ANALYSIS OF IONOSPHERIC EFFECTS ON GROUND-BASED AUGMENTATION SYSTEM (GBAS) AT KLIA, MALAYSIA

by

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ENDORSEMENT

I, Amira Nur'Izzah Binti Zamzuri hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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Date: 8/7/2021

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date: 6th July 2021

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ANALYSIS OF IONOSPHERIC EFFECTS ON GROUND-BASED AUGMENTATION SYSTEM (GBAS) AT KLIA, MALAYSIA

ABSTRACT

Instrument Landing System (ILS) is recognised by ICAO as a standard precision landing aid that provides accurate location and descent guidance for aircraft to land on the runway. An alternative to the ILS, Global Positioning System (GPS) is implemented for aircraft navigation. The current GPS navigation system cannot meet the real-time integrity monitoring required for safety needs in the aviation system. Therefore, several augmentation systems have been introduced to overcome the limitation. Global Based Augmentation System (GBAS) is one of the augmentation systems that enhanced the levels of service supporting all phases of approach, landing, departure, and surface operations. Ionospheric scintillation is the abnormality that occurs in the signal transmission during GBAS operation. It is produced by ionising radiation from the Sun and controlled by chemical interactions and transport by diffusion and neutral wind. Sufficiently intense will cause irregularities during transmission that scatter the radio waves and generate rapid fluctuations (or scintillation) in the amplitude and phase of radio signals. Data acquired from the GBAS installed at Kuala Lumpur International Airport was observed to measure the S_4 values indicating the strength of amplitude scintillation. Due to insufficient data obtained, a full year of data analysis is incomplete. However, the data is enough to conduct studies on how ionospheric scintillation can affect the GBAS operation. An equinox month suspected of the ionospheric scintillation to occur was selected to ease the study. Selected data is used to observe the behaviour of the S_4 values, and a comparison is made from that data. This is to analyse the effect of the scintillation on the signal transmission process and their effect on the GBAS system. There is a distinct difference in the three receivers located at GBAS in KLIA, Malaysia. It is found that the maximum S_4 values and the time of its occurrence are different between the three receivers.

Results show that only low ionospheric scintillation is present during the operation as the signals fluctuate when received by the GPS receiver. The highest number of PRN that experienced weak scintillation is on the 11th, 12th and 27 of September 2017, with the maximum S_4 value of 0.3492, 0.3325 and 0.3387. Meanwhile, only four PRN on 6th and 13th March 2018 experienced weak scintillation with a maximum value of 0.3735 and 0.3350. The results indicate that the highest S_4 values occur in the month cannot affect the GBAS system as it is not intense. There is no high scintillation event in September 2017 and March 2018 as it is during solar minimum.

ANALISIS KEJADIAN SINTILASI IONOSFERA PADA SISTEM GBAS DI KLIA, MALAYSIA

ABSTRAK

Instrument Landing System (ILS) diakui oleh ICAO sebagai alat bantuan mendarat yang menepati piawai berfungsi untuk memberikan petunjuk lokasi dan ketepatan yang tepat untuk pesawat mendarat di landasan. Sebagai alternatif kepada ILS, Global Positioning System (GPS) dilaksanakan untuk navigasi pesawat. Sistem navigasi GPS terkini tidak dapat memenuhi pemantauan integriti masa nyata yang diperlukan untuk keperluan keselamatan dalam sistem penerbangan. Oleh itu, beberapa sistem pembesaran telah diperkenalkan untuk mengatasi batasan tersebut. Global Augmentation System (GBAS) adalah salah satu sistem pembesaran yang meningkatkan tahap perkhidmatan dengan menaik taraf semua tahap operasi menghampiri, pendaratan, berlepas, dan permukaan pesawat. Sintilasi Ionosfera adalah sesuatu kelainan yang berlaku ketika penghantaran isyarat semasa operasi GBAS. Ia dihasilkan melalui pengionan dari Matahari dan dikawal oleh interaksi kimia serta dibawa melalui penyebaran dan angin neutral. Sintilasi yang cukup kuat akan menyebabkan penyimpangan semasa penghantaran signal yang menyebarkan gelombang radio mengalami turun naik dengan cepat pada amplitud dan fasa isyarat radio. Data yang diperoleh dari GBAS yang digunakan di Lapangan Terbang Antarabangsa Kuala Lumpur dikaji untuk mengukur nilai S_4 yang menunjukkan kekuatan sintilasi amplitud. Oleh kerana data yang diperoleh tidak mencukupi, data yang dianalisis setahun tidak lengkap. Walau bagaimanapun, data tersebut cukup untuk mengkaji mengenai bagaimana sintilasi ionosfera dapat mempengaruhi operasi GBAS. Untuk memudahkan kajian ini, bulan ekuinoks yang disyaki terdapatnya sintilasi ionosfera telah dipilih untuk menjalankan kajian. Data yang dipilih digunakan untuk melihat turun naik nilai-nilai S_4, dan perbandingan telah dibuat dari data tersebut. Ini adalah untuk menganalisis kesan sintilasi pada proses penghantaran isyarat dan kesannya terhadap sistem GBAS. Terdapat perbezaan yang ketara pada ketiga-tiga alat penerima signal yang terletak di GBAS, KLIA, Malaysia. Didapati bahawa nilai maksima S_4 dan masa ketika ia berlaku adalah berbeza antara ketiga-tiga alat penerima signal. Hasil kajian menunjukkan bahawa hanya terdapat sintilasi ionosfera yang rendah semasa operasi menyebabkan isyarat berubah-ubah ketika diterima oleh alat penerima. Bilangan tertinggi PRN yang mengalami sintilasi lemah ialah lima iaitu pada 11, 12 dan 27 September 2017, dengan nilai maksimum S_4 adalah 0,3492, 0,3325 dan 0,3387. Sementara itu, hanya terdapat empat PRN pada 6 dan 13 Mac 2018 yang mengalami sintilasi lemah dengan nilai maksimum 0.3735 dan 0.3350. Hasil kajian menunjukkan bahawa nilai S_4 tertinggi yang berlaku pada bulan tersebut tidak dapat mempengaruhi sistem GBAS kerana tidak kuat. Tidak terdapat sintilasi yang tinggi pada bulan September 2017 dan Mac 2018 kerana ia berlaku ketika minima solar.

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LIST OF ABBREVIATIONS

GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GBAS	Ground-Based Augmentation System
O	Observation file
N	Navigation file
PPS	Precise Positioning System
PRN	Pseudo-Random Number
RF	Radio Frequency
RINEX	The Receiver Independent Exchange Format
SPS	Standard Positioning System
SV	Satellite Vehicle
TEC	Total Electron Content
TOW	Time of Week
UTC	Coordinated Universal Time

LIST OF SYMBOLS

S_4 : Amplitude Scintillation Index

$\langle \bullet \rangle$: Average value over the interval of interest

S/N_0 : Signal-to-noise ratio

$\sigma_{\Delta\phi}$: Standard deviation for phase scintillation

E_S : Sporadic E layer

CHAPTER 1

INTRODUCTION

1.1 Research Background

Global Positioning System (GPS) is a navigation system that provides exact locations on the Earth by transmitting signals from GPS satellites. This project will focus on the Ground-Based Augmentation System (GBAS), a safety-critical system that augments the GPS standard positioning service. The GBAS provides enhanced levels of service supporting all phases of approach, landing, departure and surface operations within its area of coverage (Gaglione & Vultaggio, 2004). GBAS implementation aims to provide an alternative to Instrument Landing System (ILS), which is the traditional method of aircraft approach and landing operation.

Comparison can be made between the two systems as GBAS can support multiple runway ends and reduce the total number of systems used at an airport and, therefore, lessen operation costs. The GBAS monitors and corrects the errors caused by the Global Navigation Satellite System (GNSS). It provides precise navigation and approach data through VHF frequency and ground-based transmitters to all airports and runways located within 23 nm (Rodriguez, 2010). Besides, the GBAS approach guidance is steadier than the ILS approach guidance. However, some errors and abnormalities can appear in the system.

The signal transmitted from GPS satellites can also lose during transmission. The radio wave propagates into the Ionosphere, located at 60 km to 600 km above Earth's surface. The greatest concentration of free electron and ionized plasma consists in this region. Ionospheric irregularities are small-scale disturbances in the Ionosphere that may cause the signal propagation to experience rapid amplitude and phase variations, known as ionospheric scintillation. The strongest scintillations are most frequently observed when the solar terminator best aligns with the geomagnetic declination line (Mersha et al., 2021).

Data acquired from the GPS receiver at GBAS in KLIA will be used to analyse this event. The data given is a one-year data which is from September 2017 to September 2018. Parameter used to measure the scintillation happening during the signal transmission will be obtained after converting the raw data using the NOVATEL converter application and GOPI software.

This thesis will focus on the effects of ionospheric scintillation on the GBAS system at KLIA. The signal received by the GPS receiver is observed to identify the event’s occurrence based on its daily occurrence and time occurrence.

The thesis starts with Chapter 1, where it will introduce the title of this project; ionospheric effects on the GBAS at KLIA, Malaysia and the relevance of the study, as well as the problem statement that initiate this study and the main goal that needs to be achieved throughout the completion of this project. The remainder of this paper is organized as follows: Chapter 2 describes the theory part of the Ionosphere, introduce the ionospheric scintillation and how to measure it, the working principle for the GBAS and how the signals can be affected during transmission. Chapter 3 provides detailed guidance and directions to operate the hardware and software used to conduct this study. Chapter 4 will discuss the outcome of the studies made based on the processed data and the simulation. In the last part of this chapter, the impacts of the ionospheric gradient on the GBAS in KLIA is analysed. , the ionospheric parameter of Guangdong Province is analysed. Chapter 5 presents our conclusions and recommendation to further enhance the outcome results and have better analysis in the future.

1.2 Problem Statement

GBAS works by transmitting radio signals from the GPS satellites to the three GPS receivers at the ground station. The signals will propagate through the Ionosphere, consisting of free electrons and ionized plasma roaming freely within the region. Significant irregularities in the electron density will arise a problem in the radio signals propagation. The signals experience rapid fluctuation in the form of amplitude or phase. These phenomena are known as ionospheric scintillation. The signals that are passing through the region of irregularities will be perturbed due to the process of refraction and diffraction. To compute a more accurate GPS position, velocity and time to safely guide the aircraft to land on the runway, GBAS is designed to improve the GNSS system by using a differential correction broadcast by the ground station to adjust the error.

However, in the equatorial area, delay magnitudes can vary quite rapidly over short distances and thus may not be adequately mitigated even after the corrections from the GBAS ground station are applied. This will result in the complete loss of signal lock and generate various errors in GPS navigation data. The most significant manifestation of such disturbances often takes place in the equatorial region such as Malaysia. The equatorial electrojet and accompanying equatorial anomaly, greater absorption, and the geomagnetic field orientation being nearly horizontal are the reason for this event (Abdullah, 2009).

Therefore, this project will focus on studying the effect of ionospheric scintillation on the GBAS in KLIA, Malaysia, using the data retrieved from KLIA which was dated back in 2017. The ionospheric scintillation occurrence based on amplitude scintillation will be identified in the data using the $S4$ index will be used as an indicator. One of the processed data is then selected to be simulated. The scintillation effect is observed on the GPS receiver in the GBAS ground station when the scintillation parameter is amplified.

1.3 Objective

The objectives of this project are:

i. To identify the occurrence of ionospheric scintillation during the period of data collection.

ii. To analyse the ionospheric scintillation effect on the ground-based augmentation system (GBAS) at KLIA Malaysia.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter begins with an overview of the Global Navigation Satellite System (GNSS). One of the GNSS components is Global Positioning System (GPS). In 1973, the United States Department of Defense originally developed a system for three–dimensional position determination referred to as Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (Sabatini et al., 2017). At this time, GPS was only for military use but was later made accessible to civilians. Providing a precise location positioning anywhere on the Earth, the GPS has contributed a lot to the aviation system. To improve the performance of GNSS systems in flight operation, augmentation systems like Satellite Based Augmentation System (SBAS) and Ground-Based Augmentation System (GBAS) was introduced. GBAS is the most recent augmentation system that improves the lack of safety performances of GNSS.

Although the GBAS ground subsystem generates differential correction and integrity messages from three or more (usually four) sets of ground GNSS antenna and receivers, spatial decorrelation of ionospheric propagation delay is an error source for GBAS precision. The second part of this chapter summarises the causes of this major error, the ionospheric scintillation event. Occur at the Ionosphere region, which is 60 km to 600 km from the ground, the differential correction of GBAS cannot escape the significant spatial changes of ionospheric delay contributed by this event.

2.2 GNSS

International Civil Aviation Organization (ICAO) had defined the Global Navigation Satellite System (GNSS) as a worldwide position and time determination system consist of one or more satellite, aircraft receiver and augmented monitoring systems. It is used to support navigation performance for certain operations, for example, in a flight operation (Rodriguez, 2010; García & Corpac, 2018). GNSS simply refers to a system where the satellite provides the signals from space and transmits positioning and timing data to receivers. The receivers then use this data to determine location. Various GNSS systems are under development, such as the European GALILEO and the People's Republic of China BEIDOU Navigation Satellite System (BDS). Meanwhile, the US GPS and the Russian Globalnaya Navigazionnaya Sputnikovaya Sistem (GLONASS) have entirely operated since the 1990s (Sabatini et al., 2017).

The severity of ionospheric scintillation, Doppler shift, multipath, jamming and spurious satellite transmissions will lead to partial to total loss of tracking and possible tracking errors (Daly, 1995).

2.2.1 GPS

Global Positioning System (GPS) is a navigation system that provides exact locations on the Earth by transmitting signals from GPS satellites. The government of the United States introduced the system by the United States Air Force. Since 1994, they offered the ICAO the GPS standard positioning service (SPS) to support the needs of international civil aviation (de Andrade Santoro, 2013). Flying in medium Earth orbit (MEO) at an altitude of approximately 20 200 km orbits at an inclination angle of 55 degrees to the equator, there are 24 satellites in six orbital planes designed for the GPS space segment (Kaplan, 2006).

There are four GPS signal specifications designed for civilian use. In order of date of introduction, these are L1 C/A, L2C, L5 and L1C. GPS SPS, which operates on the L1 frequency (1 575.42 MHz) and uses a coarse acquisition (C/A) code, is meant to offer accurate positioning for civilian users worldwide. A precise positioning service (PPS), which uses the Precise Code (P-code) on a second frequency L2 (1 227.6 MHz), gives more exact positioning. Still, it is encrypted, so only approved agencies can use it (de Andrade Santoro, 2013).

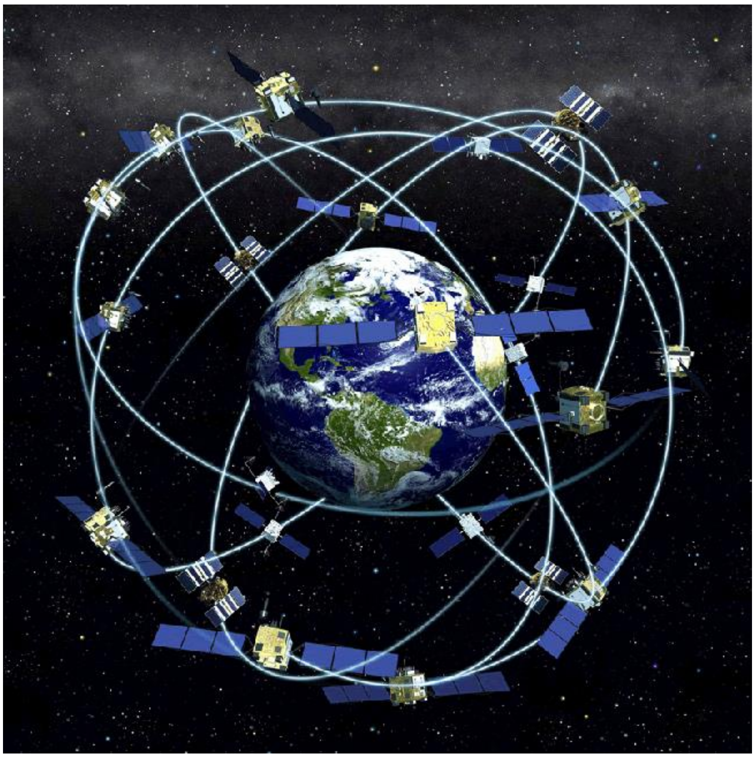

Figure 1. GPS satellites orbit the Earth

2.2.2 GPS in Aviation

Instrument Landing System (ILS) is recognised by ICAO as a standard precision landing aid that provides accurate location and descent guidance for aircraft to land on the runway. An alternative to the ILS, GPS is implemented for aircraft navigation. However, the current GPS navigation system cannot meet the real-time integrity monitoring required for safety needs in the aviation system. Therefore, several augmentation systems have been introduced to overcome the limitation. Global Based Augmentation System (GBAS) has been submitted by the U.S airspace that enhanced the levels of service supporting all phases of approach, landing, departure and surface operations (Gaglione & Vultaggio, 2004).

2.2.3 Ground-Based Augmentation System (GBAS)

GBAS consist of three subsystems which is a ground station, aircraft receiver and satellites. At the GBAS ground station, three or more GPS antennas, a central processing system that acts as a computer to generate data and a Very High Frequency (VHF) Data Broadcast (VDB) transmitter are located nearby the airport (Rodriguez, 2010). Figure 1 shows a VHF radio link is linked to the ground station to provide aircraft with GPS corrections, integrity, and approach path information. Meanwhile, the aircraft GBAS equipment consists of a GPS antenna, VHF antenna and related processing equipment. The installation of Multi-Mode Receiver (MMR) technology allows the implementation of GPS, GBAS and ILS simultaneously using common antennas and hardware (Rodriguez, 2010).

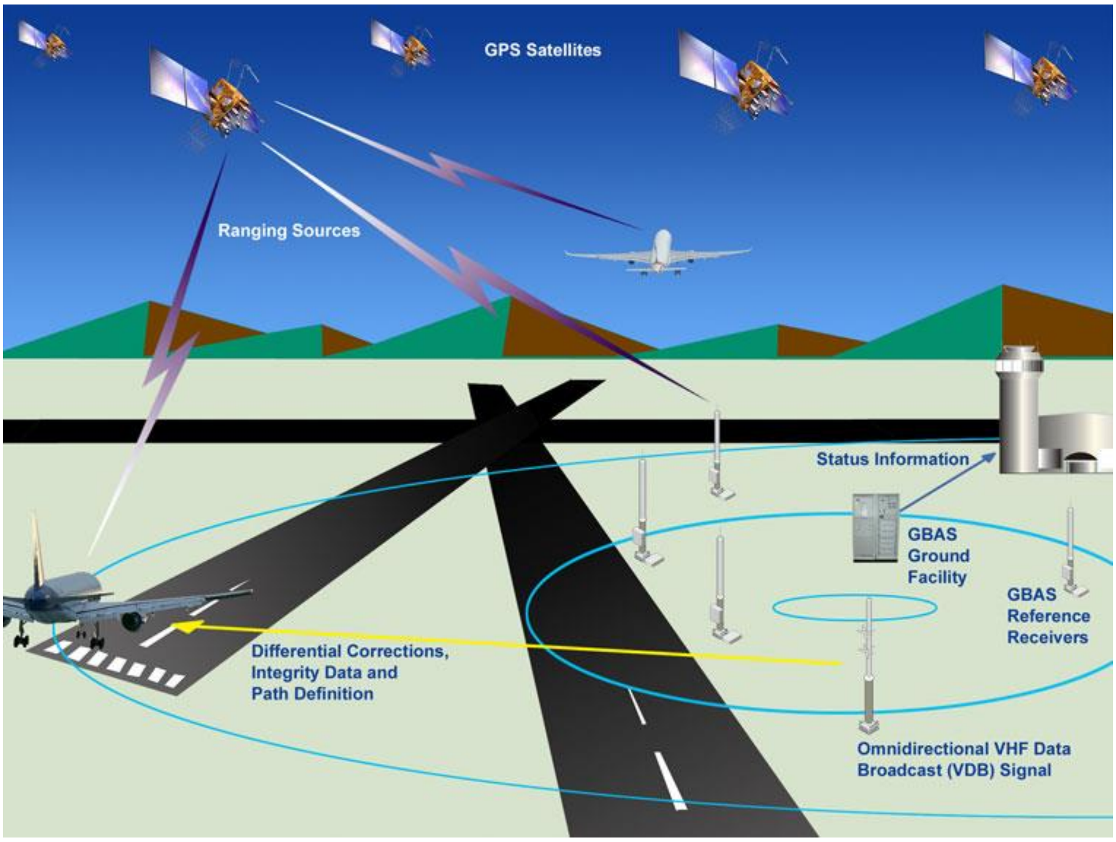

Figure 2. GBAS facilities

2.2.3.1 GBAS Operation

Starting from GBAS reference antennas in known surveyed positions, the GPS receivers will receive a signal from the GPS satellites. These receivers will measure the signal transmission time and the distance travelled. The speciality of the GBAS ground facility is that it can determine the signal error by comparing those measured distances with the actual distance between the satellite position and the GPS reference receiver position (Steen et al., 2012). The measured average error represents the correction term that needs to be modified on the satellite ranges measured by the GBAS avionics. The GBAS ground station observes the GPS satellite performance. When it detects any abnormality of the GPS satellite, or it cannot monitor the satellite activity, the GBAS ground facility will stop broadcasting the signal from that particular satellite. Hence, it can prevent the GBAS avionics from using that problematic satellite (Alexandre & Esteves, 2007).

GBAS ground facility can also permit the GBAS avionics to determine the bound on the likely incorrect calculated GPS position about one time per ten million calculations to prove the calculated position is correct (Yoon et al., 2019). GBAS ground facility then sends the correction message to the VDB transmitter, as shown in Figure 2. Broadcasting will update the correction message two times every second by using VDB. These messages contain corrections, integrity parameters, GBAS Ground Facility characteristics and approach path guidance for up to 48 approaches(Rodriguez, 2010). VDB transmitter broadcasts the GBAS signal to avionics in GBAS-equipped aircraft within the GBAS coverage area approximately a thirty-seven-kilometre radius. Thus, it can cover from the airspace terminal to the precision approaching and landing of the aircraft (Alexandre & Esteves, 2007).

To compute a more accurate GPS position, velocity, and time to safely guide the aircraft to land on the runway, the aircraft's GBAS equipment also uses the correction. However, the current system can only operate with a minimum of 200 feet above the touchdown (Kaplan & Hegarty, 2006). Research and development are being continued to extend the operation limit all the way to the runway surface.

2.2.3.2 GBAS Advantages

Nowadays, a precision system such as GBAS becomes demanded, especially at airports with geographical difficulties in making a precision approach. This geographical difficulties issue had preceded many aviation accidents because of the incapable of precise approach systems. However, GBAS has a few advantages that can ease flight operation and tighten the level of safety.

Firstly, GBAS installation and maintenance are low compare to ILS and other augmentation systems. One of the ILS features is it needs to be positioned explicitly for each runway (Rodriguez, 2010). GBAS has a benefit in which it can support more than one runway service at a lower cost. Having only one ground system can provide information to all runways at the nearby airports where it is known (Rodriguez, 2010; Steen et al., 2012).

Any disturbance in the signal pattern will cause a deviation. GBAS has a lower critical and sensitive area compared to the other precision approach system. GBAS can reduce the operational impact of vital and sensitive areas that lead to increased airport operational capabilities as it does not use antenna patterns to compose the navigation signal (de Andrade Santoro, 2013). The site constraints are more related to signal blockage and multipath effects. Besides, GBAS allow the aircraft to use a curved approach by providing lateral and vertical guidance (de Andrade Santoro, 2013). This is necessary because it creates a procedure allowing the aircraft to avoid flying over the specific areas near the airports and reduce the noise over the urban areas.

GBAS positioning service provides horizontal position information to support area navigation (RNAV) operations within the service area (de Andrade Santoro, 2013). RNAV is a method of instrument flight rules (IFR) navigation that allows an aircraft to choose any course within a network of navigation beacons rather than navigate directly to and from the beacons. Its component consists of lateral navigation and longitudinal navigation. This GBAS feature allows the increase of positioning precision information.

Comparing to other augmentation systems such as Aircraft-Based Augmentation System (ABAS) and Satellite-Based Augmentation System (SBAS), GBAS is safer for the aircraft navigation operation by offering more signal stability (Rodriguez, 2010). In addition, GBAS has no beam bending that prevents radio frequency interference from happening. Federal Aviation Administration also already stated that GBAS approach guidance is steadier than ILS approach guidance and requires less frequent flight inspections.

Raphael Guillet, 2019 the ICAO Asia Pacific Regional Sub-Office chief, has also added a few advantages of GBAS in his research, such as increasing airspace capacity and reducing environmental impact since GBAS only needs one system to assist all runways (Guillet, 2019).

2.2.3.2 GBAS Disadvantages

Being the most advanced augmentation system does not mean it does not have any flaws. For data transmission, GBAS uses navigation satellite frequencies and VHF frequencies. Both frequency bands are susceptible to suffer interference that can even block the signal (de Andrade Santoro, 2013).

The most challenging threat to this system is the extremely large spatial decorrelation in the Ionosphere during ionospheric storms leading to rapid fluctuations in the power and phase of the received signal (Jung & Lee, 2012). Different GNSS systems have different ways of correcting these ionospheric delays. For example, Single-frequency GBAS avionics systems use differential corrections broadcast by the ground station to adjust this error.

However, in the equatorial area, delay magnitudes can vary quite rapidly over short distances and thus may not be adequately mitigated even after the corrections from the GBAS ground station are applied. In addition, greater impacts of the Ionosphere, particularly with the phenomena of scintillation and plasma bubbles, will cause errors to the GBAS receivers and lose information from satellites.

Lee, Pullen, Datta-Barua, & Lee, 2017 have developed a real-time ionospheric threat modification method to mitigate this threat. A threat model that studies the delay difference between two points, the distance between the points, and the wavefront speed was conducted. They found that the reliability of GBAS was much higher than that of existing systems, arguing that the ionospheric effects could be corrected by 95% by analysing the weather forecast data obtained between 1995 and 2011 (Jinsil Lee et al., 2017).

2.3 The Ionosphere

The Ionosphere is where Extreme Ultra Violet (EUV) and solar x-ray radiation ionizes the atoms and molecules, thus creating a layer of electrons. It is located at 60 km to 600 km above Earth’s surface, called the Ionosphere region. This region is split into several layers; the D layer, E layer, F layer separates into F1 and F2 and affects the propagation of radio signals & radio communications differently.

The lowest layer of the Ionosphere is the D-layer that exist at an average height of 70 km. It exists only during the day, and its electron density is N = 400 electrons/cm^3. It absorbs MF and HF waves to some extent but reflects some VLF and LF waves. The ionization depends on the Sun’s altitude above the horizon (Stein, 1958).

Following the D-layer, E-layer thickness is about 25 km in the Ionosphere region and exist at altitudes between about 100 and 125 km. It also exists during the day and reflects some HF waves during its existence. E-layer have an electron density of N = 2x10^5 electrons/cm^3 (Gupta & Upadhayaya, 2019). At night, this layer disappears because the ions are recombined into molecules due to the absence of the Sun. E_s-layer is a sporadic E-layer that exist during the day and night. It appears closely to E-layer, has a thin layer, and its ionization density is quite high.

F-region of the Ionosphere, the latitude of 250 to 400 km from the ground, contains the greatest concentration of free electrons. Sometimes, it is highly ionized and develops small-scale irregularities as it experiences the most solar radiation (IONO Group & Walter, 2010). When sufficiently intense, these irregularities scatter radio waves and generate rapid fluctuations (or scintillation) in the amplitude and phase of radio signals.

2.3.1 Ionospheric Scintillation

Ionospheric scintillation is present due to the irregularities of electron density and plasma in the Ionosphere. Scintillations are intense in the equatorial region; they are strong at high latitudes and weak at mid-latitudes. Therefore, to study the causes of the irregularities, observation of ionospheric behaviour at these regions are quite important. However, at low latitudes, the enhancement of the eastward electric field, which are generally developed at the F-region height, and sunset time could be a major factor causing scintillation (Seif et al., 2012). Possible causes of these electron-density irregularities are plasma bubble (Ma et al., 2020; Aol et al., 2020), sporadic E-layer add to the effects of spread-F anomalies (Abdu et al., 2014), equinox season (Abadi et al., 2014; Steenburgh et al., 2008), and ionisation near the auroral zones at high latitudes due to an influx of energetic charged particles (Fagundes et al., 2016; Wernik et al., 2004).

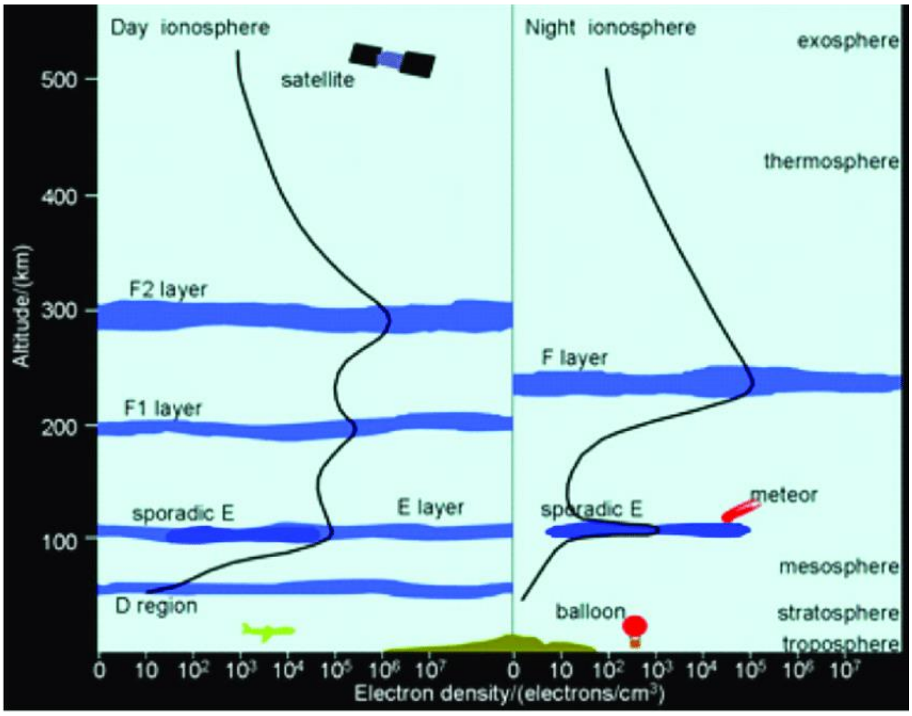

Figure 3. Different electron density on each layer of the Ionosphere (Singh, 2017)

When the Sun stops ionising the Ionosphere, plasma bubbles form after dark. Ionospheric F-region irregularities due to the Rayleigh–Taylor gravitational instability processes that recombine all the ions. It originated at the bottom of the F-region during post-sunset, rising to the topside of the Ionosphere by adding more ionized layers through convection, forming plasma bubbles that develop irregularities to produce severe scintillation. Abadi, Saito & Srigutomo, 2014 reported more frequent and stronger scintillations associated with the plasma bubble during the maximum solar period, a drastic reduction in the frequency and intensity of scintillations during the minimum solar period. A single plasma bubble can cause a vertical positioning error of more than 10m (Rungraengwajiake et al., 2015). Scintillation can happen at low latitude when the solar terminator is most closely aligned with the geomagnetic meridian. It is during equinox seasons from March to April and September to October (Mersha et al., 2021). Figure 4 shows the trend of the solar cycle since 2010.

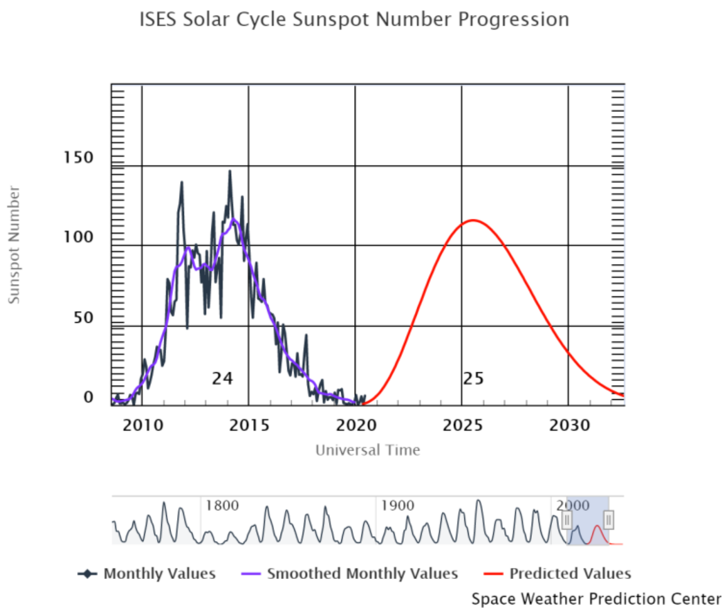

Figure 4. Solar Cycle Sunspot Number Progression.

E-layer is the middle layer of the Ionosphere at approximately 90–120 km above the Earth's surface. Ion recombination is faster at the low layers during nighttime as E-layer begins to disappear. The sporadic E (Es) layer is a non-uniform and highly wavy thin layer identified by tiny clouds of elevated electron density that can appear anywhere from minutes to hours during the night and day (Abdu et al., 2014). The occurrence of Es during the daytime can cause strong scintillation, while Es add to the effects of spread-F irregularities on ionospheric scintillation during the nighttime (Seif et al., 2012).

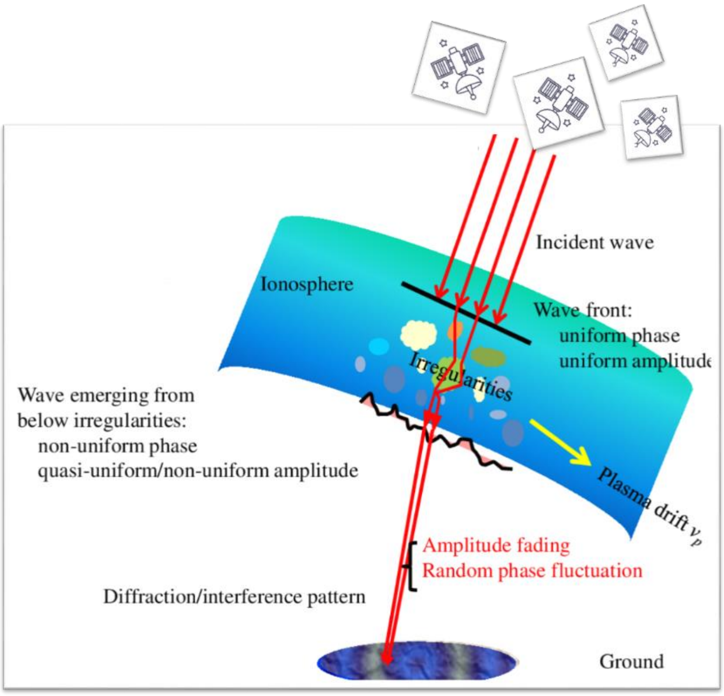

Figure 5. Ionospheric scintillation occurs due to the irregularities

At high latitude, ionospheric produce from a complex interaction of the Earth's magnetic field with the solar wind and the interplanetary magnetic field. The central polar region (greater than 75° magnetic latitude) is surrounded by a ring of increased ionospheric activity called the auroral oval. At night, energetic particles, trapped by magnetic field lines, are precipitated into the auroral oval forming an irregular electron density (IONO Group & Walter, 2010). Observations of auroral scintillations were also done using an ionospheric scintillation monitor at the FAA's National Satellite Test Bed in Fairbanks, Alaska, in 1999-

2000. There were little amplitude scintillations in Fairbanks, but there were a lot of phase scintillations. The S_4 for amplitude scintillation varied from 0.2 to 0.4 and the percentage of occurrence was less than 0.2% during the observation. However, phase scintillation happened up to 20% of the time at low and moderate levels (Skone et al., 2005).

2.3.2 Amplitude Scintillation

Small-scale irregularities in electron density can interfere with the signal, causing it to face a rapid drop, known as amplitude scintillation. During the event, the irregularities scatter the signal in random directions about the principal propagation direction. As the signal propagates down to the ground, small changes in the propagation distance along the scattered ray paths cause the signal to interfere with itself.

This amplitude scintillation is measured by the S_4 index that is derived from the signal intensity received from satellites. Signal intensity is actually received signal power, which is measured in a way that its value does not fluctuate with noise power (Van Dierendonck & Arbesser-Rastburg, 2004). The total amplitude scintillation index, S_{4T}, including the effects of ambient noise, is defined as follows:

$$S_{4T} = \sqrt{\frac{\langle s_i \rangle^2 - \langle s_i \rangle^2}{\langle s_i \rangle^2}} \tag{1}$$

Where,

S_{4T} = Total amplitude scintillation index

s_i = Satellites signal intensity

< > = Average value over the interval

Due to ambient noise, the total S_4 defined in Eq. 3 measured at L-band can have large values. It is because the ambient noise at L-band channel frequency translates to a relatively high S_4 at lower frequency VHF and UHF frequencies band (Abdullah, 2009). Therefore, to determine the expected S4 due to ambient noise, we need to estimate the average signal-to-noise density over the entire evaluation interval (60 sec). If the signal-to-noise density (S/N) is known, the predicted S4 due to ambient noise is:

$$S_{4T} = \sqrt{\frac{100}{S/N}\left(1+\frac{500}{19S/N}\right)} \tag{2}$$

Where:

S/N = Signal-to-Noise density

Subtracting Equation 1 from Equation 2 yields the corrected value of S4 as follows:

$$S_{4T} = \sqrt{\frac{\langle s_i\rangle^2 - \langle s_i\rangle^2}{\langle s_i\rangle^2} - \frac{100}{S/N}\left(1+\frac{500}{19S/N}\right)} \tag{3}$$

Abadi, Saito & Srigutomo, 2014 have stated an example of how the $\boldsymbol{S_4}$ index strength can be categorized as below.

$\boldsymbol{S_4}$ **Index Range**	**Strength**
$\boldsymbol{S_4 \leq 0.25}$	Quiet
$\boldsymbol{0.25 < S_4 \leq 0.5}$	Moderate
$\boldsymbol{0.5 < S_4 \leq 1}$	Disturbed
$\boldsymbol{S_4 > 1}$	Severe

Table 2.1 Example of S4 categorization*(Abadi et al., 2014)*

2.3.3 Phase Scintillation

Phase scintillation relates to rapid fluctuation in the carrier-phase measurements. These same irregularities can cause increased phase noise, cycle slips, and even loss of lock if the phase fluctuations are too rapid for the receiver to track (IONO Group & Walter, 2010). Unlike amplitude scintillation, $\sigma_{\Delta\varphi}$ are computed over 1, 3, 10, 30 and 60-second intervals every 60 seconds.

2.4 Effect Of Ionospheric Scintillation On GBAS

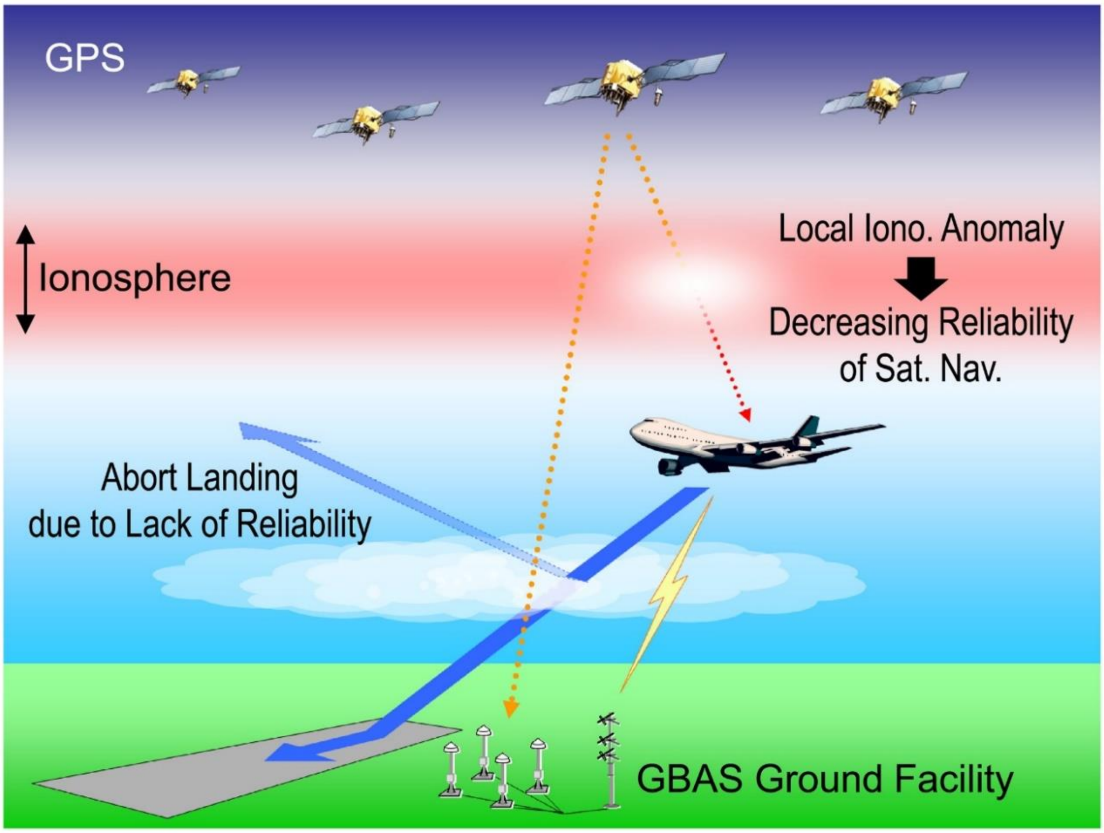

Figure 6. Effect of ionospheric scintillation on GBAS(Fujiwara & Tsujii, 2016)

Although GBAS is designed to improve the old augmentation system, spatial decorrelation of ionospheric propagation delay is one of the error sources for GBAS precision approaches, as mentioned above. GBAS system can protect users from the spatial decorrelation effects of ionospheric delay under “nominal” conditions within a certain range covered by the evaluation parameters. However, large spatial changes of ionospheric delay, which exceed the range assured by the broadcasted evaluation parameters, can cause integrity loss (Apanpirg/27, 2016).

GBAS users and GBAS ground facilities may experience different ionospheric delays, leading to considerable differential errors, which threaten the safety of users (Wang et al., 2017). Ionospheric delays can contribute several meters of error in an aircraft’s landing position. It must be corrected in real-time for a precision approach where there is little or no visibility. Wang, Wang, Zhu, & Xin, 2017 have stated that the maximum differential correction error of GBAS maybe 5 m, which can cause an airworthiness risk for the high elevation situations in their research of ionospheric gradient impacts on the GBAS system in Guangdong Province, China and (Wang et al., 2017). They conclude that when ionospheric storms occur, the use of extremely high elevation satellites for the GBAS should be reduced.

If electron density irregularities cover a large portion of the Ionosphere, there is a chance that a receiver may lose more than one satellite simultaneously. Simultaneous loss of a significant number of satellites will lead to discontinuity in communication and navigation (Seif et al., 2012).

Under anomalous ionospheric conditions, positioning errors larger than the computed protection levels may occur. These user-computed protection levels indicate upper bounds of user positioning error for lateral and vertical directions derived from evaluation parameters broadcast in GBAS messages (Apanpirg/27, 2016). Furthermore, suppose the undetected anomalous gradient occurs with the worst-case geometry. In that case, Ionosphere induced range errors increase as the effective separation between the GBAS ground facility and an approaching aircraft increases (Jiyun Lee et al., 2011).

CHAPTER 3

METHODOLOGY

This chapter presents how to process the acquired data from the three GPS receivers at the KLIA GBAS ground station. A sequence of steps to obtain the outcome is shown in this chapter. Section 3.1 describes the overall flowchart of the data processing from all the software involved and continues with section 3.2, representing the raw data recorded by the GPS receiver. All the software used to process the data are demonstrated in Section 3.3. Next to this section, the process or steps to obtain the output data are explained in detail. Section 3.5 defines the output data used to measure the scintillation event, which is the S_4 index value. The last section of this chapter shows the final output graph data constructed to analyse the scintillation event that existed in the GBAS system.

3.1 Overall flowchart

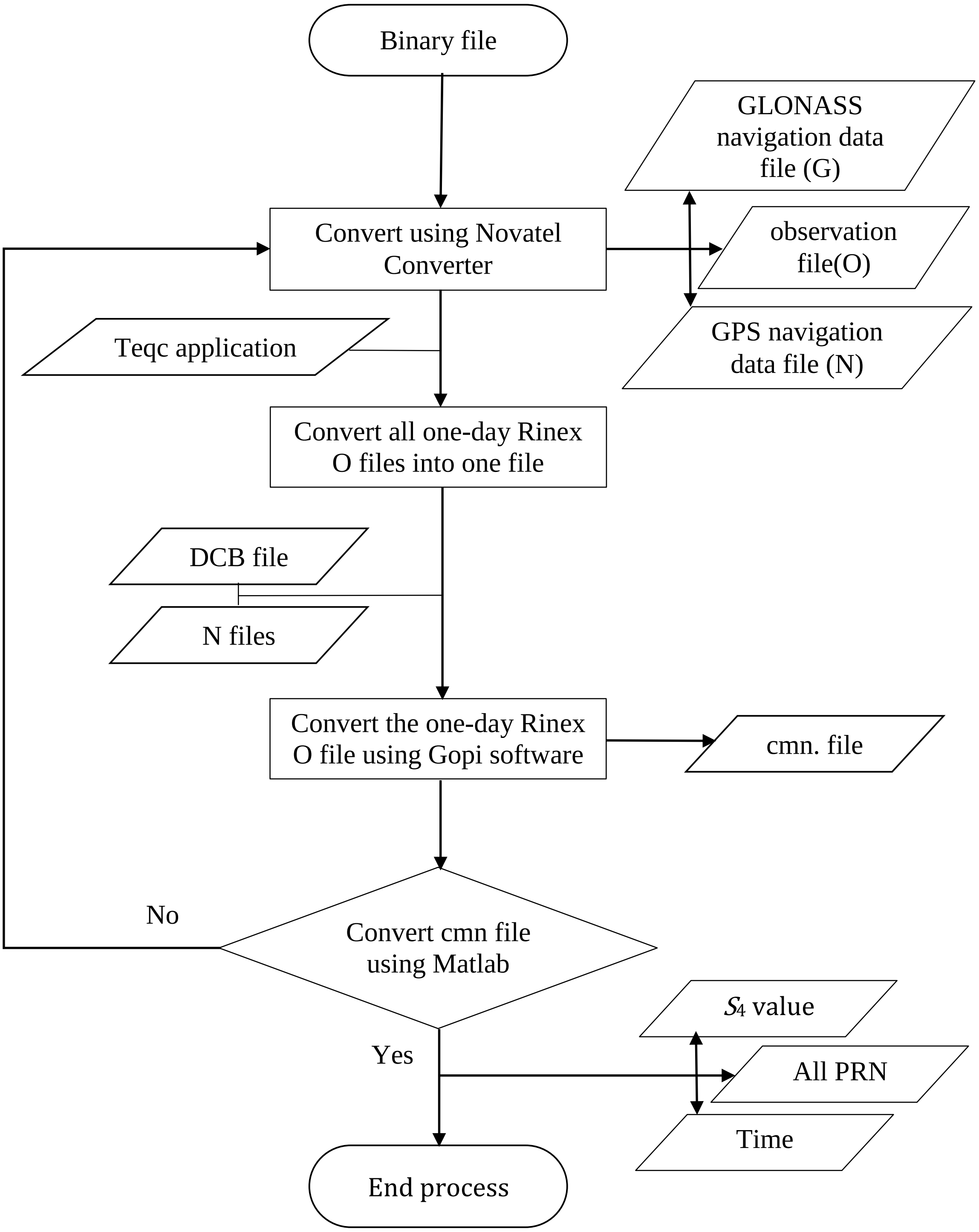

Figure 7. Flow Chart of data processing

Figure 7 shows the process to obtain the output data of this research. To observe the behaviour of ionospheric scintillation, other crucial outputs also need to analyse.

3.2 The Data

GPS data from 3 receivers at the GBAS ground station located at KLIA recorded from September 2017 to September 2018 were analysed. It is in the form of a binary file or a "non-text file". These data were collected by Three Iono Data Collection (IDAC) units installed at KLIA (Izwan et al., 2018). This device is specially used to characterise how the local ionospheric environment affects GPS signals. A Novatel FlexPak6 GPS receiver is the electronic device that decoded GPS signals and provided them to the data recorder. Figure 8 shows the location of the 3 GPS receivers.

Figure 8. Locations of the three GPS receivers at KLIA, Malaysia

3.3 Software Used

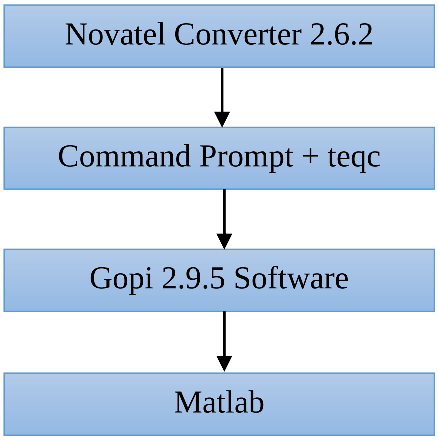

Figure 9. The flow chart of the software used to obtain the S4 value

In this study, some software is involved in obtaining the output of this data which is the readable value of the S_4 index. Figure 9 shows the sequence of the software used to get the output data. At the end of this process, a graph of S_4 will be constructed and will be analysed. All the graphs will be sorted based on their S_4 value and their strength.

3.3.1 Novatel Converter 2.6.2

The Novatel Converter is used to convert the GPS raw data into a Rinex 2.1 observation file. Rinex stands for “The Receiver Independent Exchange Format” (Pestana, 2015). A few types of Rinex files can be obtained from this software; Rinex 2.1, Rinex 3.01, Rinex 3.02, Rinex 3.03 and Rinex 3.04. All these Rinex files will observe three fundamental quantities: time, phase and pseudo-range, but Rinex 2.1 specifically allows a fourth observable; the signal strength or raw signal-noise ratio (S/N_0). This is why Rinex 2.1 is chosen in this project