mesosphere layer acts as a shield, safeguarding the Earth from large meteoroids ([Inglezakis, 2016](#)). Friction occurring in the mesosphere leads to the combustion of meteors. Afterward, they break apart into tiny fragments of dust. These fragments are observed as ionized trails left behind by the remnants of meteors with our eyes. Being characterized by exceedingly low air pressure and temperatures, this region is where meteors burn up upon entry because of the scarcity of air molecules ([Langowski, 2016](#)). Within the mesosphere lies a layer called the ionosphere, which reflects radio waves, enabling long-distance communication. This property of the mesosphere is essential for applications such as high-frequency radio and television and satellite communications ([Folkestad, 2013](#)). The mesopause begins at an altitude of 80 kilometers. At this altitude, there is a shift from the mesosphere to the thermosphere. The altitude where the mesopause is located experiences the lowest temperature before it rises with altitude in the thermosphere ([Venkat Ratnam et al., 2010](#)).

2.1.4 Thermosphere

The thickest atmospheric layer is the thermosphere, extending from approximately 80 kilometers to around 550 kilometers in altitude ([Emmert, 2015](#)). In the thermosphere, temperatures increase as altitude rises. The temperature rise occurs due to the absorption of energetic UV and X-ray

radiation emitted by the sun ([Mishra and Dubey, 2018](#)). The thermosphere consists of atmospheric gases. The primary constituents include atomic oxygen, atomic helium, and atomic nitrogen. Here, turbulence within the atmosphere thoroughly mixes the various types of gas molecules together. In the thermosphere, rare collisions between gas particles result in the separation of gases based on their chemical elements ([Rohli et al., 2021](#)). The thermosphere experiences very high temperatures, reaching up to 2,000 °C. Despite its temperature of 2,000 °C, the thermosphere's low density means it doesn't feel hot. The absorbed ionizing radiation also creates the ionosphere. Shortwave radio waves can be reflected by the Kennelly-Heaviside layer, allowing them to reach distant areas of the Earth. Therefore, this layer plays a crucial role in radio communication ([Liu et al., 2010](#)). The ionosphere's reflection and absorption of radio waves enable the reception of shortwave radio broadcasts on the Earth's surface from distant locations around the globe ([Daniel et al., 2016](#)). Ionization of molecules in this layer results from exposure to UV radiation, gamma rays, and X-rays emitted by the Sun. Its temperature varies with solar activity. As outer space is generally regarded to commence at 62 miles above the Earth's surface, the thermosphere could be seen as a component of space ([Daniel, 2002](#)). The International Space Station orbits Earth within the thermosphere. The low Earth orbit satellites are also located within this region ([Brown et al., 2021](#)).

2.1.5 Exosphere

The exosphere constitutes the outermost region of the atmosphere. It encompasses a portion of the thermosphere ranging from approximately 500 km to 190,000 km ([Hassan, 2022](#)). The rapid movement of molecules in the exosphere leads to temperatures estimated to be in the thousands of degrees Celsius ([Madhusudhan, 2019](#)). Heat transfer doesn't occur within the exosphere due to its sparse particle density, which is insufficient for collisions and interactions to take place ([Bruinsma et al., 2023](#)). The exosphere primarily consists of lighter gases. For instance, it is mainly comprised of a thin layer of gases such as hydrogen and helium ([Helling, 2019](#)). Heavier gases like carbon dioxide and atomic oxygen are found closer to the lower boundary of the exosphere ([Valeille et al., 2010](#)). The exosphere hosts the majority of satellite orbits. This encompasses the majority of GPS, telecommunication, and weather satellites. These satellites, which continually observe outer space and Earth, reside within the exosphere ([Sibiya, 2016](#)).

Particles within the exosphere are under the influence of Earth's gravity, but those moving at high speeds can escape, gradually leaking out of the atmosphere. The majority of gas particles trace a curved trajectory without coming into contact with other particles ([Tian, 2015](#)).

2.2 Ionosphere

This is the region of the earth's upper atmosphere which is about 60–1000 km from the earth's surface with high enough charged ions and free electrons to significantly affect radio wave propagation and GPS signal travel ([Atiq, 2018](#)). A fascinating layer known as the ionosphere intersects with the mesosphere, thermosphere, and exosphere ([Malins, 2019](#)). The ionosphere is a dynamic segment of the atmosphere, expanding and contracting in response to the solar energy it absorbs. Its designation originates from the phenomenon whereby gases in these layers become energized by solar radiation, resulting in the formation of ions with electrical charges ([Council et al., 2004](#)). The ionosphere is characterized as the segment of Earth's atmosphere that becomes ionized due to solar and cosmic radiation ([Velinov et al., 2013](#)). The Sun's upper atmosphere, the corona, is very hot and produces a constant stream of plasma, UV and X-rays that flow out from the Sun and ionize the Earth's ionosphere ([Koskinen, 2011](#)). During nighttime, cosmic rays ionize the ionosphere, although their effect is not as pronounced as that of the Sun. These high-energy rays stem from various sources within our galaxy and the wider universe, including rotating neutron stars, supernovae, radio galaxies, quasars, and black holes ([Liu et al., 2011](#)).

2.2.1 Importance of the ionosphere

The ionosphere plays a crucial role as it reflects and alters radio waves utilized in communication and navigation ([Bora, 2017](#)). It hosts all the charged particles present in the Earth's atmosphere. The earth's ionosphere overlaps the top of the atmosphere and the very beginning of space. The Sun heats gases in the ionosphere until they shed one or more electrons, resulting in a multitude of electrically charged particles ([Shuman et al., 2015](#)). The ionosphere marks the boundary between Earth's atmosphere and outer space. The ionosphere delineates the border between the lower atmosphere of Earth, where life exists and the air that is breathed, and the void of space ([Eddy, 2009](#)). The ionosphere undergoes continual fluctuations. Due to its formation

through the ionization of particles by the Sun's energy, the ionosphere undergoes alterations from Earth's daytime to nighttime regions. As night approaches, the ionosphere becomes less dense as previously ionized particles return to a neutral state through relaxation and recombination (Elmunim et al., 2021). This border with space is precisely where numerous Earth-orbiting satellites, such as the International Space Station, are located. This implies that these satellites may experience the impact of the ever-changing conditions within the ionosphere, including abrupt surges of charged particles that elevate drag on satellites and reduce their orbital durations (Li, 2020). The ionosphere also contributes to our everyday communication and navigation systems. Radio and GPS signals either pass through this atmospheric layer or depend on reflecting off the ionosphere to reach their intended destinations. In either scenario, alterations in the density and composition of the ionosphere can disturb these signals (Komjathy, 2023). Weather phenomena on Earth, such as hurricanes or extensive thunderstorm systems, can generate pressure waves that propagate upward into the ionosphere. This is among the factors that can lead to alterations in the ionosphere (Borchevkina et al., 2020).

2.2.2 Production of the ionosphere

The primary formation of the ionosphere results from solar electromagnetic radiation via a process known as photoionization, hence the highest densities of the ionosphere are located on the daytime side. Nevertheless, during the night, the ionosphere persists to some extent as the time it takes for ions and electrons to recombine is similar to the Earth's rotation rate (Elmunim et al., 2021). The rate of recombination relies on the background density. As a result, it is elevated at lower altitudes and diminishes as altitude increases. The level of ionization is established by the equilibrium between the generation of ions (photoionization) and their loss (recombination) (Chan et al., 2012).

2.2.3 The structure of the ionosphere

Due to the varying physical characteristics and chemical processes involved in ionosphere formation at different altitudes, the ionosphere is segmented into four distinct layers, namely D, E, F1, and F2, arranged from bottom to top (Gulyaeva and Bilitza, 2012). This is observed in Figure

2.2.

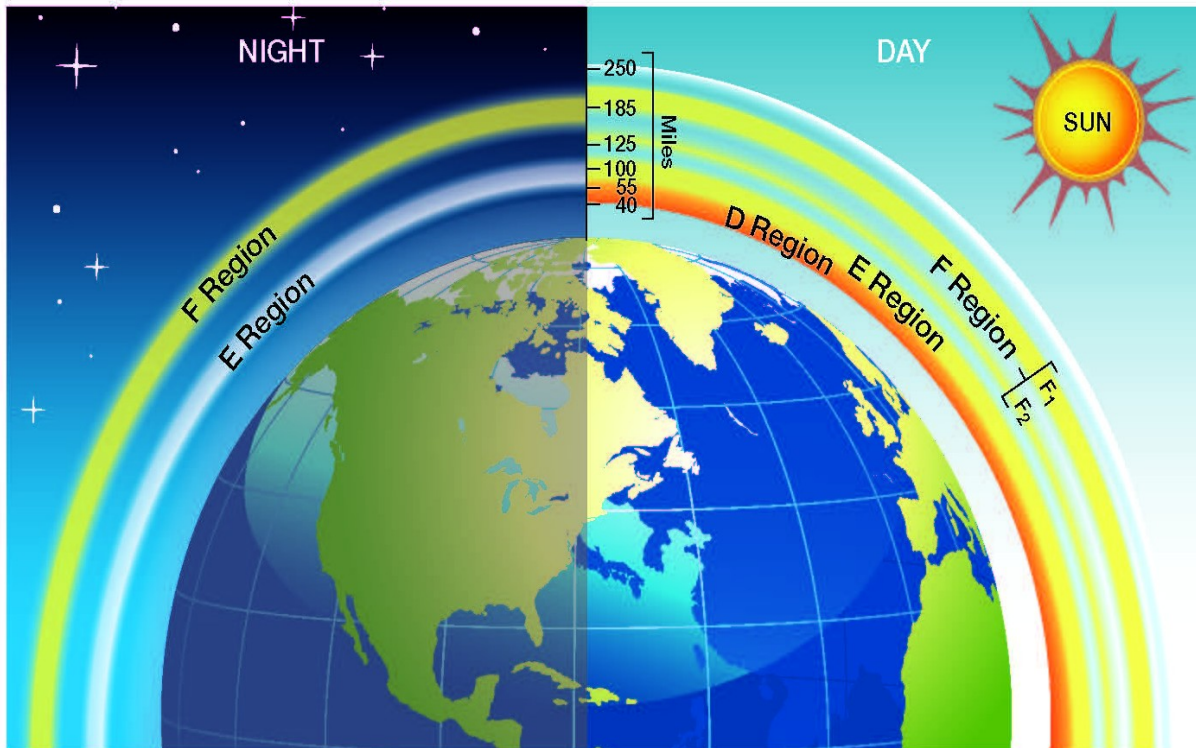


Figure 2.2: The structure of the ionosphere
(Budden, 2009)

2.2.3.1 The D region

The D region, situated at altitudes of approximately 50 to 90 km, represents the lowest segment of the ionosphere, extending into the mesosphere (Ridley et al., 2006). Solar UV photons ionizing nitric oxide (NO) molecules constitute the primary ionization source in the D region (Bailey et al., 2002). In times of solar maximum activity, air molecules, consisting of molecular nitrogen and oxygen, are ionized by solar hard X-rays. Furthermore, ionization occurs at this altitude due to cosmic rays (Velinov et al., 2013). It accumulates at sunrise, dissipates at sundown, and achieves its peak ionization density at midday. The D-layer is present exclusively during daylight hours (Shulha, 2016). Due to the relatively high neutral density in the D region, recombination occurs at a significant rate (Hellmann et al., 2003). Hence, the D region is predominantly active only during daytime, although residual ionization from cosmic rays persists at night. The D region exhibits the lowest level of ionization among all ionospheric regions (Atiq, 2018). Its daytime presence enables radio waves to penetrate deeper into the ionosphere. The D-layer experiences low ionization due to diminished penetration of ultraviolet light at this altitude (Daniel et al.,

2016). The D layer primarily absorbs High Frequency (HF) radio waves, especially below 10 MHz, with absorption decreasing as the frequency increases. Absorption levels are minimal during nighttime and peak around midday (Atiq, 2018).

2.2.3.2 The E region

The region immediately above in altitude is known as the E region, also referred to as the Kennelly–Heaviside layer (Kenrick and Jen, 1929). Extending from 90 to 120 km, the E region is created by the ionization of molecular oxygen through either low-energy (soft X-rays) or UV solar radiation (Bhardwaj et al., 2007). The E layer can reflect radio waves only if their frequencies are below approximately 10 MHz (Norton, 1937). Throughout daylight hours, peak ionization occurs around local midday and largely diminishes during nighttime. Depending on latitude, the E-region will either nearly vanish entirely during the night or persist with very minimal ionization (Bristow, 1992). The E-layer also exhibits another remarkable phenomenon known as sporadic E (Es). The Es region is an ionospheric layer characterized by a high electron density and narrow altitude range, typically observed at around 100 km altitude. At times, the density is sufficiently high to allow reflection and propagation of Very High Frequency (VHF) radio waves from the ground beyond the radio horizon (Chu et al., 2009). Sporadic E layers can develop when space debris disintegrates in the ionosphere, generating a cluster of intensely ionized electron density. The Es occurs when concentrated patches of ionization emerge within the E region of the ionosphere (Deacon, 2023). The degree of ionization can reach up to approximately five times the levels observed during the peak of a sunspot cycle, when they typically attain their maximum (Hathaway, 2015). The heightened ionization levels induced by Sporadic E allow signals extending deep into the VHF spectrum to be refracted by these ionized clouds (Deacon et al., 2020). The exceedingly elevated levels of ionization within the clouds reflect any signals within the HF segment of the radio spectrum. This could hinder their progression to the upper F regions, consequently limiting their potential to cover significantly greater distances. In such situations, short-range signals are observed instead of the anticipated longer-range signals. As this region is less dense than the D-layer, the recombination rate is also slightly reduced. As a result, the electron density is elevated, and the decline following sunset is less abrupt (Adekoya et al., 2015).

2.2.3.3 The F region

The most densely populated portion of the ionosphere is the F region, stretching from 120 km and typically reaching its zenith at 300 km (Goodman, 2005). The F region is present both during the day and at night. During daylight hours, it undergoes ionization from solar radiation, while during nighttime, it experiences ionization from cosmic rays (Reid, 1976). In daylight, it divides the layer into two segments. The lower section commences at around an altitude of approximately 120 km, forming the “F1-LAYER”. The upper segment commences around an altitude of about 200 km, forming the “F2-LAYER” (Witvliet, 2015). The F1-layer is considerably weaker and has a minor impact on propagation. It behaves in a manner more similar to the E-layer than the F2-region. The peak ionization of the F1-layer typically occurs around local noon. The degree of ionization in the F1 layer fluctuates similarly to the E-layer, relying on the elevation of the sun (Klimenko et al., 2012). The F2-layer persists both during day and night and can sustain sky wave propagation at certain HF almost continuously (Wagner and Goldstein, 1985). This layer is the most resilient and fully ionized of all, making it the most crucial contributor to short-wave signal propagation. Electron recombination happens at a slower pace in the F-region compared to the D and E-regions, as it is the least dense of the three layers (Golubkov et al., 2014). This implies that the unbound electrons must cover a greater distance before being attracted to an ion. Just before sunrise, we observe the lowest electron density (Schunk and Walker, 1973). Following sunrise, ionization levels rise, reaching the average ionization level within 1 to 2 hours. Throughout the night, despite a reduced ionization level, the F-layer remains suitable for our lower frequency bands. In daylight hours, the F-layer proves highly beneficial for the HF bands (Nicolls, 2006). The F layer stands as the uppermost prominent layer in the ionosphere, with its central portion boasting the highest electron density in Earth’s atmosphere. This is the primary area where HF radiation from beneath is refracted downward (Utlaut, 1975).

2.2.4 Ionospheric Irregularities

Ionospheric irregularities refer to disturbances in electron density on a small scale, exhibiting irregular variations spanning from a few meters to several tens of kilometers (Ossakow, 1979). These irregularities include among others Sporadic E, Spread F, Equatorial Plasma Bubbles

(EPBs), and Traveling Ionospheric Disturbances (TIDs).

2.2.4.1 The Sporadic E Irregularities

The small-sized irregularities that occur in the E region of the ionosphere shortly after noon are referred to as sporadic E irregularities. Mostly appearing during daylight hours, particularly in the afternoon, these irregularities manifest in various shapes and sizes ([Fejer and Kelley, 1980](#)). Wind shear effectively converges metallic ions to form a thin layer, leading to the production of Es ([Haldoupis, 2011](#)). Wind shear refers to the change in wind speed or direction with altitude, typically occurring in the atmosphere. It can be horizontal or vertical and is often associated with weather phenomena such as thunderstorms, turbulence, and the formation of atmospheric layers like the Es layer in the ionosphere ([Council et al., 1983](#)). Vertical wind shear is typically considered the primary cause of Es layer formation. At times, the Es layer can negatively impact the positioning accuracy of GPS satellites by causing unusual delays in microwave signals due to ionospheric anomalies. Additionally, the Es layer leads to extraordinary long-distance propagation of VHF waves ([Cerruti, 2007](#)). The problem with extraordinary long-distance propagation of VHF waves is that it can interfere with communication systems and disrupt signal reliability, leading to inaccuracies or disruptions in transmission ([Sim, 2002](#)).

2.2.4.2 The Spread F irregularities

The plasma irregularities that typically occur in the F layer of the ionosphere shortly after sunset are referred to as spread F irregularities. It arises from plasma instability primarily in the equatorial region of the ionosphere, commonly identified as the Rayleigh–Taylor instability (RTI) ([Abdu, 2001](#)). In the ionosphere, the RTI refers to a phenomenon where the denser plasma at higher altitudes sinks into the lighter plasma below, leading to the formation of irregularities in the plasma distribution. This instability is often observed in the equatorial region of the ionosphere after sunset, contributing to the occurrence of spread F irregularities ([Bagiya, 2010](#)). Traditionally, the detection of diffused F-region echoes on ionograms is referred to as spread-F, a term coined upon the initial observation of F-region ionogram traces ([Wright et al., 1996](#)). This phenomenon primarily occurs during nighttime, typically before midnight, except under magnetically disturbed conditions. It is confined to a region approximately 30° – 40° wide,

centered around the magnetic equator ([Lanzerotti, 2007](#)). The Spread-F generates significant coherent echoes. Coherent echoes produced by spread F refer to strong and stable radar or ionospheric signals that maintain a consistent phase relationship with the transmitted signal, indicating significant reflection from the irregularities in the F layer of the ionosphere ([Rodrigues, 2008](#)). The presence of spread F irregularities can result in disturbances to satellite operations, communication networks, navigation systems, and electrical power grids, potentially resulting in extensive economic losses ([Abdu, 2001](#)).

2.2.4.3 The Equatorial Plasma Bubbles

Equatorial plasma bubbles are defined as areas extending vertically from the lower boundary of the equatorial F region, characterized by notably reduced plasma density compared to the surrounding ionosphere ([Abdu et al., 1983](#)). Equatorial plasma bubble irregularities are formed via the generalized RTI in the F region's bottom side of the ionosphere during the post-sunset period ([Timoçin et al., 2020](#)). These irregularities scatter radio waves emitted by celestial radio sources, resulting in variations in both the phase and amplitude of the received signal ([Tenerelli et al., 2008](#)).

2.2.4.4 The Travelling Ionospheric Disturbances

The TIDs manifest as wave-like characteristics within the ionosphere. The TIDs result from gravity waves (GW) in the thermosphere and plasma instabilities in the ionosphere ([Fritts and Lund, 2011](#)). Travelling ionospheric disturbances can lead to swift variations in both the amplitude and phase of GNSS signals. The fluctuations in the signal can greatly affect the positional accuracy of GNSS and the performance of communication and navigation systems ([Atabati et al., 2019](#)).

2.2.5 Ionospheric Scintillation

Scintillations refer to rapid changes in both the phase and amplitude of the wave ([Yeh and Liu, 1982](#)). Ionospheric scintillations are swift temporal variations in both the amplitude and phase of trans-ionospheric GNSS signals, resulting from the scattering of irregularities in electron distribution encountered along the radio propagation path ([Oke and Akala, 2009](#)). Primarily, these scintillations occur within the F layer ([Martin and Aarons, 1977](#)). Ionospheric scintillation varies

depending on solar activity, geomagnetic activity, the time of year, local time, and geographic location (Jiao and Morton, 2015).

2.2.5.1 Types of scintillations

The GPS measurements exhibit two types of ionospheric scintillation and they include amplitude scintillations and phase scintillations. (Beach and Kintner, 2001)

2.2.5.2 Amplitude scintillations

Amplitude scintillation refers to the swift variations in the signal intensity as detected by a receiver (Xu et al., 2018). Amplitude Scintillation is quantified using the amplitude scintillation index (S4). The S4 is defined as the normalized standard deviation of signal intensity measured at 50Hz over a one-minute period and is given by;

$$S4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}} \quad (2.1)$$

Where I is the signal intensity and $\langle \rangle$ is the mean value of the signal intensity. This index quantifies the swift fluctuations in radio wave signal amplitudes attributed to small-scale structures of ionospheric irregularities within the ionosphere (Hunsucker, 1982). Intense amplitude scintillation lowers the signal-to-Noise Ratio (SNR) at the GPS receiver, resulting in the received signal intensity falling below the receiver's lock threshold. This necessitates the receiver to re-establish the signal, resulting in errors in both GPS carrier measurements and GPS code (Kintner et al., 2007). The SNR is a measure used in communication systems to quantify the strength of the desired signal compared to the level of background noise present in the signal. It represents the ratio of the power of the signal to the power of the noise, typically expressed in decibels (dB). A higher SNR indicates a stronger, clearer signal relative to the noise, while a lower SNR indicates a weaker, more difficult-to-distinguish signal amidst the noise (Tandra and Sahai, 2008).

2.2.5.3 Phase scintillations

Phase scintillation is defined as the rapid fluctuations in carrier-phase measurements (Bhattacharyya et al., 2000). Phase scintillation is quantified using the index known as the phase scintillation index (σ_ϕ). The phase scintillation index σ_ϕ is basically a standard deviation of carrier-phase measurements. Nevertheless, there is a trend in carrier-phase measurements related to the variation in geometric range (Mushini et al., 2012). As a result, it is necessary to detrend the carrier—phase measurements initially. Defining ϕ' as the detrended carrier—phase measurements, σ_ϕ can be defined as:

$$\sigma_\phi = \sqrt{\langle \phi'^2 \rangle - \langle \phi' \rangle^2} \quad (2.2)$$

Phase scintillation can lead GPS receiver systems to lose signal lock as a result of abrupt fluctuations in signal frequency. The errors in apparent range rate can induce changes in Doppler shift within GPS signals. If the shift surpasses the bandwidth of the phase lock loop (PLL), it leads to the phase lock being lost (Razavi et al., 2008).

2.2.5.4 Causes of scintillations

The primary cause of scintillation is the localized fluctuation in ionospheric electron density. In equatorial regions of the ionosphere, following local evening, there occurs a sudden reduction in ionospheric density that migrates from near the equator towards higher latitudes. Ionospheric scintillation arises from random electron density irregularities that disperse the wave (Priyadarshi, 2015). These variations stem from rapid local changes in the refractive index of the medium through which the wave travels (Clifford, 2005).

2.2.5.5 Effects of scintillation

Intense ionospheric scintillation conditions may hinder a GPS receiver from acquiring signal lock and render position calculation impossible. Milder scintillation conditions can diminish both the accuracy and confidence in positioning outcomes. When signal fluctuations become sufficiently intense, GPS receivers may fail to track signals from GPS satellites, resulting in loss of lock, which could amplify navigation errors or lead to navigation failure (Carrano et al., 2005). Ionospheric disturbances significantly impact radio communication systems, thereby restricting

the receiver system's ability to effectively integrate weak signals coherently (Xu et al., 2004).

2.2.6 Scintillation Proxy

This proxy is referred to as S4proxy. This proxy is derived from the S1 observable that records the Carrier-to-Noise Ratio (C/No) on the L1 GPS frequency. It is expressed in dB (Olowendo and Cilliers, 2018). The C/No refers to the ratio of the power of the received GPS satellite signal carrier wave to the power of the background noise in the receiver's bandwidth. It measures the strength of the GPS signal relative to the noise present in the environment. A higher C/No indicates a stronger GPS signal and typically correlates with better positioning accuracy and reliability. GPS receivers use C/No measurements to assess the quality of satellite signals and to determine the satellites' visibility and suitability for navigation and positioning purposes (Balaei et al., 2006). The S1 observable is converted from dB to absolute values by means of the equation;

$$S_1(abs) = 10^{\frac{(S_1)}{10}} \quad (2.3)$$

The proxy index for scintillation, S4proxy, is subsequently calculated from the normalized standard deviation of S1 observations as follows:

$$S4_{proxy} = \sqrt{\frac{\langle S_1^2 \rangle - \langle S_1 \rangle^2}{\langle S_1 \rangle^2}} \quad (2.4)$$

The averaging described in equation (2.4) is performed over a typical period of 5 minutes. This definition closely resembles that of the S4, except that the amplitude is replaced by the C/No. If the noise level remains constant throughout the observation period, equation (2.4) can be demonstrated to simplify to the definition of the traditional S4 (Beach and Kintner, 1999).

2.3 Multipath

Multipath is a phenomenon that occurs when a signal from the satellite arrives at the receiver through one or multiple alternative paths, in addition to the direct path (Braasch, 2017). This is observed in Figure 2.3. The multipath phenomenon arises when GPS signals reach an antenna through various paths, caused by reflections or diffraction from nearby objects like the ground,

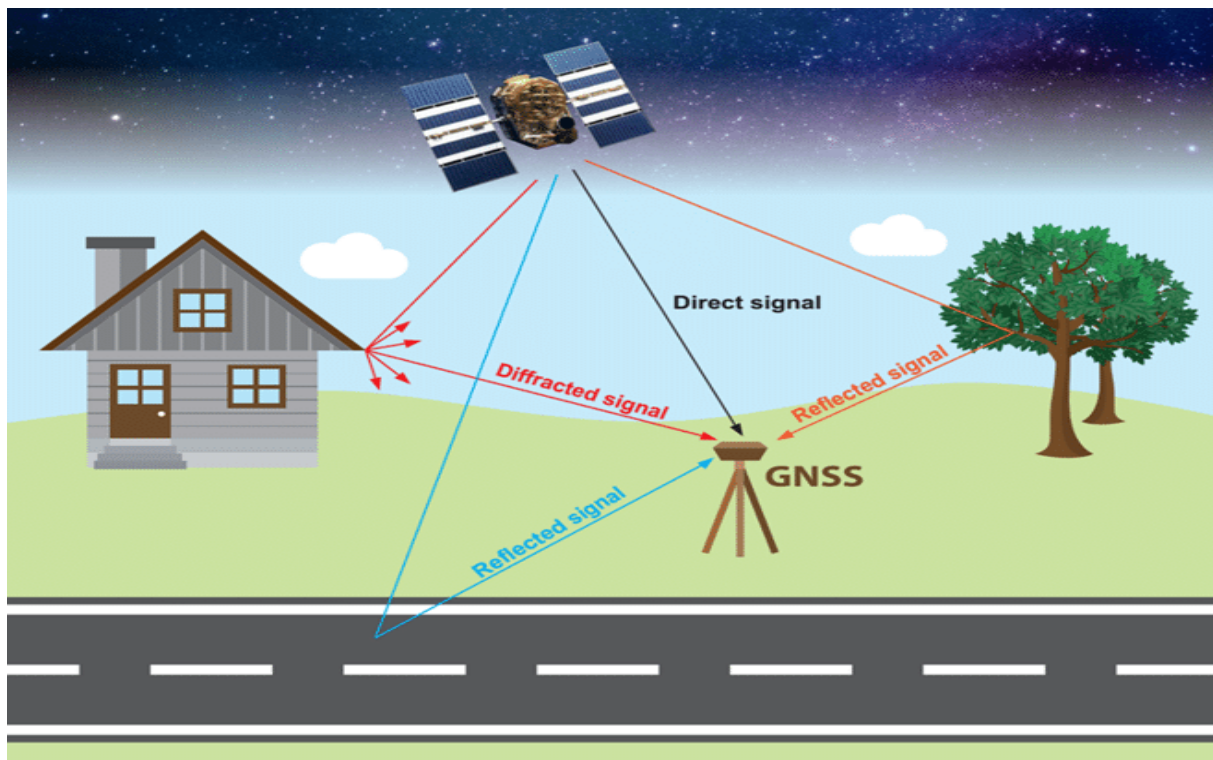


Figure 2.3: The Multipath phenomenon
 Adapted <https://www.NASA.com/multipath-mitigation-technology>

buildings, vehicles, trees, and so forth. The primary signal, typically the strongest at the receiving antenna, travels directly from the transmitter to the receiver. Conversely, indirect signals, arriving after the direct ray, tend to be weaker in power because they follow more convoluted paths to reach the receiving antenna (Islam, 2019). Reflection happens when an electromagnetic wave strikes an object, such as the Earth's surface, a building, a car, etc., and bounces. Diffraction happens when the incoming signal bends as it interacts with an obstacle in its path. Scattering happens when the incoming signal spreads as it passes through a medium filled with objects, such as leaves on a tree, which are small relative to the wavelength of the signal. All these phenomena contribute to multipath since they generate signals that propagate along paths different from the line-of-sight path (Andrews, 2023). Multipath is widely acknowledged as a significant source of error associated with GPS positioning (Hannah, 2001). The impact of multipath error on positioning remains consistent on a daily basis for the same baseline due to its dependence on receiver-satellite geometry (Wang et al., 2016). reported that signals received from satellites with low elevation angles are more prone to multipath effects compared to signals from satellites with high elevation angles. Therefore, the multipath effect is primarily contingent on two factors: the surrounding environment of the GNSS antenna, including the type and quality of the antenna,

and the geometry of the satellites.

2.3.1 Multipath effects

Multipath propagation diminishes the accuracy of GNSS positioning (Closas et al., 2009). This is because some signals do not reach the receiver leading to inadequate data collected by the receiver and other signals arrive at the receiver with a certain time delay in comparison with the direct signal (Fishler and Poor, 2004). This was illustrated using figure 2.4. In the presence of

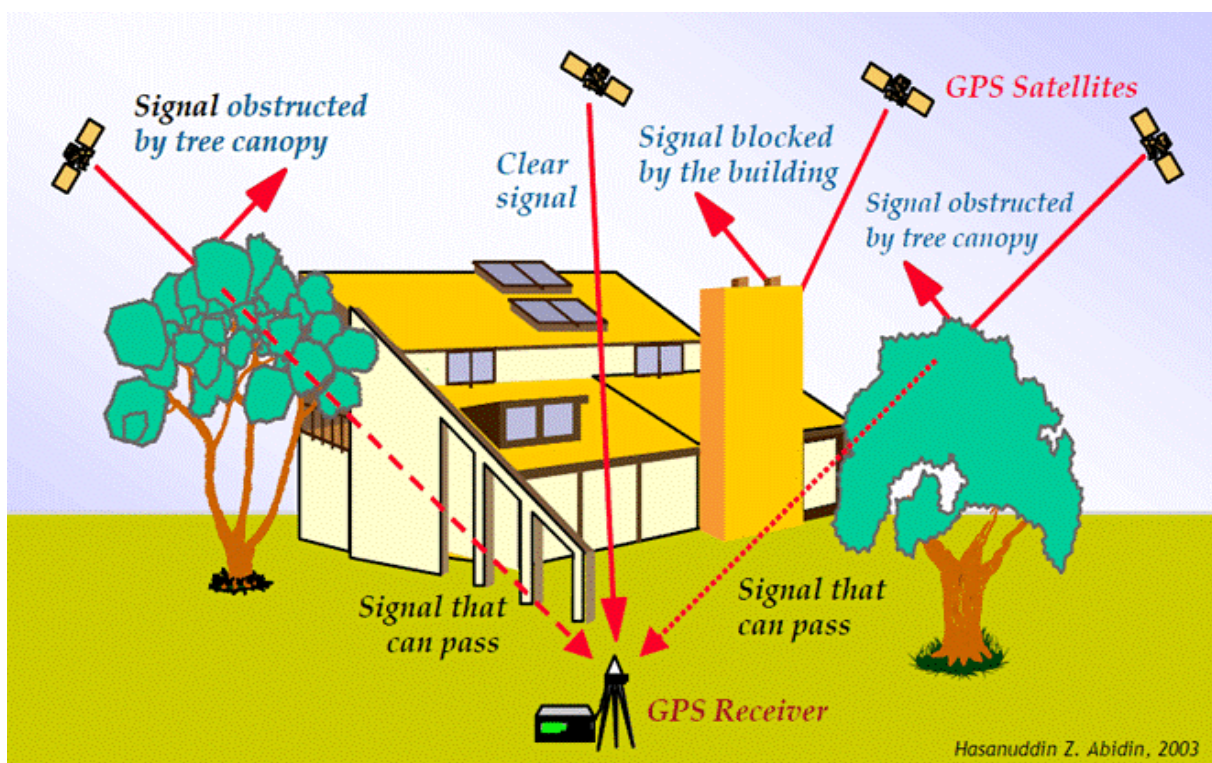


Figure 2.4: The Multipath effect

Adapted from <https://www.researchgate.net/figure/Multipath-propagation>

multipath signals, the correlation peak in the receiver becomes distorted, leading to errors in the pseudo-range calculated by the receiver (Wu et al., 2019). The correlation peak of a GNSS receiver refers to the highest point in the correlation function generated by comparing the received signal with a locally generated replica of the expected signal. This peak indicates the degree of similarity between the received and expected signals, helping to determine the timing and phase information necessary for accurate positioning (Fernandez-Prades et al., 2016). Pseudo-range is a measurement used in satellite-based navigation systems, such as GPS. It represents the estimated distance between a receiver and a satellite based on the time it takes for the satellite's signal to

travel to the receiver. Despite its name, it's not a true geometric range because it includes errors caused by factors like clock discrepancies between the receiver and satellite, atmospheric delays, and multipath effects (Mosavi et al., 2013). Multipath leads to increase in the signal strength as well as signal fading due to interference of both the direct and indirect signals. When a reflected signal arrives at the receiver in phase with the direct signal, it will cause constructive interference which will increase the strength of the signal, while destructive interference occurs when they are out of phase, which causes signal fading (Atilaw, 2015).

2.3.2 Multipath mitigation

Siting the antenna appropriately and removing or altering reflective structures near the antenna is the simplest and most effective method to enhance signal quality. An open field serves as an optimal environment for antenna placement, and positioning the antenna closer to the ground can additionally reduce observed multipath errors (Macnamara, 2010). This was depicted by figure 2.5. As the horizon primarily contributes to multipath effects, diminishing multipath errors can



Figure 2.5: The GNSS receiver in an open place
Adapted from <https://www.usgs.gov/media/images/campaign-gps-antenna>.

be accomplished by elevating the cutoff angle for received signals, typically to 15° to 30° above

the horizon (Atilaw, 2015). The horizon is the apparent line that separates the Earth's surface from the sky when viewed from a specific location. It marks the limit of one's sight, beyond which the ground or objects are not visible due to the curvature of the Earth (Mark and Sinha, 2020). Furthermore, it is customary to only take into account the contribution from observations at elevation angles, computed from the receiver to the chosen satellite, exceeding a specified threshold, usually ranging from 15° to 30° . Excluding measurements taken at low elevation angles aids in maintaining a high SNR and removing non-ionospheric related effects, such as multipath (Beach, 1998). However, obtaining an open environment may not be possible in every place and yet data from congested places is also needed for ionospheric studies. In addition, setting a fixed elevation is not very effective since the receiver environments are different. Therefore, the most outstanding mitigation approach is using a varying elevation threshold since it applies in all receiver environments (Atilaw, 2015).

2.3.2.1 Cubic spline

Being a piecewise polynomial function consisting of multiple polynomials, the cubic splines provide a smooth approximation of the data both at equal and unequal intervals implying that high sampling rates can be used where changes are rapid and low sampling rates can be used where changes are slow (Perperoglou et al., 2019). For the interval between two adjacent data points, a cubic spline function is defined as;

$$G_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3 \quad (2.5)$$

where $i = 0, 1, 2, \dots, n - 1$

n = data points

$x - x_i$ = interval between two data points

The coefficients a_i , b_i , c_i and d_i are unknown and can be determined based on the following constraints. Each spline must pass through the given data points. The interior data points between each spline must be continuous. The first and second derivatives of the splines must be continuous across the interior data points. The boundary conditions must be applied on the first and second derivatives of the splines (Knott, 1999).

Chapter Three

Materials and Methods

3.1 Data sources

The IGS data for receivers located at Mount Baker, Entebbe and Mbarara with station codes of BAKC, EBBE, and MBAR respectively, for the years 2010, 2011 and 2014 was obtained from the Crustal Dynamics Data Information System (CDDIS). The S4proxy was derived from the S1 observable. The S1 observable is the Signal- to-Noise ratio that is derived from the GPS L1 frequency of the amplitude fluctuation of the satellite signal. The “S1” is a specific type of observable in the RINEX observation file that represents the first signal that a receiver can track (Olwendo and Cilliers, 2018). The SCINDA data utilized in this study was sourced from SCINDA receivers located at Makerere and Mbarara, with station codes of MAK and MBA. Figure 3.1 and Table 3.1 show the geographical location of the receivers used in the study.

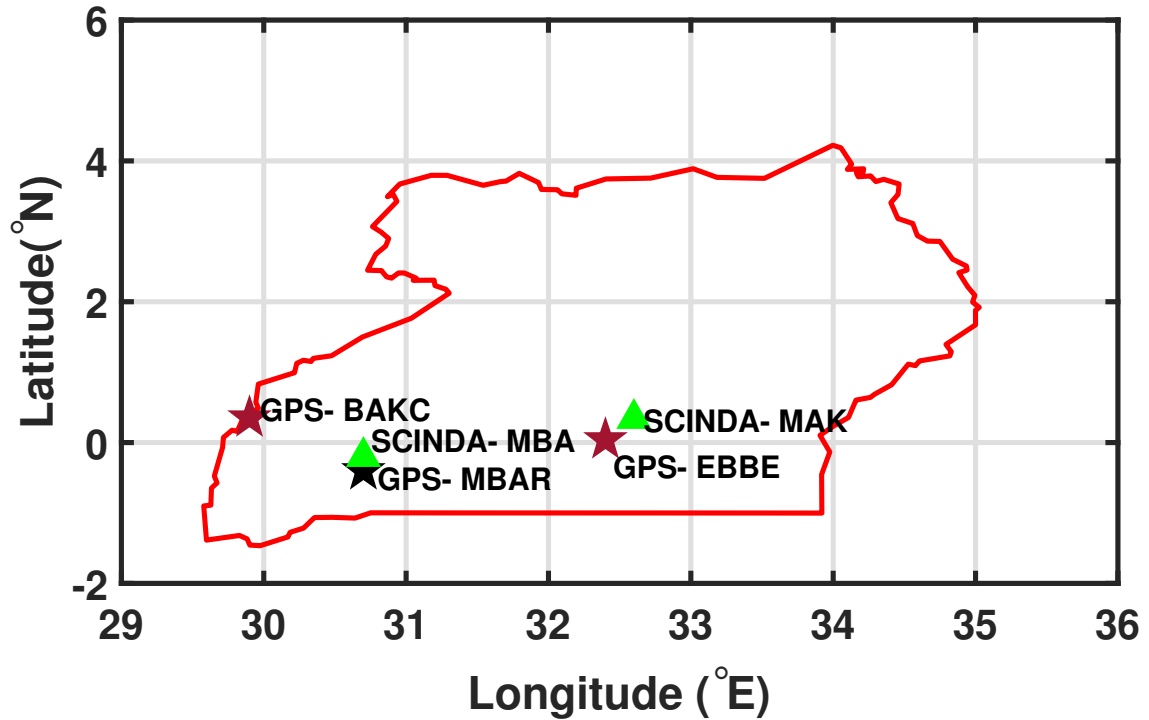


Figure 3.1: Map of Uganda showing SCINDA and GPS receivers.

Table 3.1: Location of SCINDA and GPS receiver stations in Uganda

Station	Station ID	Geographic		Geomagnetic	
		Long (⁰ E)	Lat (⁰ N)	Long (⁰ E)	Lat (⁰ N)
SCINDA					
Makerere	MAK	32.57	0.34	104.87	-9.71
Mbarara	MBA	30.66	-0.62	102.83	-11.03
IGS					
Mbarara	MBAR	30.74	-0.60	102.36	-11.00
Entebbe	EBBE	32.44	0.04	104.10	-10.07
Mt. Baker	BAKC	29.89	0.35	102.23	-10.63

3.2 Data processing

3.2.1 IGS Data

The IGS data was processed using the GPS-TEC analysis program (version 3.03) by converting the GPS data saved in the Receiver INdependent EXchange (RINEX) format into files with extension .CMN. This software can be downloaded from GOPI Krishina Seemala blog website ³ (Li et al., 2018). At extraction level, the lower and upper scintillation thresholds were fixed at 0.10 and 1.20 respectively for filtering out the amplitude scintillation values (Poda, 2021). The GPS-TEC software has an algorithm that processes the RINEX files, estimates and removes biases and writes the data in ASII format (Cors Espinal, 2021). This ASCII output file is in 10 columns separated by a tab, which is created in the same folder as the data, with filename "STATddd-YYY-MM-DD.CMN" (Bryant and Harrison, 2013). The output was recorded after every time interval of 30 s. A matlab function that outputs amplitude measurements from the GPS RINEX observation files was used to obtain the S4proxy data, using the formula in equation 2.4 which is in chapter two.

3.2.2 SCINDA Data

The scintillation data obtained from the SCINDA receiver stations located at Makerere University with station code MAK and Mbarara University of Science and Technology with station code MBA, was processed using the GPS-TEC software program. This program converts scintillation

³<http://seemala.blogspot.com>

data, contained in ionospheric scintillation monitor (ism) format into files with extension .CMN. Subsequently, the processed data was used to calculate the amplitude scintillation index, using equation 2.1. According to [Kornilov et al. \(2012\)](#), the background noise and outliers were filtered out of the data by defining the lower and upper scintillation thresholds at 0.10 and 1.20 respectively.

3.3 Methods used to analyze the data

3.3.1 Determination of obstacle structures in the vicinity of GNSS receivers

The method employed to determine structures responsible for multipath involved analyzing the satellite visibility in the azimuth-elevation space. These two parameters were selected because they offer the most accurate positioning. Therefore, at every azimuth with corresponding elevation, the satellites in view were identified. Stationary structures that cause multipath were identified to exist in the areas where the satellites were not visible at low elevation angles. This is because these areas contained structures that blocked the signals from reaching the receiver.

3.3.2 Determination of signals that are affected by multipath

The characterization of the multipath environment involved gathering daily data from each station over the course of a year. Due to presence of only two SCINDA receivers in the region of study, there was need to use a proxy for amplitude scintillation, it is referred to as the S4proxy in this study. Before it was used, it was first validated with amplitude scintillation from a collocated receiver. This was done by comparing the diurnal and seasonal patterns, and then computing the correlation coefficient at a 95% confidence level. This was done to determine the degree of the relationship between amplitude scintillation and the S4proxy. To determine the monthly characteristics, the percentage occurrence of scintillations for the selected months was used. Equation 3.1 was used to calculate the percentage occurrence of the scintillation events.

$$\text{Percentage of Occurrence} = \frac{\text{Actual Observations}}{\text{Total number of observations}} \times 100\% \quad (3.1)$$

Where the actual observations represent the scintillation events exceeding the threshold, and the total number of observations encompasses all scintillation events that occurred during the entire month. To identify signals affected by multipath, amplitude scintillation was varied with time over a span of five (5) consecutive days in order to distinguish multipath signals from those linked to ionospheric scintillations, as the latter are inconsistent in their appearance. The study considered the five consecutive days because that time span was sufficient to filter out signals caused by ionospheric scintillations since the ionospheric electron density cannot remain uniform for all that time. Identifying signals affected by multipath was guided by the occurrence of amplitude scintillation at nearly identical times over the course of five consecutive days, indicating a shift in the satellite path. For the case of receivers where no Scintillation data was available, the S4proxy was used.

3.3.3 Determination of the azimuth dependent elevation threshold

To determine the varying elevation threshold, the occurrence percentage of amplitude scintillation greater than the threshold value of 0.2 was varied on an azimuth–elevation map. This method was used in order to identify the areas with scintillation values greater than 0.2. The threshold value of 0.2 was adopted for this study such that any scintillation value below it could be considered as the receiver background noise. The mean amplitude scintillation was also varied on an azimuth–elevation map as a method of obtaining the areas with regular scintillation occurrence. These areas were the centre of interest because they contained signals scattered by stationary structures around the receivers. Finally the method of cubic spline was employed in this study to fit a curve to the points with regular scintillation occurrence because it creates a curve that aligns the true data dynamics, reflecting how the data smoothly transition between known data points, offering a high degree of precision and realism (Daly, 2000). A set of data points through which a piecewise cubic polynomial curve passed was determined. These data points were denoted as (x_i, y_i) , where $i = 0, 1, 2, \dots, n$. The data points considered had the highest mean scintillation occurrence at each point in the azimuth – elevation space. The cubic spline involved constructing piecewise cubic polynomials between each pair of adjacent data points. At each interval, a cubic polynomial model was assumed as shown in equation 2.5, Where $G_i(x)$ is the cubic spline function for the interval $[x_i, x_{i+1}]$. At junction points (knots), the model ensured that the spline

passed through each given data point in order to ensure continuity of the curve. The derivatives up to the second order were continuous at each knot to avoid abrupt changes in the curvature. The cubic spline ensured that the resulting piecewise function was not only continuous but also smooth, making it a powerful model for interpolating data points effectively.

Chapter Four

Results and Discussion

4.1 Determination of the obstacle structures in the vicinity of the GNSS receivers

Figure 4.1 shows that there are no satellites visible in the southern direction, corresponding to an azimuth of 180^0 . This is due to the 55^0 inclination of GPS satellites ([Santerre, 1991](#)). This means that the orbit of GPS satellites is tilted at an angle of 55 degrees to the Earth's equatorial plane. This inclination allows the satellites to cover a wide range of latitudes, ensuring global coverage for the GPS system ([Hugentobler and Montenbruck, 2017](#)). The minimum elevation angle required for satellite visibility was contingent upon the receiver's horizon. The minimum elevation profile of each receiver was depicted by blank areas below the visibility curves. The receivers at Makerere and Mbarara— SCINDA had a minimum elevation angle for satellite visibility referred to as the built in cutoff elevation angle of ten degrees (10^0) while the rest of the receivers had a built in cutoff angle of zero degrees (0^0). Figure 4.1 presents the variation of elevation with azimuth for Mbarara—SCINDA, Mbarara—IGS, Makerere—SCINDA, Entebbe—IGS and Mt. Baker—IGS receivers.

The figure displays the satellite visibility observed from receivers in Uganda over the course of one month, selected from each of the years of 2010, 2011 and 2014 . Given that the aim of this study was to characterize the multipath environment surrounding the receiver, the elevation angle threshold was set to zero, even though the minimum built-in elevation angle for GPS satellite visibility at the selected stations was typically set above zero degrees. In areas where there were vacant spaces most especially at low elevation angles, it indicated the absence of visible satellites, suggesting the presence of obstacles such as stationary structures that contribute to multipath interference. For Mbarara—IGS receiver, the stationary obstacles were observed at an azimuth of $240^0 - 330^0$, at elevation between 0^0 and 20^0 . The satellite paths were not visible at an azimuth of

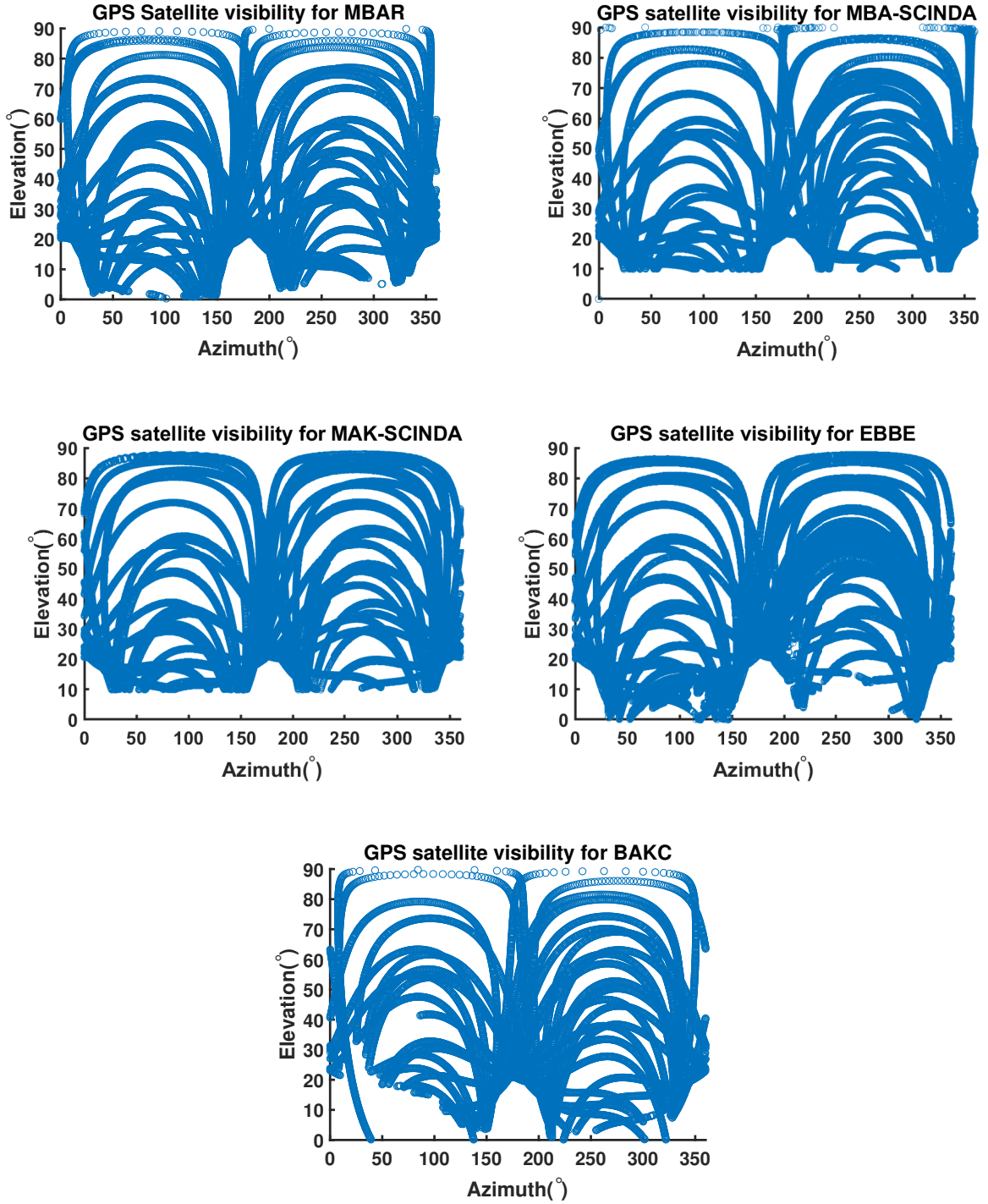


Figure 4.1: Variation of Azimuth with Elevation.

$0^{\circ} - 30^{\circ}$ and $330^{\circ} - 360^{\circ}$ at elevation between 0° and 20° . This is due to the inclination angle of the GPS satellites. Likewise for Mbarara–SCINDA receiver, the satellite paths were not visible at azimuth of $0^{\circ} - 20^{\circ}$ and $340^{\circ} - 360^{\circ}$ at an elevation of $10^{\circ} - 20^{\circ}$. Similarly, the satellite paths in the vicinity of Makerere–SCINDA receiver were not observed at an azimuth of $0^{\circ} - 20^{\circ}$ and $340^{\circ} - 360^{\circ}$ at an elevation ranging between $10^{\circ} - 20^{\circ}$ while the satellite paths near Entebbe–IGS

receiver were not found at an azimuth of 0° – 30° and 350° – 360° . The stationary structures were observed at azimuth of 50° – 120° and 220° – 330° , at elevation ranging between 0° and 20° . Finally, the obstacles identified near Mt. Baker–IGS receiver were found at an azimuth of 40° – 140° , while satellite paths were not visible at 340° – 360° at an elevation ranging between 0° and 20° . The stationary sources of multipath were not determined at the same position in all the receiver environments. This is because the receivers were installed in different locations in Uganda and each location was characterised by unique features. It was also noticed that blank spaces also existed at high elevation angles. Those blank spaces were attributed to the presence of ionospheric irregularities (Nguyen et al., 2021).

4.2 Determination of signals affected by multipath

To determine the fluctuations that can be attributed to multipath, amplitude scintillation and its proxy were used. The proxy was first validated. The validation was done on a diurnal basis, monthly basis and then the correlation coefficient was calculated. Data for 2014 from the Mbarara–SCINDA receiver collocated with the GPS receiver was used. The data sets from 2014 were selected due to their availability from both receivers. Figure 4.2 illustrates the diurnal variation of amplitude scintillation and S4proxy acquired from MBA and MBAR for the selected days of the year 116, 118, 120, and 136 in 2014. These days were selected basing on the fact that they had high scintillation occurrence for both amplitude scintillation and the S4proxy. For this study, scintillation values below 0.2 and above 1.0 were not considered. The scintillation values below 0.2 were categorized as background noise while those exceeding 1.0 were treated as outliers (Dravins et al., 1997). The existence of a significant noise level reaching up to 0.2 may be linked to disturbances caused by solar activities in the ionosphere, given the fact that data from the solar maximum year of 2014 was utilized (Yasyukevich et al., 2020). Hence, scintillation values above 0.2 to 1.0 were regarded as meaningful. Scintillation events were categorized as weak if their values fell between 0.2 and 0.3, whereas values above 0.3 to 1.0 were designated as strong scintillations. It can be observed that the SCINDA receivers show day time scintillations. This is because they are specifically designed to monitor and study ionospheric scintillations, thus they are highly sensitive to variations in the ionosphere (Olwendo et al., 2016). Meanwhile, GPS

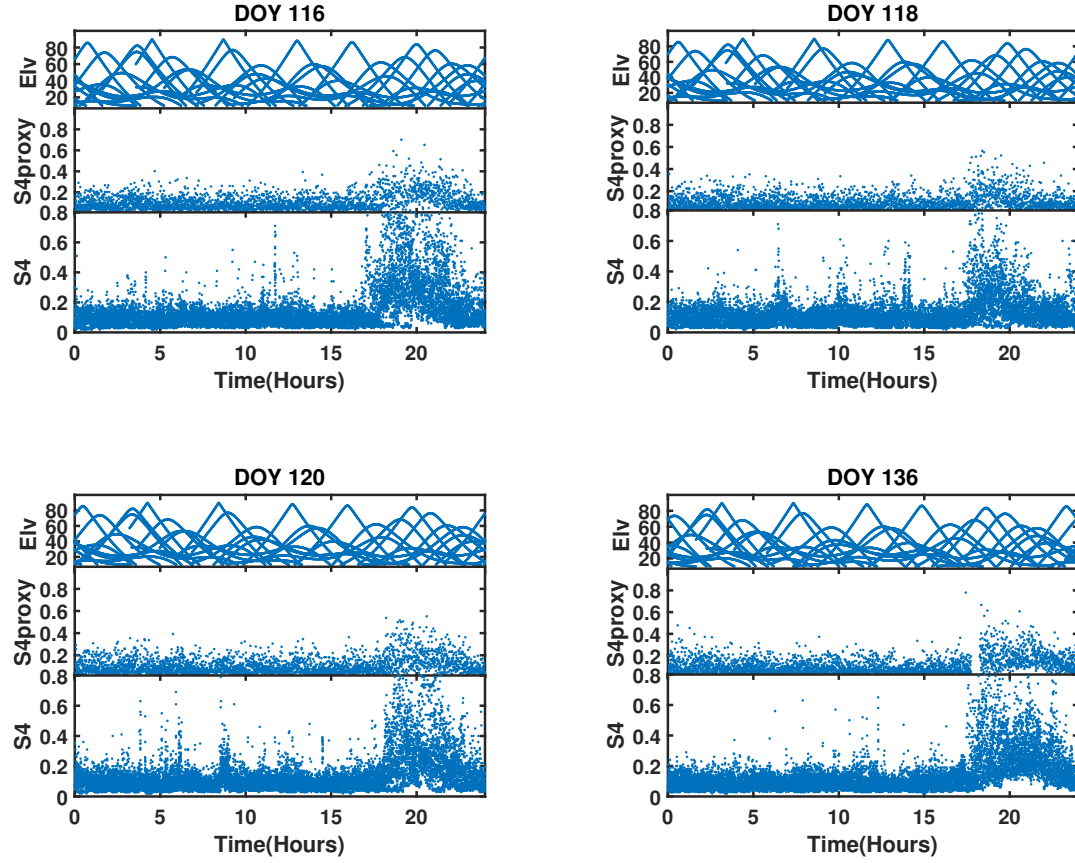


Figure 4.2: Diurnal variation of S4, S4proxy and elevation with time

receivers do not show day time scintillations. This is because the GPS receivers are designed to provide accurate positioning information and are generally less sensitive to scintillations compared to SCINDA receivers (Andima et al., 2020). Figure 4.2 demonstrates notable scintillation occurrences recorded over Uganda during the four days of the year, from 17:00 to 24:00 UT. These results were in agreement with those of (Abiriga et al, 2021). Local time (LT) = Universal time (UT) + 3 hours. During day 116 of the year, it was noted that significant scintillations commenced at 17:00 UT, peaked to 0.8 by 20:00 UT, and gradually declined to 0.4 by 24:00 UT. Similarly, with S4proxy, scintillation activity escalated from 17:00 UT, reaching a peak of approximately 0.4 at 20:00 UT, before gradually subsiding to around 0.2 by 24:00 UT. At elevation angles below 30° , numerous satellite paths were present, whereas at elevation angles exceeding 30° , satellite paths were few. This occurred because stationary structures at low elevation angles diffract signals, resulting in numerous paths, whereas at high elevation angles, the absence of such structures leads to fewer paths (Pérez-Fontán et al., 1998). On day 118, significant scintillation levels were observed, reaching nearly 0.8 at 18:00 UT, before gradually diminishing to a range between 0.4

and 0.6 as the time approached 24:00 UT. Meanwhile, the S4proxy reached its peak of 0.5 at 18:00 UT and declined to 0.2 by 24:00 UT. Likewise, on day 120, significant scintillation occurred with S4 reaching 0.8 between 18:00 UT and 22:00 UT, followed by a decline to 0.4 by 24:00 UT. This result is in line with that of [Jurua et al. \(2024\)](#). Similarly, the S4proxy increased at 18:00 UT until 22:00 UT, before decreasing to 0.2 by 24:00 UT. On day 136, there were notable instances of strong scintillation, reaching a peak of 0.8 at 18:00 UT and maintaining high levels until 22:00 UT, before decreasing to 0.2 by 24:00 UT. During the same day, the S4proxy peaked to 0.5 at 18:00 UT and sustained high levels until 22:00 UT, before declining to 0.3 by 24:00 UT. Hence, the majority of scintillation events took place between 18:00 UT and 22:00 UT, indicating that scintillation predominantly occurs during nighttime. These findings align with those reported by [Chatterjee et al. \(2013\)](#). Daytime scintillations observed may be linked to tropospheric effects, such as atmospheric gravity waves ([Booker, 1979](#)). The scintillation events witnessed after sunset and before sunrise were caused by irregularities in the ionosphere. The irregularities in the ionosphere responsible for scintillations in low latitude regions have been linked to plasma drifts, neutral winds, and the pre-reversal enhancement (PRE) of the equatorial eastward electric field. The factors contributing to ionospheric irregularities in this region mainly occur after sunset and are not primarily influenced by transient solar activities, as they can occur even during periods of geomagnetic calm ([Ogwala et al., 2022](#)). The strong scintillation occurrences could also be explained by the placement of the two receivers situated in western Uganda. According to [Hide and Roberts \(1961\)](#), this region is known for its weak geomagnetic field strength. Western Uganda is located near the geographic equator. At the equator, the magnetic field lines run parallel to the Earth's surface, thus the magnetic field is spread out over a larger area compared to higher latitudes where the field lines are more perpendicular to the Earth's surface. As a result, the magnetic field strength decreases at the equator ([Rastogi and Patel, 1975](#)). Basing on the RTI growth equation, the vertical component of plasma drift rises as the magnetic field strength decreases. This triggers the onset of significant ionospheric irregularities, which in turn result in ionospheric scintillations ([Kashchenko et al., 2021](#)). The observed daytime ionospheric scintillations occur due to the daytime equatorial eastward dynamo electric fields generated in the E region by thermospheric winds, which frequently diffuse along magnetic field lines to altitudes in the F region. During the daytime, these electric fields induce upward plasma drift, initiating

the formation of ionospheric irregularities responsible for the occurrence of scintillations (Abdu, 2005).

To further veridate the S4proxy, its monthly variation was compared with that of amplitude scintillation observed from the receivers collocated in the same region. In Figure 4.3, the percentage occurrence of scintillations for months where both the SCINDA and IGS datasets were accessible was shown. According to figure 4.3, the percentage occurrence of amplitude scintillation is higher

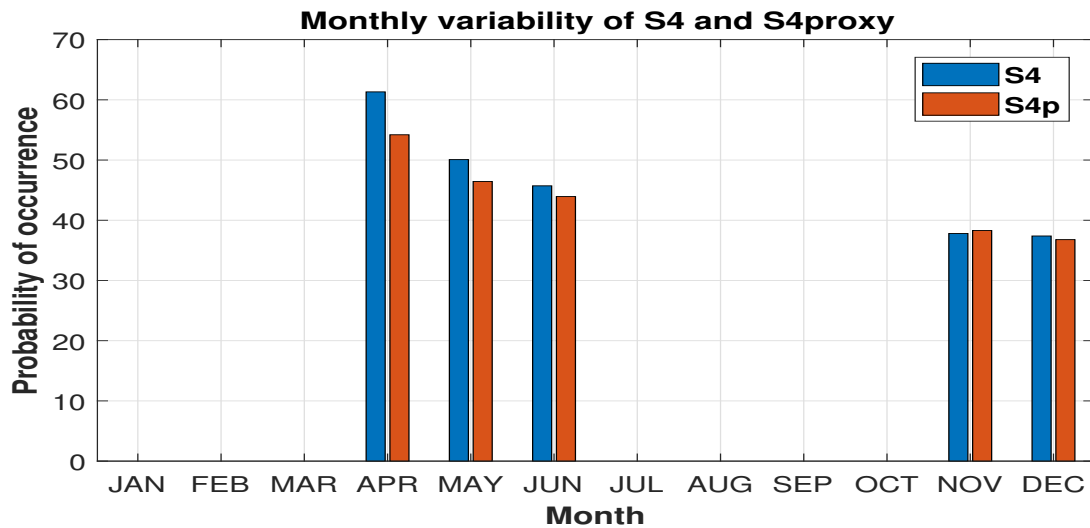


Figure 4.3: Monthly variability of occurrence of amplitude scintillation over Mbarara in 2014.

in equinox months and lower in solstice months. During the equinox months, there was increased ionization in the low latitude ionosphere due to the Sun being directly overhead the Equator. As a result of the PRE, the vertical plasma drift experiences significant strengthening. This establishes favorable conditions for the RTI mechanism to trigger the formation of ionospheric irregularities responsible for the scintillation occurrence (Sousasantos et al., 2018). The fluctuations occur less frequently during the solstice months of November and December because the ionosphere experiences reduced ionization, attributed to the Sun's position away from the Equator, resulting in their low percentage of occurrence (Balan et al., 2018). Hence, scintillation peaks are observed during the Equinox months of March–April and September–October, whereas the lowest occurrences of scintillations were noted during the solstice months of June–July and November–December (Srinivasu et al., 2018). Figure 4.3 shows that the percentage occurrence of amplitude scintillation in April was 60 using the amplitude scintillation data, whereas that using S4proxy was 55. During May, the percentage occurrence of S4 was 49, whereas that of S4proxy was 47. During June, the percentage occurrence of amplitude scintillation was 48,

while that of the proxy was 47. Observations indicated that during the months of November and December, the percentage occurrence of both amplitude scintillation and the proxy was 39. In general, the percentage occurrence of both amplitude scintillation and the proxy was similar during the chosen months. These results are in agreement with those of [Chatterjee et al. \(2013\)](#). Therefore, the S4proxy was used in the study when amplitude scintillation data was unavailable.

For additional validation of the S4proxy's efficacy in detecting ionospheric scintillations, the correlation coefficient, R , was computed at a 95% confidence level. Figure 4.4 shows the correlation between S4 and S4proxy using data gathered on days 116, 118, 120, and 136 of the year. The least squares method was used to determine the line of best fit, aiming to illustrate a precise relationship between S4 and S4proxy. In this study, an R value below 0.4 was deemed indicative of a low linear correlation between S4 and S4proxy, while an R value between 0.4 and 0.7 signified a high correlation, and an R value exceeding 0.7 indicated a very high linear correlation between amplitude scintillation and S4proxy. According to Figure 4.4, the correlation

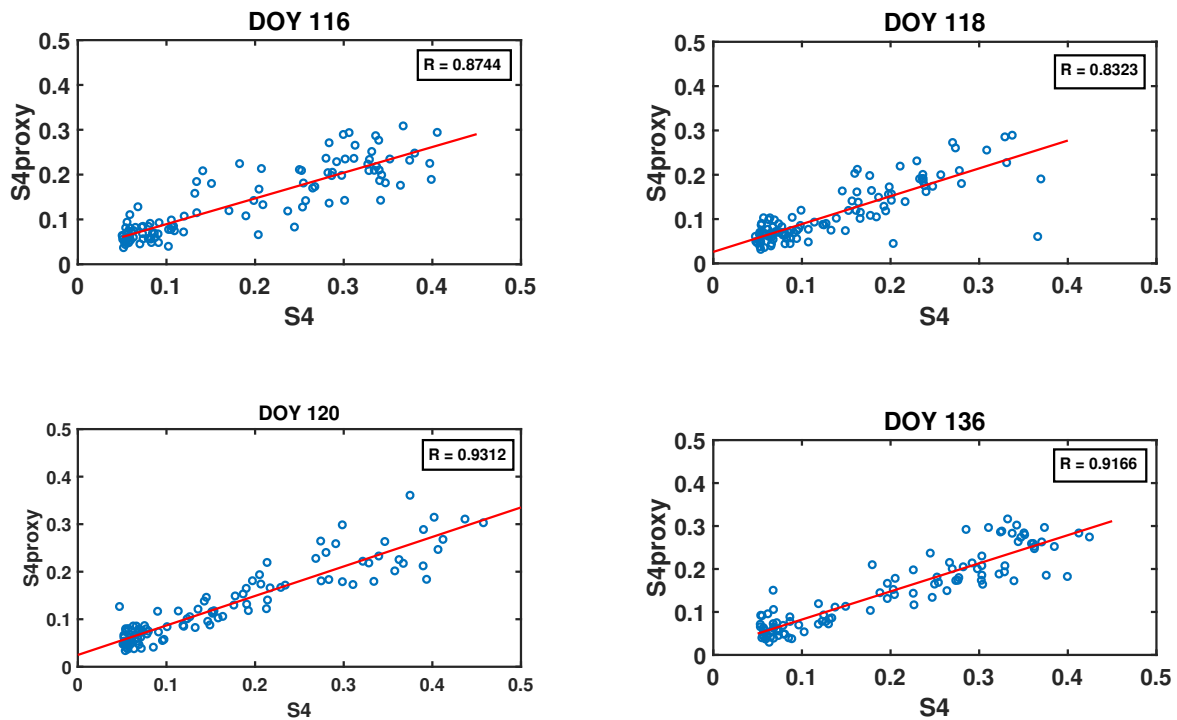


Figure 4.4: Diurnal variation of S4, S4proxy and elevation with time

coefficient between amplitude scintillation and S4proxy was 0.8744 on day of the year (DOY) 116, 0.8323 on DOY 118, 0.9312 on DOY 120, and 0.9166 on DOY 136. Based on the forementioned

figure, it is evident that the various days of the year exhibited a highly significant correlation between amplitude scintillation and S4proxy. Hence, it was proposed that GPS receiver data could be utilized in instances where SCINDA receivers are unavailable.

4.2.1 Variation of S4 with time for Mbarara—SCINDA

For Pseudo Random Number (PRN) 31, data for the consecutive days of the year 289, 290, 291, 292 and 293 for Mbarara—SCINDA receiver is presented in Figure 4.5. Satellite number 31 was selected for this receiver because it was visible throughout the five days of scintillation occurrence. Signals affected by multipath are known to occur consistently for the selected period of time (Gurrieri et al., 2008). The figure shows that scintillations occurred between 8:00 UT and 10:00

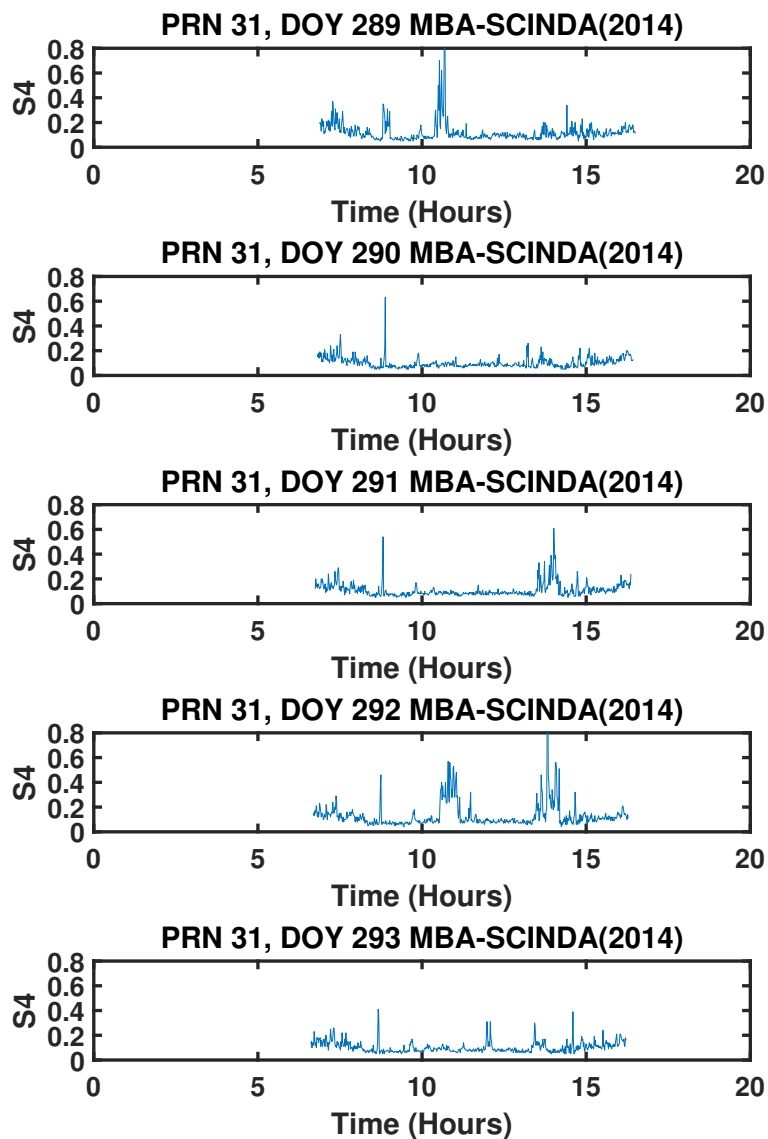


Figure 4.5: Variation of S4 with time for Mbarara—SCINDA for PRN 31.

UT on days of the year (DOY) 289, 290, 291, 292 and 293. The data obtained from satellite number 31 indicated that the scintillation incidents took place during the five consecutive days mentioned above. Hence, those scintillations were attributed to multipath effects. The signals affected by multipath were identified by the rapid increase in the amplitude of the signal observed between 8:00 UT and 10:00 UT during the selected days with scintillation events. The time of the occurrence of the scintillations presented by the same satellite within the five days was not exactly the same because satellite paths always shift slightly ([Kintner et al., 2007](#)).

4.2.2 Variation of S4proxy with time for Mbarara-GPS

To determine the signals affected by multipath, the variation of S4proxy with time for the PRN 22 on the consecutive days of the year; 002, 003, 004, 005 and 006 for Mbarara-GPS receiver is presented in Figure 4.6. According to the above figure, signal scintillations were observed to take place from 5:00 UT to 6:00 UT on days of the year (DOY) designations of 002 through 006. S4proxy was plotted as a function of time to identify and statistically depict small scale irregularities. These fluctuations result in variations in the amplitude of the signal, as observed between 5:00 UT and 6:00 UT. Since these signal fluctuations occurred almost within the same time and were consistent day by day, they were caused by multipath. Figure 4.6 depicts the signals impacted by multipath at the Mbarara–GPS receiver, showcasing a sudden increase in signal amplitude between 5:00 UT and 6:00 UT on the selected days throughout the year.

4.2.3 Variation of S4 with time for Makerere–SCINDA

Data collected from satellite number 18 indicates the occurrence of scintillations between 2:00 UT and 3:00 UT on Days of the Year (DOY) 041 through 045. The satellite number 18 was selected for Makerere – SCINDA because it was visible between 2:00 UT and 3:00 UT for all the five days the scintillation events occurred. The scintillation events presented in figure 4.7 were a result of multipath since they occurred regularly for all the five days. For this receiver, the signals affected by multipath were identified by a consistent increase in the amplitude of the satellite signal between 2:00 UT and 3:00 UT throughout the five days the scintillation events were present.

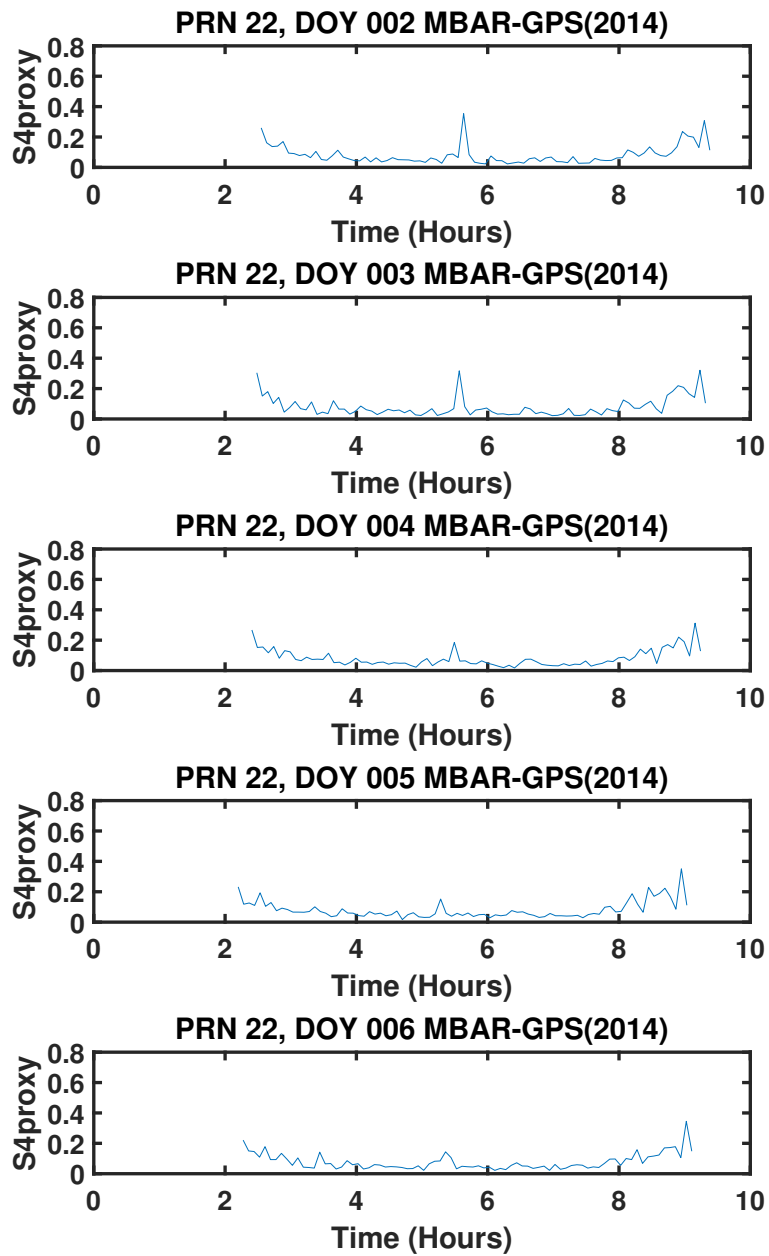


Figure 4.6: Variation of S4proxy with time for Mbarara–GPS for PRN 22.

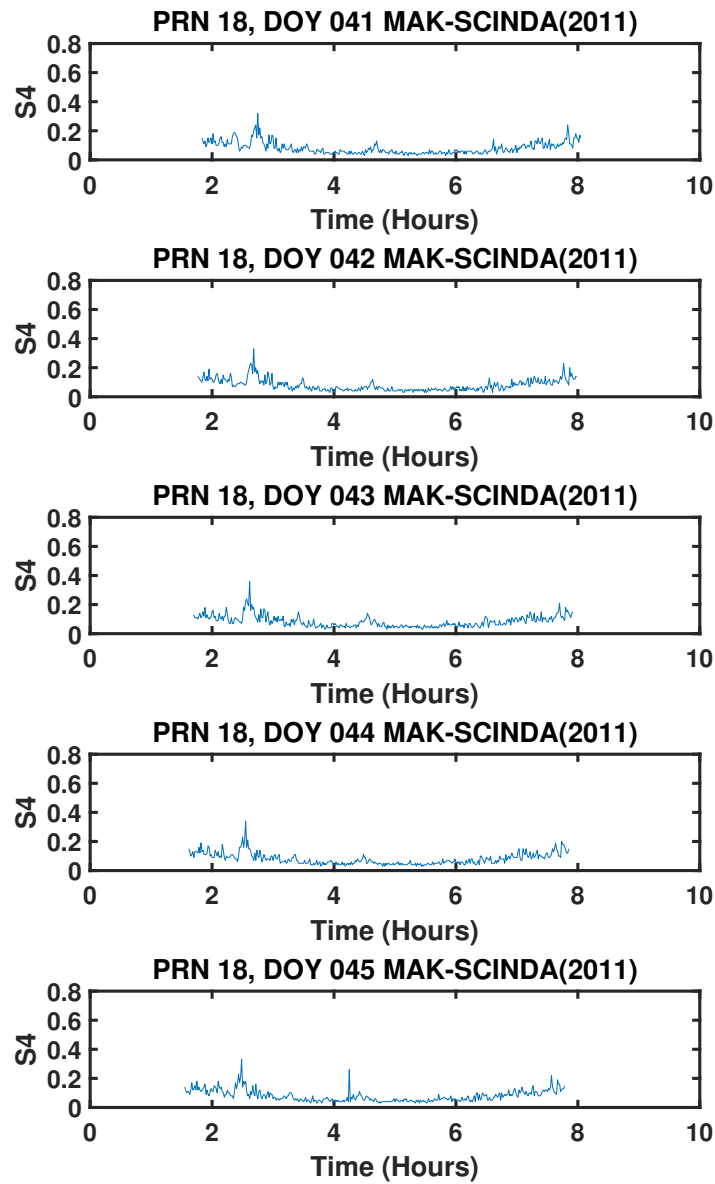


Figure 4.7: Variation of S4 with time for Makerere–SCINDA for PRN 18.

4.2.4 Variation of S4proxy with time for Entebbe–GPS

The change of the S4proxy with universal time for the selected days of the year was depicted by satellite number 25 as shown in figure 4.8. The above figure showcases scintillation occurrences observed between 2:00 UT and 4:00 UT on days 003, 004, 005, 006, and 007 of the year. The consistent occurrence of those scintillations day after day indicated that they were caused by multipath interference. The identification of signals impacted by multipath was based on the enhanced amplitude of the satellite signal consistently occurring around 3:00 UT across the chosen days of scintillation events. The satellite was not visible at exactly 3:00 UT on all the selected days because it's path kept on shifting slightly as the satellite was orbiting the earth for

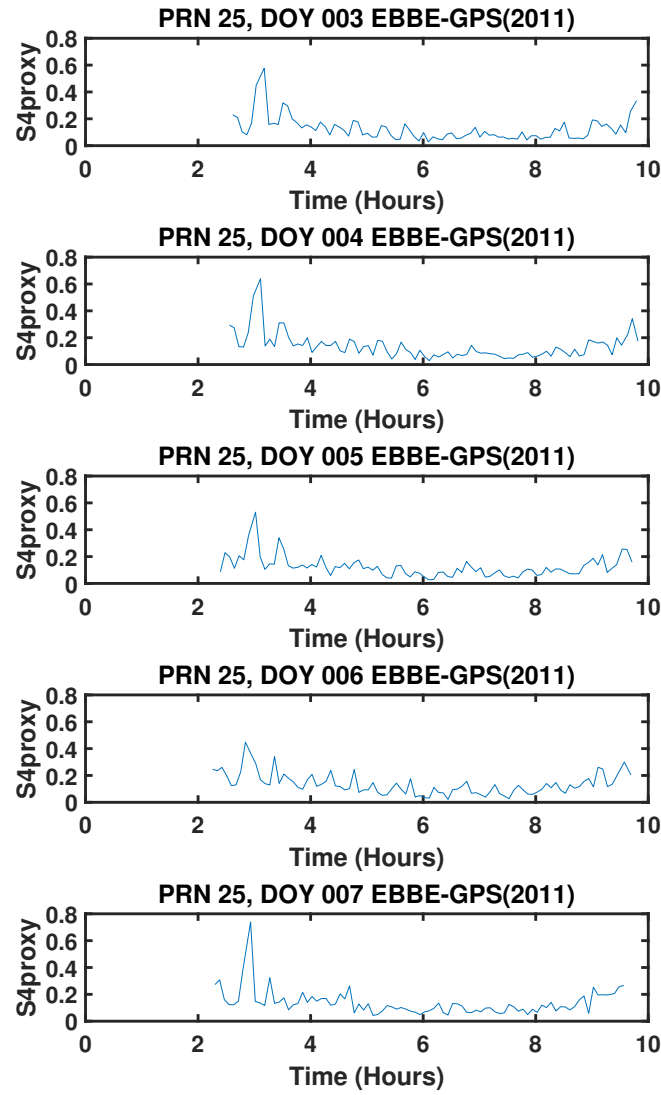


Figure 4.8: Variation of S4proxy with time for Entebbe–GPS (2011) for PRN 25.

the five days.

4.2.5 Variation of S4proxy with time for Mt. Baker–GPS

Figure 4.9. shows the data for the consecutive days of the year 017, 018, 019, 020 and 021 for Mt. Baker–GPS receiver as provided by PRN 18. Scintillation events that occurred between 9:00 UT and 10:00 UT on days of the year mentioned above were presented by figure 4.9. The data captured from PRN 18 at the Mt. Baker receiver indicated a boost in the amplitude of the satellite signal around 9:00 UT consistently across all the chosen days of the year. The recurrent increase in signal amplitude serves as evidence for the presence of signals impacted by multipath interference. This observation is similar to that made by [Gifford et al. \(2020\)](#). Since there is no other mechanism responsible for the manifestation of consecutive scintillation occurrence,

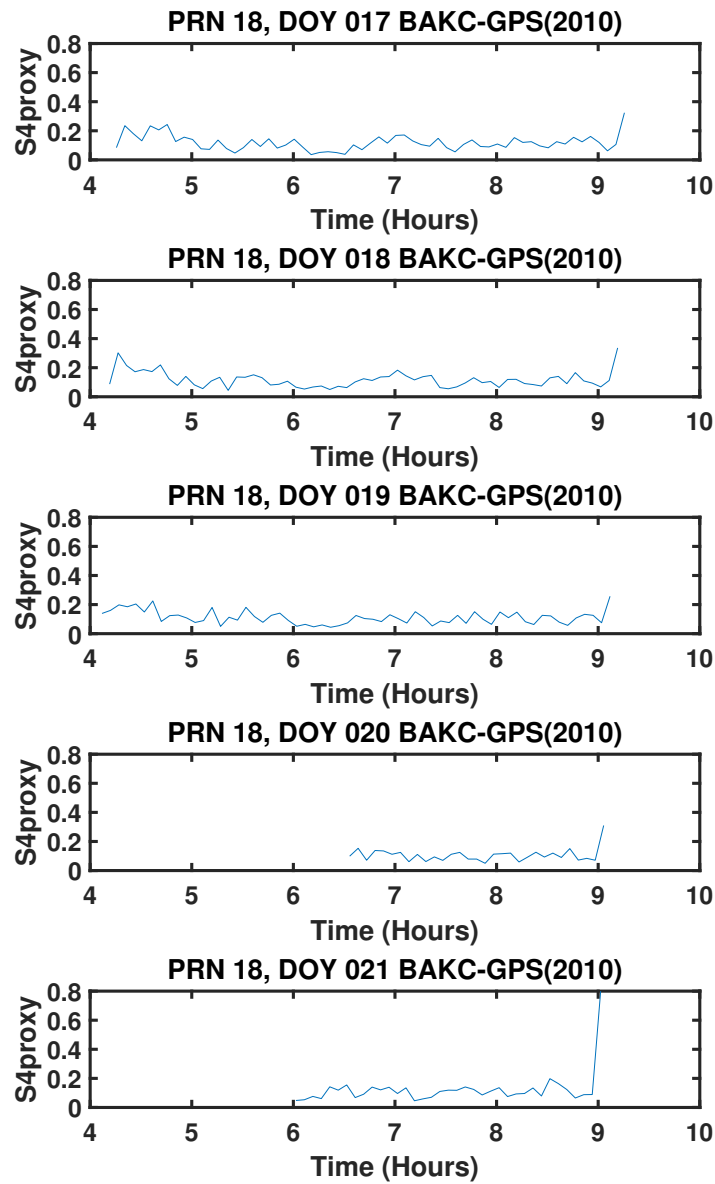


Figure 4.9: Variation of S4proxy with time for Mt. Baker–GPS (2010) for PRN 18.

the signals affected by multipath were identified in all the receiver stations as the signals with a uniform fluctuation within almost the same time for consecutive days. The nature of the signals affected by multipath was varying from receiver to the other. This is because the receivers were installed in different geographical locations. It is for this reason therefore that different satellites were in view at different time and the features in the receiver environments were also different. The days for the scintillation occurrence were also not the same for all the receivers because the days were selected basing on the satellite that was visible for the five days for a given receiver. The reader should also take note that not all satellites rise and set at the same time. Finally, the magnitude of the fluctuations in the amplitude of the signals was also not the same across the

receivers. This is because the obstacles in the receiver environments were not of the same size, height and they were not at the same distance from the receiver.

4.3 Determination of the azimuth dependent elevation threshold

To determine the varying elevation threshold, the occurrence percentage of amplitude scintillations greater than the threshold value of 0.2 and the average amplitude scintillation were plotted on an azimuth–elevation map. Locations where the occurrence percentage of S4 that exceeds 0.2 existed consistently throughout the year were pinpointed as regions where stationary objects routinely caused diffraction and reflection of GPS signals. These signals would reach the receiver with a different path length and with a short time delay from the direct signal hence leading to a fluctuation in the amplitude measurement.

4.3.1 Occurrence percentage and mean occurrence of $S4 > 0.2$

Figure 4.10 presents the areas with high and regular scintillation occurrence. A cubic spline curve fitting tool was used to fit a curve to the points that had high and regular scintillations. An Azimuth Dependent Elevation Threshold (ADET) derived from the curve fitted to points with high and regular scintillations was used to filter out high scintillation occurrence that was related to multipath. For each station, a varying elevation threshold was derived to filter out multipath signals.

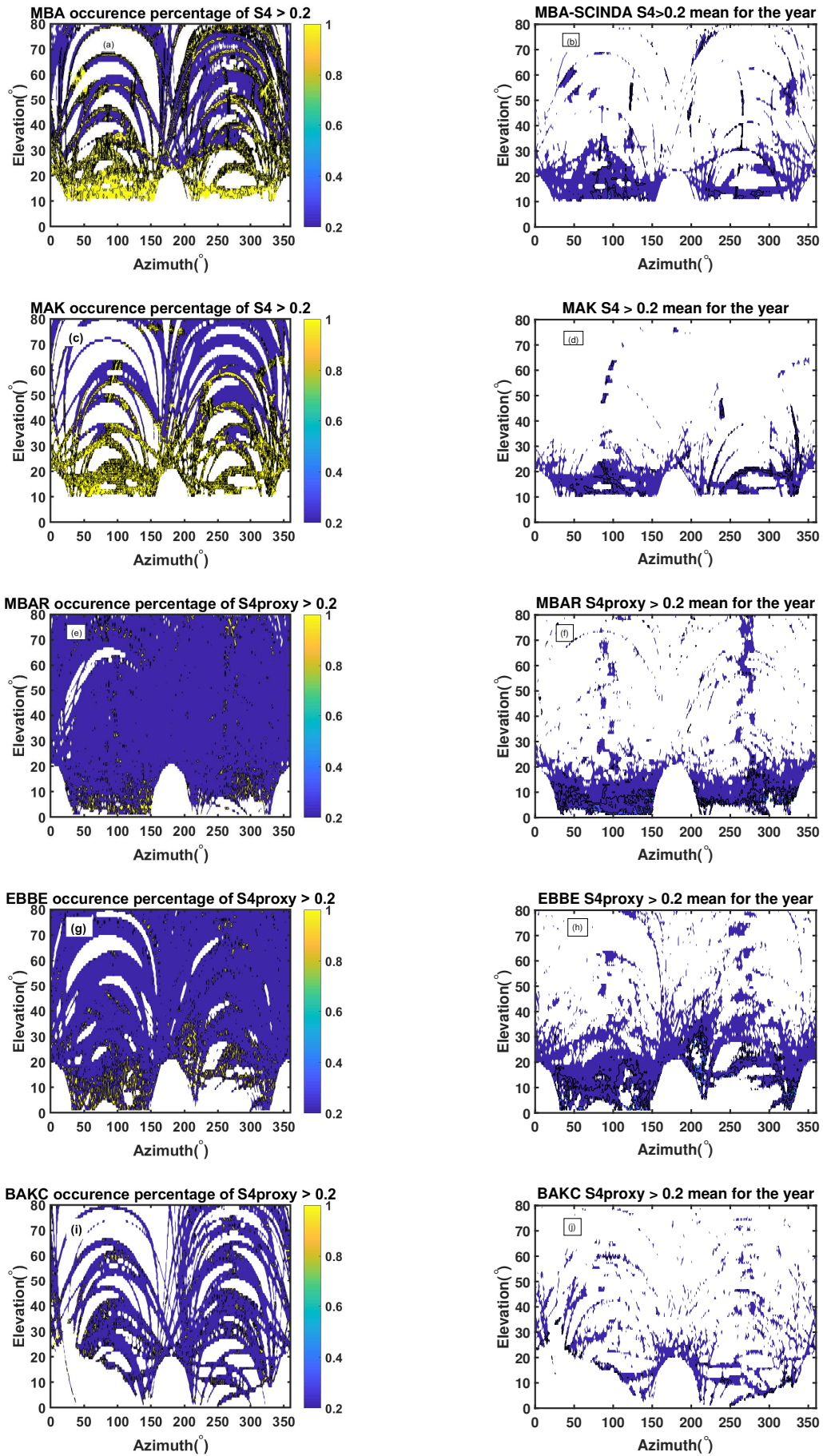


Figure 4.10: Occurrence percentage and mean occurrence of scintillations > 0.2 .

The blank areas on the azimuth–elevation map showed that there were no ray paths through these areas as presented by figure 4.10 (a). The scintillation events of 0.9–1.0 dominated at elevation angles fluctuating between 25° and 35° at azimuth angles ranging between 0° and 170° . This was depicted by the yellow colour and the events were attributed to the presence of stationary structures in the vicinity of the receiver. At an azimuth of 180° corresponding with elevation of 30° , weak scintillation of 0.2 occurred as shown by the blue colour. From the azimuth of 200° to 360° , scintillation events of 0.9 to 1.0 occurred at an elevation of 30° . However, at elevation angles between 35° and 80° corresponding with azimuth angles of 0° to 180° , weak scintillation events of 0.2 to 0.3 dominated as shown by the blue colour while from azimuth angles of 200° to 360° , both scintillation events of 0.9–1.0 and 0.2–0.3 occurred. This was attributed to turbulence in the ionosphere. The receiver only logged data above a built-in elevation threshold of 10° . The mean occurrence of amplitude scintillation for Mbarara–SCINDA was shown by figure 4.10 (b). The regular scintillation occurrences were concentrated at elevation angles ranging between 10° and 35° and they were scarce at elevation angles greater than 40° . Figure 4.10 (b) shows that at elevation of 30° corresponding with an azimuth ranging between 10° and 40° , there were regular scintillation occurrences. These occurrences continued to fluctuate at elevation angles between 20° and 39° from an azimuth of 50° to 360° . Since the regular scintillations were concentrated at low elevation angles between 0° and 40° , they were attributed to the presence of stationary structures in the receiver environment of Mbarara–SCINDA that reflected the signals. The receiver only logged data above a built–in elevation threshold of 10° . From figure 4.10 (c), high scintillation events of 0.8–1.0 were observed at elevation angles ranging between 10° and 50° corresponding with different azimuth angles as shown by the yellow colour. This confirmed that these regions contained stationary obstacles where GPS signals were always diffracted and reflected from. There were also scintillation occurrences ranging between 0.2 and 0.3 at elevation angles of 40° to 80° corresponding with different azimuth angles as shown by the blue colour. This was as a result of the presence of ionospheric irregularities since their occurrence was not consistent. Figure 4.10 (d) depicted regular scintillation occurrence at elevation of 29° corresponding with azimuth of 30° , then decreased to an elevation of 2° at an azimuth of 50° . The regular scintillation occurrence increased gradually to an elevation of 30° corresponding with an azimuth of 120° and then reduced to an elevation of 20° at an azimuth of

150°. At an elevation of 31°, the scintillation occurrence peaked and then gradually reduced to 15° at an azimuth approaching 250°. It then varied from an elevation of 15° to 30° from 250° azimuth angle to 360°. It was therefore discovered that the regular scintillation were as a result of multipath since they were dense at low elevation angles less than 32°. Figure 4.10 (e) shows that high scintillations of 0.8 to 1.0 were observed at elevation angles ranging between 0° and 10° with corresponding azimuth angles of 40° to 150°. High scintillation events then manifested at elevation angles of 10° to 20° with corresponding azimuth angles of 270° to 330°. Since these scintillations manifested at low elevation angles of 0°–20° and were consistent, they were occurring as a result of reflection from stationary structures near the receiver. The scintillation events of 0.2–0.3 dominated the graph and were associated with ionospheric irregularities since the data for the solar maximum year 2014 was used implying that the ionosphere was disturbed throughout the year. At an elevation ranging between 20° and 30°, the consistent scintillation occurrence was registered with an azimuth ranging between 0° and 20°. Figure 4.10 (f) shows that the regular scintillation occurrence fluctuated from an elevation of 20° to a maximum of 31° at an azimuth of 30° to 280°. There was an increase in the scintillation occurrence to an elevation of about 40° at an azimuth of 290°, then the occurrence declined to 30° elevation from azimuth of 300° to 360°. It was therefore evident that the occurrence of regular scintillation was as a result of the presence of reflecting and diffracting structures of GPS signals in the vicinity of Mbarara–GPS receiver. Figure 4.10 (g) shows that dense scintillations of 0.8 to 1.0 occurred at elevation of 19° corresponding with azimuth angles ranging between 40° and 150° as shown by the yellow colour. They then occurred at an elevation of 35° with corresponding azimuth of 230°. The high scintillations then reduced at an elevation of 20° to 3° at azimuth ranging between 260° and 330°. These scintillations were associated with reflection from stationary structures since they occurred at low elevation angles ranging between 0° and 35° and were regular. The blank areas on the azimuth-elevation map showed that there were no ray paths through these areas. Figure 4.10 (h) shows that regular scintillations occurred at an elevation less than 40° at azimuth angles ranging between 0° to 160°. The occurrence then increased to an elevation of about 42° and then reduced to about 30° from azimuth of 160° to 360°. Therefore majority of the scintillation events occurred at an elevation less than 42°. Such scintillations are attributed to the presence of stationary structures in the vicinity of Entebbe–GPS receiver. Figure

4.10 (i) shows that weak scintillation occurrence events of 0.2 to 0.3 were evenly distributed throughout the azimuth-elevation map. High scintillation occurrence events of 0.9 to 1.0 as represented by the yellow colour were also distributed throughout the azimuth-elevation map at all elevation angles although they were limited as compared with the weak scintillation occurrence as shown by the blue colour. However, at elevation angles below 40° corresponding with all azimuth angles, the scintillation events of 0.9 to 1.0 were more compared with the ones that occurred at elevation angles above 40° . Therefore such scintillations were a result of reflections from stationary structures near the receiver. Figure 4.10 (j) showed that majority of the regular scintillation events occurred at elevation angles less than 50° . This implied that most of the signals from the satellite were scattered by stationary structures in the receiver environment of Mt. Baker.

4.3.2 Curve fitted on points with high and regular scintilations

Figure 4.11 (a) shows that consistent scintillation events occurred from 30° elevation and declined to 22° elevation from 0° to 40° azimuth angles and then started to increase to about 35° elevation at azimuth between 40° and 120° . There was then a decrease in the occurrence of regular scintillation from 35° to about 20° elevation at azimuth ranging between 120° and 200° . There was then a fluctuational increase in the manifestation of the consistent scintillation events to about 39° elevation from 200° to 300° azimuth angles. Finally there was a fluctuational decline in the occurrence of regular scintillation from 300° to 360° azimuth angles. Figure 4.11 (b) shows that at azimuth of 10° , there was high scintillation occurrence corresponding to an azimuth of 28° , the occurrence was again high at an azimuth of 50° with elevation of 19° . The occurrence then shoots to an elevation of 31° at an azimuth of 120° . Therefore the curve fluctuated mainly between 20° and 30° elevation corresponding with different azimuth angles. This was attributed to the presence of stationary structures that regularly reflected the signals before reaching the receiver. Figure 4.11 (c) presents that from 29° to 25° elevation corresponding to an azimuth of 0° to 30° , there was a decline in the scintillation occurrence and then there was a fluctuation in the occurrence of scintillation from 25° to 30° elevation corresponding with azimuth of 30° to 110° . The scintillation occurrence then decreased from 30° to 20° at azimuth between 110° to 150° . There was a fluctuation in the occurrence between 25° and 28° elevation at azimuth between 155°

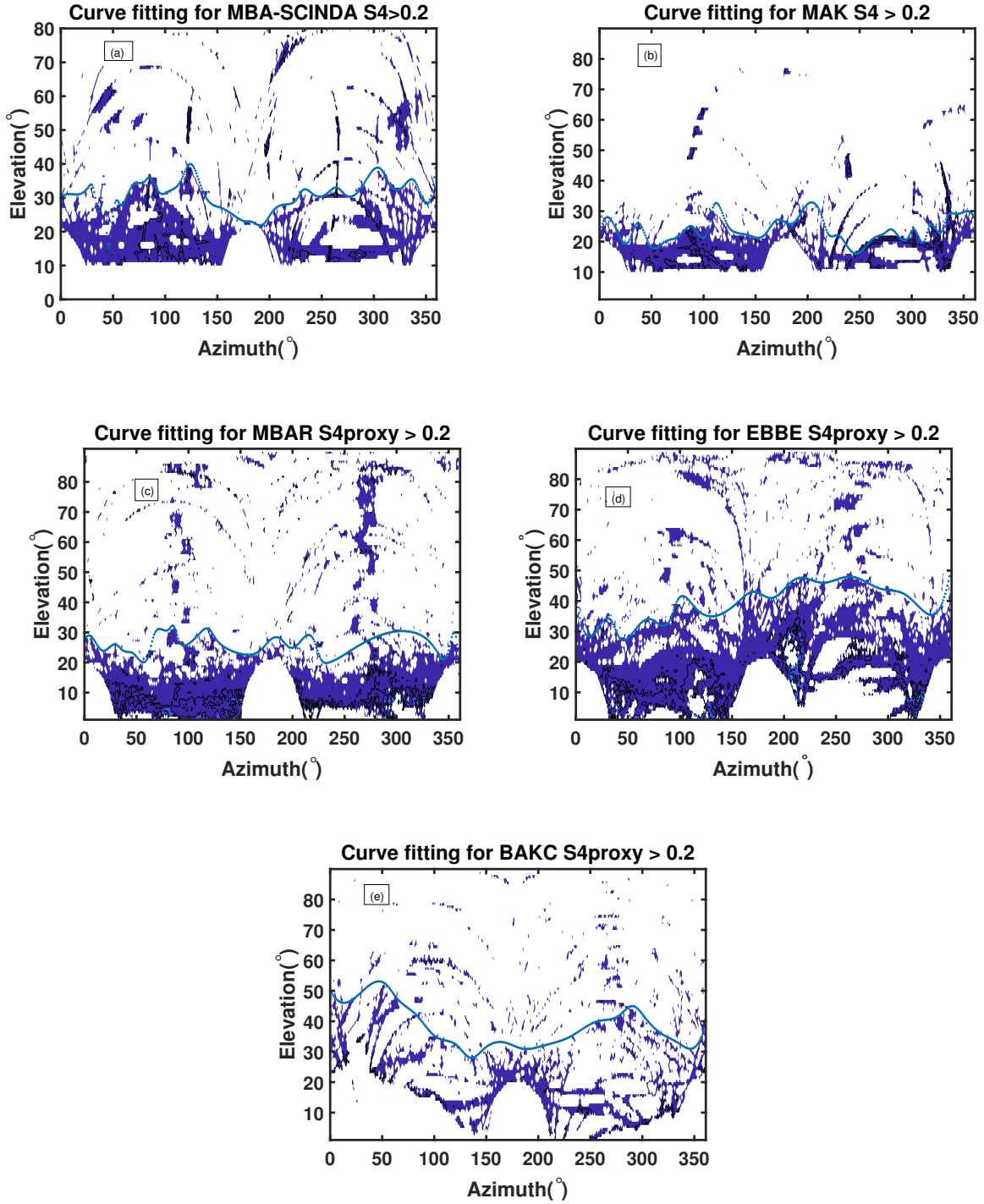


Figure 4.11: Curve fitted on the points with high and regular scintillation occurrence for both SCINDA and GPS receivers in Uganda.

and 230° . There was a decrease in the occurrence from 28° to 19° elevation and a fluctuation between 19° to 35° elevation from 230° to 290° azimuth. Finally, the occurrence of regular scintillation decreased from 35° to 25° elevation from azimuth of 290° to 360° . Figure 4.11 (d) shows that at an elevation of 35° to 32° with respect to azimuth of 0° – 50° , there was regular scintillation occurrence with the exception of the blank areas where there were no ray paths. From

an azimuth of 50° to 100° , there was an increase in the occurrence of the scintillations from 29° to 40° elevation. From an azimuth of 100° to 180° , there was a trough like pattern in the occurrence of regular scintillations from an elevation of 40° to 30° . From 42° elevation angle, there was a depression at 38° elevation which corresponds to 190° azimuth angle. From an azimuth of 190° to 340° , there was a crest like pattern in the occurrence of scintillations from elevation angle of 40° through 42° to 38° . At an azimuth of 340° to 360° , there was a sharp increase in the occurrence of scintillation to 45° elevation. For this receiver environment, the regular scintillation occurrence fluctuated below 45° elevation with the exception of the blank areas. The concentration of the regular scintillations at elevation angles less than 45° was attributed to the presence of stationary structures in the vicinity of Entebbe—GPS receiver. Figure 4.11 (e) shows that from 50° elevation, there was a reduction in the regular occurrence of scintillations to an elevation of 48° and then there was a drastic increase in the occurrence to an elevation of 52° at an azimuth of 0° to 49° . From 50° azimuth to 290° , there was a decrease in the occurrence of regular scintillations from an elevation of 54° to about 29° and there was an increase in the occurrence to 45° . There was a decline in the occurrence of scintillations from elevation angles of 48° to 30° at azimuth angles of 300° to 350° . For Mt. Baker—GPS receiver environment, the regular scintillation occurrence fluctuated below 55° elevation angle which is higher than the elevation angles of other receivers. This was attributed to the presence of stationary structures in the receiver environment that had high elevation angles of up to 55° .

4.3.3 Varying and fixed elevation threshold

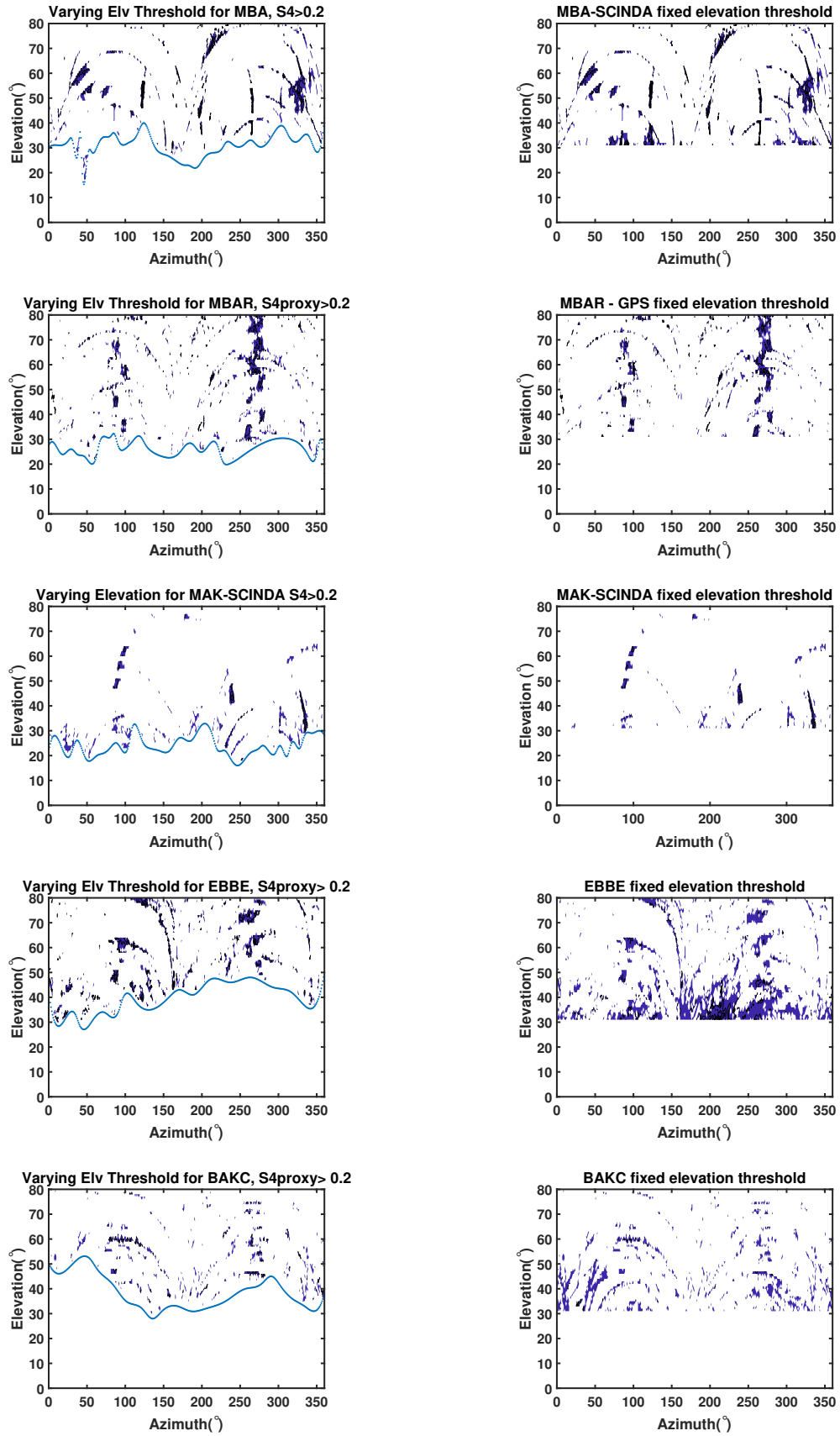


Figure 4.12: Varying and fixed elevation threshold.

Table 4.1: Comparison between Varying and Fixed elevation threshold

Station	Station ID	Varying Elv(%)	Fixed Elv(%)	Retrieved Data(%)
SCINDA				
Makerere	MAK	60.45	49.47	10.98
Mbarara	MBA	49.29	48.75	00.54
GPS				
Mbarara	MBAR	52.89	43.85	09.04
Entebbe	EBBE	31.52	47.19	15.67
Mt. Baker	BAKC	36.74	49.01	12.27

For MBA receiver, using a fixed elevation threshold of 30^0 , 51.25% of the data was eliminated and 48.75% was the remaining useful data, while when using a varying elevation, 50.71% of the data was lost, implying that the remaining useful data was 49.29%. Therefore, more data was lost when a fixed elevation threshold was used than when a varying elevation threshold was used since the data of 0.54% was retrieved . Comparing the varying and fixed elevation threshold for MAK, 50.53% was lost when using a fixed elevation threshold and the remaining useful data was 49.47% whereas 39.55% of the data was eliminated when a varying elevation threshold was used. This implies that significant data was lost when a fixed elevation threshold was used. For this receiver station, 60.45% significant and uncorrupted data was obtained and this improves on the quality and quantity of data captured by the receiver. Therefore, 10.98% of the data was regained when using an azimuth dependent elevation threshold. Considering MBAR receiver station, using a fixed elevation threshold of 30^0 , 56.15% of the data was lost, implying that the remaining useful data was 43.85%. While using a varying elevation threshold, 47.11% of the data was lost and 52.89% was the uncorrelated data that remained. This implies that there was a reduction in the data loss by 9.04% when a varying elevation threshold was used. Basing on EBBE receiver, 68.48% of the data was lost when a varying elevation threshold was used. This means that only 31.52% was the useful data that remained. While using an fixed elevation threshold, 52.81% of the data was lost and the remaining meaningful data was 47.19%. This implies that there was an increase in the data lost by 15.67% when a variable elevation threshold was used. For BAKC station, 50.99% of the data was lost by the receiver when a fixed elevation threshold was used and 49.01% was the remaining useful data. However, when a variable elevation threshold was used, 63.26% of the data was lost. Thus, only 36.74% was the only meaningful data that remained.

This implies that there was an increase in the data lost by 12.27%. Therefore, using a varying elevation threshold was better than using a fixed elevation threshold since all the data that was affected by multipath was eliminated. Table 4.1 shows the summary of the percentage of the data that remained after using a varying elevation threshold and a fixed elevation threshold. The significant data that was retrieved when a varying elevation threshold was used, was also included in the last column of the table.

Chapter Five.

Conclusions and Recommendations

5.1 Conclusion.

The errors introduced by the distorted signals around the GNSS receivers distort the quality of the data obtained by the receiver. The study identified various characteristics of each receiver environment, encompassing stationary structures responsible for reflecting and diffracting satellite signals and the signals impacted by multipath as well. The identification of stationary structures responsible for multipath involved varying elevation with azimuth to pinpoint the precise locations of stationary obstacles. The findings revealed that the stationary structures inducing multipath were found in regions where satellites were not visible at various low elevation angles, which varied from one receiver to another. Signals influenced by multipath were discerned by observing the fluctuation of amplitude scintillations over a period of five consecutive days using data provided by any satellite visible throughout the entire duration. The findings indicated that signals impacted by multipath were distinguished as those consistently occurring day after day over the course of the five-day period. After identifying the characteristics of each receiver environment, the study determined a variable elevation cutoff for each receiver. The percentage occurrence of amplitude scintillation was varied on an azimuth–elevation map to identify areas with high scintillations of $S_4 > 0.2$. The average amplitude scintillation was varied on an azimuth–elevation map in order to differentiate between signals affected by multipath from those attributed to ionospheric irregularities. The signals affected by multipath were identified in areas with high and regular scintillation occurrence. A cubic spline curve was used to model a curve across points exhibiting high and consistent scintillation events. The curve was used as the varying elevation threshold for each obstacle for a specific receiver. When comparing the fluctuating elevation threshold with the constant elevation threshold, the data gathered was notably more substantial with the fluctuating elevation threshold. This data will enhance the quality and quantity of the data captured by the receivers.

5.2 Recommendations for future research.

The azimuth dependent elevation threshold should be used instead of the fixed elevation threshold since more sufficient and quality data can be obtained using the varying elevation threshold. The characterization of the multipath environment surrounding GNSS receivers should be extended to the receivers situated across East Africa to enhance both the quality and quantity of data that is captured by the receivers over the region. A comprehensive site survey should be conducted to identify and map out stationary structures such as buildings, towers and bridges in the vicinity of the GNSS receiver. Robust algorithms to monitor and analyze signal quality metrics such as Signal-to-Noise Ratio and pseudorange residuals should be implemented. These metrics can indicate anomalies or fluctuations that may be indicative of multipath effects.

References

- Abdu, M. (2001). Outstanding problems in the equatorial ionosphere–thermosphere electrodynamics relevant to spread f. *Journal of Atmospheric and Solar-Terrestrial Physics*, 63(9):869–884.
- Abdu, M. (2005). Equatorial ionosphere–thermosphere system: Electrodynamics and irregularities. *Advances in Space Research*, 35(5):771–787.
- Abdu, M., De Medeiros, R., Sobral, J., and Bittencourt, J. (1983). Spread f plasma bubble vertical rise velocities determined from spaced ionosonde observations. *Journal of Geophysical Research: Space Physics*, 88(A11):9197–9204.
- Adekoya, B., Chukwuma, V., and Reinisch, B. (2015). Ionospheric vertical plasma drift and electron density response during total solar eclipses at equatorial/low latitude. *Journal of Geophysical Research: Space Physics*, 120(9):8066–8084.
- Aditya, S., Molisch, A. F., and Behairy, H. M. (2018). A survey on the impact of multipath on wideband time-of-arrival based localization. *Proceedings of the IEEE*, 106(7):1183–1203.
- Allen, P. A. (2009). *Earth surface processes*. John Wiley & Sons.
- Andima, G., Amabayo, E. B., Jurua, E., and Cilliers, P. J. (2020). Gps derived amplitude scintillation proxy model: A case over a low latitude station in east africa. *Journal of Atmospheric and Solar-Terrestrial Physics*, 211:105461.
- Andrews, S. S. (2023). *Light and waves*.
- Atabati, A., Jazireeyan, I., Alizadeh, M., Pirooznia, M., Flury, J., Schuh, H., and Soja, B. (2019). Analyzing the ionospheric irregularities caused by the september 2017 geomagnetic storm using ground-based gnss, swarm. Technical report, and FORMOSAT-3/COSMIC Data near the Equatorial Ionization Anomaly in East
- Atilaw, T. Y. (2015). Characterization of the multipath environment of ionospheric scintillation receivers.

- Atiq, M. (2018). Historical review of ionosphere in perspective of sources of ionization and radio waves propagation. *Research & Reviews: Journal of Space Science & Technology*, 7(2):28.
- Bagiya, M. S. (2010). Multitechnique studies of ionospheric phenomena. PhD thesis, Saurashtra University.
- Bailey, S. M., Barth, C. A., and Solomon, S. C. (2002). A model of nitric oxide in the lower thermosphere. *Journal of Geophysical Research: Space Physics*, 107(A8):SIA–22.
- Balaei, A. T., Dempster, A. G., and Barnes, J. (2006). A novel approach in detection and characterization of cw interference of gps signal using receiver estimation of c/no. In *Proceedings of IEEE/ION PLANS 2006*, pages 1120–1126.
- Balan, N., Liu, L., and Le, H. (2018). A brief review of equatorial ionization anomaly and ionospheric irregularities. *Earth and Planetary Physics*, 2(4):257–275.
- Barry, R. G. and Chorley, R. J. (2009). *Atmosphere, weather and climate*. Routledge.
- Beach, T. L. (1998). Global positioning system studies of equatorial scintillations. Cornell University.
- Beach, T. L. and Kintner, P. M. (1999). Simultaneous global positioning system observations of equatorial scintillations and total electron content fluctuations. *Journal of Geophysical Research: Space Physics*, 104(A10):22553–22565.
- Beach, T. L. and Kintner, P. M. (2001). Development and use of a gps ionospheric scintillation monitor. *IEEE transactions on geoscience and remote sensing*, 39(5):918–928.
- Bharadwaj, S. C. and Vidyarthi, A. (2020). Process of detection, determination and correction cycle slip error: A review. In *2020 6th International Conference on Signal Processing and Communication (ICSC)*, pages 331–336. IEEE.
- Bhardwaj, A., Elsner, R. F., Gladstone, G. R., Cravens, T. E., Lisse, C. M., Dennerl, K., Branduardi-Raymont, G., Wargelin, B. J., Waite Jr, J. H., Robertson, I., et al. (2007). X-rays from solar system objects. *Planetary and Space Science*, 55(9):1135–1189.

- Bhattacharyya, A., Beach, T., Basu, S., and Kintner, P. (2000). Nighttime equatorial ionosphere: Gps scintillations and differential carrier phase fluctuations. *Radio Science*, 35(1):209–224.
- Birner, T., Sankey, D., and Shepherd, T. (2006). The tropopause inversion layer in models and analyses. *Geophysical research letters*, 33(14).
- Booker, H. G. (1979). The role of acoustic gravity waves in the generation of spread-f and ionospheric scintillation. *Journal of Atmospheric and Terrestrial Physics*, 41(5):501–515.
- Bora, S. (2017). Ionosphere and radio communication. *Resonance*, 22(2):123–133.
- Borchevkina, O., Karpov, I., and Karpov, M. (2020). Meteorological storm influence on the ionosphere parameters. *Atmosphere*, 11(9):1017.
- Braasch, M. S. (2017). Multipath. *Springer handbook of global navigation satellite systems*, pages 443–468.
- Bristow, W. A. (1992). The formation and characteristics of E-region thin ionization layers at high latitudes. University of Alaska Fairbanks.
- Brown, M. K., Lewis, H., Kavanagh, A., and Cnossen, I. (2021). Future decreases in thermospheric neutral density in low earth orbit due to carbon dioxide emissions. *Journal of Geophysical Research: Atmospheres*, 126(8):e2021JD034589.
- Bruinsma, S., de Wit, T. D., Fuller-Rowell, T., Garcia-Sage, K., Mehta, P., Schiemenz, F., Shprits, Y. Y., Vasile, R., Yue, J., and Elvidge, S. (2023). Thermosphere and satellite drag. *Advances in Space Research*.
- Bryant, F. B. and Harrison, P. R. (2013). How to create an ascii input data file for unioda and cta software. *Optimal Data Analysis*, 2.
- Budden, A. (2009). The role of shame in posttraumatic stress disorder: A proposal for a socio-emotional model for dsm-v. *Social science & medicine*, 69(7):1032–1039.
- Carrano, C. S., Groves, K. M., and Griffin, J. M. (2005). Empirical characterization and modeling of gps positioning errors due to ionospheric scintillation. In *Ionospheric Effects Symposium*, pages 1–9. JMG Assoc. Alexandria, Va.

- Cerruti, A. P. (2007). Solar radio burst effects on global positioning system receivers.
- Chan, A. H., Jenkins, P. A., and Song, Y. S. (2012). Genome-wide fine-scale recombination rate variation in *drosophila melanogaster*. *PLoS genetics*, 8(12):e1003090.
- Chatterjee, S., Chakraborty, S., and Majumdar, S. (2013). Summer time scintillations near the transition zone of the indian longitude sector. *Journal of Atmospheric and Solar-Terrestrial Physics*, 95:102–115.
- Chu, Y.-H., Wu, K.-H., and Su, C.-L. (2009). A new aspect of ionospheric e region electron density morphology. *Journal of Geophysical Research: Space Physics*, 114(A12).
- Clifford, S. (2005). The classical theory of wave propagation in a turbulent medium. *Laser beam propagation in the atmosphere*, pages 9–43.
- Closas, P., Fernandez-Prades, C., and Fernandez-Rubio, J. A. (2009). A bayesian approach to multipath mitigation in gnss receivers. *IEEE Journal of Selected Topics in Signal Processing*, 3(4):695–706.
- Cors Espinal, À. (2021). Dual-frequency smartphones for ionospheric research. B.S. thesis, Universitat Politècnica de Catalunya.
- Council, N. R., on Engineering, D., Sciences, P., Board, S. S., on Solar, C., and Physics, S. (2004). *Plasma physics of the local cosmos*. National Academies Press.
- Council, N. R., on Engineering, D., Sciences, P., on Engineering, C., Systems, T., on Atmospheric Sciences, B., Aeronautics, Board, S. E., on Low-Altitude Wind Shear, C., and to Aviation, I. H. (1983). *Low-altitude wind shear and its hazard to aviation*. National Academies Press.
- Daly, N. M. (2000). *Scintillation analysis of solar wind dynamics*. University of Glasgow (United Kingdom).
- Daniel, A., Tilahun, G., and Teshager, A. (2016). Effect of ionosphere on radio wave propagation. *International Journal of Research*, 3(9):65–74.
- Daniel, R. (2002). *Concepts in Space Science*. Universities Press.

- De Paz, J. F., Tapia, D. I., Alonso, R. S., Pinzón, C. I., Bajo, J., and Corchado, J. M. (2013). Mitigation of the ground reflection effect in real-time locating systems based on wireless sensor networks by using artificial neural networks. *Knowledge and information systems*, 34:193–217.
- Deacon, C. J. (2023). Radio propagation through ionospheric sporadic-e.
- Deacon, C. J., Witvliet, B. A., Steendam, S. N., and Mitchell, C. N. (2020). Rapid and accurate measurement of polarization and fading of weak vhf signals obliquely reflected from sporadic-e layers. *IEEE Transactions on Antennas and Propagation*, 69(7):4033–4048.
- Dravins, D., Lindegren, L., Mezey, E., and Young, A. T. (1997). Atmospheric intensity scintillation of stars, i. statistical distributions and temporal properties. *Publications of the Astronomical Society of the Pacific*, 109(732):173.
- Eddy, J. A. (2009). *The sun, the earth, and near-earth space: a guide to the sun-earth system*. Government Printing Office.
- Elmunim, N., Abdullah, M., Elmunim, N., and Abdullah, M. (2021). Ionosphere. *Ionospheric Delay Investigation and Forecasting*, pages 19–29.
- Emmert, J. T. (2015). Thermospheric mass density: A review. *Advances in Space Research*, 56(5):773–824.
- Fejer, B. G. and Kelley, M. (1980). Ionospheric irregularities. *Reviews of Geophysics*, 18(2):401–454.
- Fernandez-Prades, C., Arribas, J., and Closas, P. (2016). Robust gnss receivers by array signal processing: Theory and implementation. *Proceedings of the IEEE*, 104(6):1207–1220.
- Ferreira, A., Matias, B., Almeida, J., and Silva, E. (2020). Real-time gnss precise positioning: Rtklib for ros. *International Journal of Advanced Robotic Systems*, 17(3):1729881420904526.
- Fishler, E. and Poor, H. V. (2004). Low-complexity multiuser detectors for time-hopping impulse-radio systems. *IEEE Transactions on Signal Processing*, 52(9):2561–2571.
- Folkestad, K. (2013). *Ionospheric radio communications*. Springer.

- Fritts, D. C. and Lund, T. S. (2011). Gravity wave influences in the thermosphere and ionosphere: Observations and recent modeling. In *Aeronomy of the Earth's Atmosphere and Ionosphere*, pages 109–130. Springer.
- Fueglistaler, S., Dessler, A., Dunkerton, T., Folkins, I., Fu, Q., and Mote, P. W. (2009). Tropical tropopause layer. *Reviews of Geophysics*, 47(1).
- Gadsden, M. (1998). Noctilucent clouds seen at 60 n: Origin and development. *Journal of atmospheric and solar-terrestrial physics*, 60(18):1763–1772.
- Gifford, W. M., Dardari, D., and Win, M. Z. (2020). The impact of multipath information on time-of-arrival estimation. *IEEE Transactions on Signal Processing*, 70:31–46.
- Golubkov, G. V., Golubkov, M., Manzhelii, M., and Karpov, I. (2014). Optical quantum properties of gps signal propagation medium—d layer. *The Atmosphere and Ionosphere: Elementary Processes, Monitoring, and Ball Lightning*, pages 1–68.
- Goodman, J. M. (2005). The ionosphere. *Space Weather & Telecommunications*, pages 81–173.
- Granger, R. and Simpson, S. (2008). An analysis of multipath mitigation techniques suitable for geodetic antennas. In *Proceedings of the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2008)*, pages 2755–2765.
- Grocott, M. P., Martin, D. S., Levett, D. Z., McMorrow, R., Windsor, J., and Montgomery, H. E. (2009). Arterial blood gases and oxygen content in climbers on mount everest. *New England Journal of Medicine*, 360(2):140–149.
- Gulyaeva, T. and Bilitza, D. (2012). Towards iso standard earth ionosphere and plasmasphere model. *New developments in the standard model*, pages 1–39.
- Gurrieri, L. E., Willink, T. J., Petosa, A., and Noghianian, S. (2008). Characterization of the angle, delay and polarization of multipath signals for indoor environments. *IEEE Transactions on Antennas and Propagation*, 56(8):2710–2719.
- Haldoupis, C. (2011). A tutorial review on sporadic e layers. *Aeronomy of the Earth's Atmosphere and Ionosphere*, pages 381–394.

- Hannah, B. M. (2001). Modelling and simulation of GPS multipath propagation. PhD thesis, Queensland University of Technology.
- Hassan, H. (2022). Fundamentals of geothermal energy extraction. In *Utilization of Thermal Potential of Abandoned Wells*, pages 11–33. Elsevier.
- Hathaway, D. H. (2015). The solar cycle. *Living reviews in solar physics*, 12(1):4.
- Haynes, P. (1999). Transport, stirring, and mixing in the atmosphere. *Mixing: Chaos and Turbulence*, pages 229–272.
- Helling, C. (2019). Exoplanet clouds. *Annual Review of Earth and Planetary Sciences*, 47(1):583–606.
- Hellmann, I., Ebersberger, I., Ptak, S. E., Pääbo, S., and Przeworski, M. (2003). A neutral explanation for the correlation of diversity with recombination rates in humans. *The American Journal of Human Genetics*, 72(6):1527–1535.
- Hide, R. and Roberts, P. (1961). The origin of the main geomagnetic field. *Physics and Chemistry of the Earth*, 4:27–98.
- Hocking, W. K., Röttger, J., Palmer, R. D., Sato, T., and Chilson, P. B. (2016). *Atmospheric radar: Application and science of MST radars in the Earth’s mesosphere, stratosphere, troposphere, and weakly ionized regions*. Cambridge University Press.
- Hofmann-Wellenhof, B., Lichtenegger, H., and Wasle, E. (2007). *GNSS—global navigation satellite systems: GPS, GLONASS, Galileo, and more*. Springer Science & Business Media.
- Huddart, D. and Stott, T. A. (2020). *Earth environments*. John Wiley & Sons.
- Hugentobler, U. and Montenbruck, O. (2017). Satellite orbits and attitude. *Springer handbook of global navigation satellite systems*, pages 59–90.
- Hunegnaw, A. and Teferle, F. N. (2022). Evaluation of the multipath environment using electromagnetic-absorbing materials at continuous gnss stations. *Sensors*, 22(9):3384.
- Hunsucker, R. D. (1982). Atmospheric gravity waves generated in the high-latitude ionosphere: A review. *Reviews of Geophysics*, 20(2):293–315.

- Inglezakis, V. (2016). Extraterrestrial environment. In *Environment and Development*, pages 453–498. Elsevier.
- Islam, M. R. (2019). Effect of shadowing and diffraction on the received gnss signal. Master's thesis, M. Islam.
- Jiao, Y. and Morton, Y. T. (2015). Comparison of the effect of high-latitude and equatorial ionospheric scintillation on gps signals during the maximum of solar cycle 24. *Radio Science*, 50(9):886–903.
- Jin, S., Cardellach, E., and Xie, F. (2014). *GNSS remote sensing*, volume 16. Springer.
- Jurua, E., Andima, G., Oleni, P., and Amabayo, E. B. (2024). Analysis of the scintillation characteristics on the different satellite links derived from gps observations and scinda data over mbarara. *Journal of Atmospheric and Solar-Terrestrial Physics*, 265:106353.
- Karaim, M., Elsheikh, M., Noureldin, A., and Rustamov, R. (2018). Gnss error sources. *Multi-functional operation and application of GPS*, 32:137–144.
- Kashchenko, N., Ishanov, S., and Matsievsky, S. (2021). Numerical study of the gradient-drift instability's growth rate at the fronts of equatorial plasma bubbles. *Mathematical Models and Computer Simulations*, 13:623–630.
- Kenrick, G. and Jen, C. (1929). Measurements of the height of the kennelly-heaviside layer. *Proceedings of the Institute of Radio Engineers*, 17(4):711–733.
- Kintner, P. M., Ledvina, B. M., and De Paula, E. (2007). Gps and ionospheric scintillations. *Space weather*, 5(9).
- Klimenko, M., Zhao, B., Karpachev, A., and Klimenko, V. (2012). Stratification of the low-latitude and near-equatorial f2 layer, topside ionization ledge, and f3 layer: What we know about this? a review. *International Journal of Geophysics*, 2012(1):938057.
- Knott, G. D. (1999). *Interpolating cubic splines*, volume 18. Springer Science & Business Media.
- Komjathy, A. (2023). Global ionospheric total electron content mapping using the global positioning system.

- Kornilov, V., Sarazin, M., Tokovinin, A., Travouillon, T., and Voziakova, O. (2012). Comparison of the scintillation noise above different observatories measured with mass instruments. *Astronomy & Astrophysics*, 546:A41.
- Koskinen, H. (2011). *Physics of space storms: From the solar surface to the Earth*. Springer Science & Business Media.
- Kumar, A., Kumar, S., Lal, P., Saikia, P., Srivastava, P. K., and Petropoulos, G. P. (2021). Introduction to gps/gnss technology. In *GPS and GNSS Technology in Geosciences*, pages 3–20. Elsevier.
- Langley, R. B., Teunissen, P. J., and Montenbruck, O. (2017). *Introduction to gnss*. Springer handbook of global navigation satellite systems, pages 3–23.
- Langowski, M. (2016). *Investigation of metal atom and ion number densities in the mesosphere and lower thermosphere by satellite remote sensing with SCIAMACHY/Envisat*. PhD thesis, Universität Bremen.
- Lanzerotti, L. J. (2007). *Space weather effects on communications*. Space Weather-Physics and Effects. Springer, Praxis Publishing, Chichester, pages 247–268.
- Li, A. S. (2020). Ruling outer space: Defining the boundary and determining jurisdictional authority. *Okla. L. Rev.*, 73:711.
- Li, M., Yuan, Y., Wang, N., Li, Z., and Huo, X. (2018). Performance of various predicted gnss global ionospheric maps relative to gps and jason tec data. *GPS solutions*, 22:1–11.
- Liu, H.-L., Foster, B., Hagan, M., McInerney, J., Maute, A., Qian, L., Richmond, A., Roble, R., Solomon, S., Garcia, R., et al. (2010). Thermosphere extension of the whole atmosphere community climate model. *Journal of Geophysical Research: Space Physics*, 115(A12).
- Liu, L., Wan, W., Chen, Y., and Le, H. (2011). Solar activity effects of the ionosphere: A brief review. *Chinese Science Bulletin*, 56:1202–1211.
- Macnamara, T. (2010). *Introduction to antenna placement and installation*. John Wiley & Sons.

- Madhusudhan, N. (2019). Exoplanetary atmospheres: key insights, challenges, and prospects. *Annual Review of Astronomy and Astrophysics*, 57(1):617–663.
- Malins, J. B. (2019). Using natural phenomena to study the ionosphere.
- Mark, D. M. and Sinha, G. (2020). The horizon: Ontology and conceptualization. *Handbook of the Changing World Language Map*, pages 3077–3095.
- Martin, E. and Aarons, J. (1977). F layer scintillations and the aurora. *Journal of Geophysical Research*, 82(19):2717–2722.
- Mishra, R. K. and Dubey, S. (2018). *The Role of Sun on the Earth's Atmosphere and Climate*. LAP LAMBERT Academic Publishing.
- Mohanakumar, K. (2008). *Stratosphere troposphere interactions: an introduction*. Springer Science & Business Media.
- Mosavi, M. R., Azad, M. S., and EmamGholipour, I. (2013). Position estimation in single-frequency gps receivers using kalman filter with pseudo-range and carrier phase measurements. *Wireless personal communications*, 72:2563–2576.
- Mushini, S. C., Jayachandran, P., Langley, R. B., MacDougall, J., and Pokhotelov, D. (2012). Improved amplitude-and phase-scintillation indices derived from wavelet detrended high-latitude gps data. *GPS solutions*, 16:363–373.
- Nguyen, C. T., Oluwadare, S. T., Le, N. T., Alizadeh, M., Wickert, J., and Schuh, H. (2021). Spatial and temporal distributions of ionospheric irregularities derived from regional and global rotI maps. *Remote Sensing*, 14(1):10.
- Nicolls, M. (2006). Radar and airglow studies of f-region composition and dynamics at low latitudes.
- Norton, K. A. (1937). The propagation of radio waves over the surface of the earth and in the upper atmosphere. *Proceedings of the Institute of Radio Engineers*, 25(9):1203–1236.

- Ogwala, A., Oyedokun, O. J., Akala, A. O., Amaechi, P. O., Simi, K., Panda, S. K., Ogabi, C., and Somoye, E. O. (2022). Characterization of ionospheric irregularities over the equatorial and low latitude nigeria region. *Astrophysics and Space Science*, 367(8):79.
- Oke, A. and Akala, O. (2009). Simulation of Ionospheric Irregularities on Transionospheric Radio Systems for the Enhancement of Safety in the Aviation Industry. PhD thesis, University of Lagos (Nigeria).
- Olwendo, J. and Cilliers, P. (2018). A comparison of ionospheric scintillation proxy indices derived from low rate igs data with the amplitude scintillation index, s4, in a low latitude region over africa. *Journal of Atmospheric and Solar-Terrestrial Physics*, 173:160–167.
- Olwendo, O., Baki, P., Cilliers, P., Doherty, P., and Radicella, S. (2016). Low latitude ionospheric scintillation and zonal plasma irregularity drifts climatology around the equatorial anomaly crest over kenya. *Journal of Atmospheric and Solar-Terrestrial Physics*, 138:9–22.
- Ossakow, S. L. (1979). Ionospheric irregularities. *Reviews of Geophysics*, 17(4):521–533.
- Palmer, P. I. (2017). The atmosphere: a very short introduction, volume 518. Oxford University Press.
- Panchuk, K., Lyashkov, A., and Lyubchinov, E. (2018). Geometric model of pseudo-distance measurement in satellite location systems. In *Journal of Physics: Conference Series*, volume 998, page 012021. IOP Publishing.
- Pérez-Fontán, F., Vazquez-Castro, M. A., Buonomo, S., Poiares-Baptista, J. P., and Arbesser-Rastburg, B. (1998). S-band lms propagation channel behaviour for different environments, degrees of shadowing and elevation angles. *IEEE transactions on broadcasting*, 44(1):40–76.
- Perperoglou, A., Sauerbrei, W., Abrahamowicz, M., and Schmid, M. (2019). A review of spline function procedures in r. *BMC medical research methodology*, 19:1–16.
- Poda, D. (2021). Scintillation in low-temperature particle detectors. *Physics*, 3(3):473–535.
- Priyadarshi, S. (2015). A review of ionospheric scintillation models. *Surveys in geophysics*, 36:295–324.

- Ramaswamy, V., Chanin, M.-L., Angell, J., Barnett, J., Gaffen, D., Gelman, M., Keckhut, P., Koshelkov, Y., Labitzke, K., Lin, J.-J., et al. (2001). Stratospheric temperature trends: Observations and model simulations. *Reviews of Geophysics*, 39(1):71–122.
- Rastogi, R. and Patel, V. (1975). Effect of interplanetary magnetic field on ionosphere over the magnetic equator. In *Proceedings of the Indian academy of sciences-Section A*, volume 82, pages 121–141. Springer.
- Razavi, A., Gebre-Egziabher, D., and Akos, D. M. (2008). Carrier loop architectures for tracking weak gps signals. *IEEE transactions on aerospace and electronic systems*, 44(2):697–710.
- Reid, G. C. (1976). Ion chemistry in the d region. In *Advances in atomic and molecular physics*, volume 12, pages 375–413. Elsevier.
- Ridley, A., Deng, Y., and Toth, G. (2006). The global ionosphere–thermosphere model. *Journal of Atmospheric and Solar-Terrestrial Physics*, 68(8):839–864.
- Rodrigues, F. d. S. (2008). Incoherent and coherent scatter radar studies of the equatorial f region.
- Rohli, R. V., Li, C., Rohli, R. V., and Li, C. (2021). Atmospheric composition, structure, and evolution. *Meteorology for Coastal Scientists*, pages 9–23.
- Santerre, R. (1991). Impact of gps satellite sky distribution. *Manuscripta geodaetica*, 16(1):28–53.
- Schubert, G., Turcotte, D. L., and Olson, P. (2001). *Mantle convection in the Earth and planets*. Cambridge University Press.
- Schunk, R. and Walker, J. (1973). Theoretical ion densities in the lower ionosphere. *Planetary and Space Science*, 21(11):1875–1896.
- Sen Mandi, S. and Sen Mandi, S. (2016). Natural ultraviolet radiation. *Natural UV Radiation in Enhancing Survival Value and Quality of Plants*, pages 1–22.
- Sharman, R., Trier, S., Lane, T., and Doyle, J. (2012). Sources and dynamics of turbulence in the upper troposphere and lower stratosphere: A review. *Geophysical Research Letters*, 39(12).
- Shulha, M. O. (2016). Investigation of the ion composition in the topside ionosphere at solar maximum using incoherent scatter technique. Master’s thesis, UiT Norges arktiske universitet.

- Shuman, N. S., Hunton, D. E., and Viggiano, A. A. (2015). Ambient and modified atmospheric ion chemistry: From top to bottom. *Chemical reviews*, 115(10):4542–4570.
- Sibiya, S. S. (2016). Integration of satellite system and Stratospheric Communication Platforms (SCP) for weather observation. PhD thesis, Durban University of Technology.
- Sim, C. Y. D. (2002). The propagation of VHF and UHF radio waves over sea paths. PhD thesis, University of Leicester.
- Sousasantos, J., de Oliveira Moraes, A., Sobral, J. H., Muella, M. T., de Paula, E. R., and Paolini, R. S. (2018). Climatology of the scintillation onset over southern brazil. In *Annales Geophysicae*, volume 36, pages 565–576. Copernicus Publications Göttingen, Germany.
- Srinivasu, V., Dashora, N., Prasad, D., Niranjana, K., and Krishna, S. G. (2018). On the occurrence and strength of multi-frequency multi-gnss ionospheric scintillations in indian sector during declining phase of solar cycle 24. *Advances in Space Research*, 61(7):1761–1775.
- Tandra, R. and Sahai, A. (2008). Snr walls for signal detection. *IEEE Journal of selected topics in Signal Processing*, 2(1):4–17.
- Tang, W., Wang, Y., Zou, X., Li, Y., Deng, C., and Cui, J. (2021). Visualization of gnss multipath effects and its potential application in igs data processing. *Journal of Geodesy*, 95(9):103.
- Tenerelli, J. E., Reul, N., Mouche, A. A., and Chapron, B. (2008). Earth-viewing l-band radiometer sensing of sea surface scattered celestial sky radiation—part i: General characteristics. *IEEE Transactions on Geoscience and Remote Sensing*, 46(3):659–674.
- Teunissen, P. J. (2020). Gnss precise point positioning. *Position, navigation, and timing technologies in the 21st century: integrated satellite navigation, sensor systems, and civil applications*, 1:503–528.
- Tian, F. (2015). Atmospheric escape from solar system terrestrial planets and exoplanets. *Annual Review of Earth and Planetary Sciences*, 43(1):459–476.
- Timoçin, E., Inyurt, S., Temuçin, H., Ansari, K., and Jamjareegulgarn, P. (2020). Investigation of equatorial plasma bubble irregularities under different geomagnetic conditions during the equinoxes and the occurrence of plasma bubble suppression. *Acta Astronautica*, 177:341–350.

- Ustin, S. L. and Middleton, E. M. (2021). Current and near-term advances in earth observation for ecological applications. *Ecological Processes*, 10(1):1.
- Utlaut, W. F. (1975). Ionospheric modification induced by high-power hf transmitters—a potential for extended range vhf-uhf communications and plasma physics research. *Proceedings of the IEEE*, 63(7):1022–1043.
- Vaille, A., Combi, M. R., Tennishev, V., Bougher, S. W., and Nagy, A. F. (2010). A study of suprathermal oxygen atoms in mars upper thermosphere and exosphere over the range of limiting conditions. *Icarus*, 206(1):18–27.
- Velinov, P. I., Asenovski, S., Kudela, K., Lastovicka, J., Mateev, L., Mishev, A., and Tonev, P. (2013). Impact of cosmic rays and solar energetic particles on the earth's ionosphere and atmosphere. *Journal of Space Weather and Space Climate*, 3:A14.
- Venkat Ratnam, M., Patra, A., and Krishna Murthy, B. (2010). Tropical mesopause: Is it always close to 100 km? *Journal of Geophysical Research: Atmospheres*, 115(D6).
- Wagner, L. and Goldstein, J. (1985). High-resolution probing of the hf ionospheric skywave channel: F2 layer results. *Radio Science*, 20(3):287–302.
- Wallace, J. M. and Hobbs, P. V. (2006). *Atmospheric science: an introductory survey*, volume 92. Elsevier.
- Wang, M., Chai, H., Liu, J., and Zeng, A. (2016). Bds relative static positioning over long baseline improved by geo multipath mitigation. *Advances in Space Research*, 57(3):782–793.
- Williamson, C. E., Neale, P. J., Hylander, S., Rose, K. C., Figueroa, F. L., Robinson, S. A., Häder, D.-P., Wängberg, S.-Å., and Worrest, R. C. (2019). The interactive effects of stratospheric ozone depletion, uv radiation, and climate change on aquatic ecosystems. *Photochemical & Photobiological Sciences*, 18(3):717–746.
- Witvliet, B. A. (2015). Near vertical incidence skywave: interaction of antenna and propagation mechanism.

- Wright, J., Argo, P., and Pitteway, M. (1996). On the radiophysics and geophysics of ionogram spread f. *Radio Science*, 31(2):349–366.
- Wu, J., Tang, X., Li, Z., Li, C., and Wang, F. (2019). Cascaded interference and multipath suppression method using array antenna for gnss receiver. *IEEE Access*, 7:69274–69282.
- Xie, J., Wang, H., Li, P., and Meng, Y. (2021). *Satellite navigation systems and technologies*. Springer.
- Xu, D., Morton, Y., Jiao, Y., Rino, C., and Yang, R. (2018). Implementation and performance evaluation of a vector-based receiver during strong equatorial scintillation on dynamic platforms. In *Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018)*, pages 3611–3622.
- Xu, Z.-W., Wu, J., and Wu, Z.-S. (2004). A survey of ionospheric effects on space-based radar. *Waves in Random media*, 14(2):S189.
- Yasyukevich, Y., Vasilyev, R., Ratovsky, K., Setov, A., Globa, M., Syrovatskii, S., Yasyukevich, A., Kiselev, A., and Vesnin, A. (2020). Small-scale ionospheric irregularities of auroral origin at mid-latitudes during the 22 june 2015 magnetic storm and their effect on gps positioning. *Remote Sensing*, 12(10):1579.
- Yeh, K. C. and Liu, C.-H. (1982). Radio wave scintillations in the ionosphere. *Proceedings of the IEEE*, 70(4):324–360.