CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The first GNSS constellation of satellites is the Global Positioning System (GPS) developed by the U.S military in the mid-20th century which transmits signals at mainly two L-band frequencies, L1 (1575.42 MHz) and L2 (1227.60 MHz). GPS is found to be a promising resource and a unique method for characterising the temporal and spatial behaviours of the ionosphere (Abdu et al., 2008; Mukherjee et al., 2010; Karia & Pathak, 2011; Fayose et al., 2012). A part of the earth's upper atmosphere is commonly referred as ionosphere stretches from a height of about 50 to 1000 km above the earth surface (Klobuchar, 1991) and the existence is primarily due to the action of the extreme ultraviolet (EUV) radiation from the sun and population of electrons in this region.

Many modern applications and communications, e.g. the short wave radio communication, and satellite positioning and navigation, rely on this highly variable propagation medium (Jakowski et al., 2012). The space weather threats can induce severe ionosphere perturbations and may severely impact those applications. Introducing significant propagation delay in the GPS signal may degrade the position accuracy, as well as affect the signal integrity (Jakowski et al., 2004). During the severe disturbances, rapid fluctuations in the signals can cause a complete loss of lock. In other words, the ionospheric irregularities can cause the signal fading which affects the operations of the GPS receivers. The GPS receiver will stop tracking the signals from the GPS satellites during this period. This indirectly affects the accuracy of the navigation systems due to the loss of satellite signals for a short period (Tulunay et al., 2004; Jakowski et al., 2005; Tulunay et al., 2006; Mane et al., 2014). The ionospheric perturbations can even severely impact the earth infrastructure and may lead to missing and erroneous data. Knowing the effects of the space weather threats over the space-borne technological systems, constant monitoring and forecasting the ionospheric state in advance are considered as an important requirement in the space science research.

Total electron content (TEC) is a fundamental and important parameter of the ionosphere. Indeed, the TEC is relatively a simple parameter to measure and able to describe the signature of the upper atmosphere variability continuously, as the GPS signal propagates through the ionosphere layer (Maruyama, 2010). TEC is the amount of electron content in the ionosphere which mainly builds up when a direct sunlight interacts with the upper atmosphere. The irregular fluctuations in the TEC with respect to the behaviour of ions and molecules in the ionosphere cause the TEC varies non-linearly. Some variables mainly known to influence the TEC variations such as the hour of the day (diurnally), day of the year (seasonally), geographical location (polar and equatorial regions), as well as solar and geomagnetic activity levels. The ionospheric TEC is found to have the largest effect on the GPS signal propagations. The time delay on the electromagnetic radio frequency waves that propagate through the ionosphere is directly proportional to the number of the free electron along the ray path from the satellite to the receiver on the ground. In other words, the TEC is an important space weather concern because it determines time delays in the trans-ionospheric radio propagation. Forecasting the TEC ahead can reduce the errors and the effects on the GPS applications. Knowing the importance of the TEC, the availability and accessibility of the TEC measurements are very significant in ionospheric studies.

Historically, the ionospheric TEC studies has been widely studied with the aid of measurements obtained from different observing techniques such as the incoherent scatter radar, Faraday rotation measurements (Sethia et al., 1979) and vertical incidence ionosonde techniques (Alex, 1987; Mosert et al., 2007). However, in the recent years, the increases in the availability of the TEC data from the GPS have contributed significant knowledge in characterizing the ionosphere property. This has urged and increased the space researchers at various different locations to study the TEC, both regionally and globally (Shankar, 2007; Abdullah et al., 2009; Obrou et al., 2009; Mukherjee et al., 2010; D'ujanga et al., 2012; Unglaub et al., 2012).

In Malaysia, as the GPS TEC has become a valid instrument to study the ionosphere, it offers an opportunity to analyse the TEC for post-processing application where the TEC data were retrieved from the GPS observations and analysed later for future application. Knowing the importance of the post-processing analysis, this thesis describes the efforts undertaken to construct and develop a TEC estimation and forecasting models based on the TEC values derived from a single GPS station over Wireless and Radio Science Centre (WARAS), Parit Raja, Malaysia during the medium solar activity (February 2005- December 2006). The term "estimation" is commonly used by the researchers in the ionospheric study which means to predict or estimate the missing value in the existing data. In other words, it is possible to estimate value at times within the range of the tested data for which no data exists. It is an expectation for a combination of estimator values. On the other hand, the term "forecasting" in ionospheric research means a time-series analyse is usually performed to make predictions of future observations based on the historical observations (the lag of the variable). Estimation basically involves estimator variables while forecasting involves times.

In this work, for estimation, a data-driven model based on artificial neural network (NN) is implemented to estimate the non-linear TEC variations. The validation of the NN-based TEC is carried out by doing a comparative analysis with the standard global empirical model known as the International Reference Ionosphere (IRI) as well as with the GPS derived TEC. On the other hand, for forecasting, a hybrid SARIMA –NN time series technique is designed to forecast the ionospheric TEC in advance. The seasonal auto regressive integrated moving average (SARIMA) is combined with a neural network (NN) model to form a short term forecast model. The hybrid model is validated with the individual model, SARIMA and NN, respectively.

1.2 RESEARCH ON MALAYSIA IONOSPHERIC TEC

The advent of the modern and low-cost networks of dual frequency Global Positioning System (GPS) has initiated ionospheric research in Malaysia. The contribution of the ionosphere in radio and satellite communications has attracted the interest of researchers and geodesists in Malaysia. The study on ionospheric research over Malaysia has been going on for past two decades. The early researches mainly focus on characterising the spatial and temporal behaviours of the local ionospheric TEC using the GPS network maintained by Jabatan Ukur dan Pemetaan Malaysia (JUPEM) (Zain & Abdullah, 1999; Zain & Abdullah, 2000). Furthermore, the existence of Wireless and Radio Science Centre (WARAS), a new observatory station with the GPS and ionosonde measurements, a number of publications on computation, analysis and comparison of the TEC and scintillations are done between different stations which differ in geographical location (Zain et al., 2005b; Abdullah et al., 2009). A short duration (from 31 July - 13 August 2005) ionospheric experimental campaign was conducted at Fraser's Hill, Malaysia to analyse the ionospheric TEC variations over this location. The TEC results obtained from this experiment were compared to the main observatory at the WARAS Centre, Parit Raja, West Malaysia (Zain et al., 2005b). On the other hand, one-month ionospheric experimental campaign was carried out at Sipitang, East Malaysia and the results were compared to the aforementioned observatory station at Parit Raja, West Malaysia (Abdullah et al., 2009). In both experiments, the ionospheric TEC values at Parit Raja station were generally higher than the other two stations. Besides short-term analysis, a long-term analysis on the TEC variability at Marak Parak, Sabah was carried out by Hassan et al. (2002) during the ascending solar cycle. The work also investigated the correlation between TEC and the parameters known to influence the TEC variations such as solar and magnetic indices.

The increasing number of GPS receivers expands the Malaysian ionospheric research where a regional TEC latitude (10˚S to 16˚N) and longitude (90˚E to 120˚E) profile map is constructed during a normal quiet day from the dual frequency GPS receivers in the Malaysia Active GPS system (MASS) operated by JUPEM (Zain et al., 2005a). The variability of electron content in the ionosphere is also affected by the space weather conditions (e.g. solar and geomagnetic storms) and natural hazards (e.g. earthquake). All these phenomena are manifested as waves travelling in the ionosphere and cause anomalous variations within the ionosphere. Knowing the significant effects of those phenomena on ionosphere, in Malaysia, a few publications have been reported on the ionospheric TEC variability during these phenomena based on the GPS measurements from JUPEM. Hasbi et al. (2007) have investigated the ionospheric TEC variability during a major storm beginning from the period of 12-17 May 2005 at Arau (geographic coordinate: 6.5˚N, 100.28˚E) and observed pronounced TEC enhancement approximately for 3 hours during the storm. Continuously, Hasbi et al. (2009) have investigated the ionospheric TEC and geomagnetic responses during 2005 earthquakes (i.e. 28 March and 14 May, 2005) in Sumatra based on two different measurements, namely the GPS and ground-based magnetometer measurements, located in the near zone of the epicenters. Ya'acob et al. (2007), Mubarak et al. (2009) and Hasbi et al. (2011) have investigated on pre- and post-earthquake ionospheric anomalies based on the GPS station measurements. The GPS TEC is used as an ionospheric precursor of earthquake to detect the seismic waves in the ionosphere, which appeared few days before the time of seismic shock.

Furthermore, since the TEC is considered as an important descriptive quantity for ionosphere, accurate estimation of ionospheric TEC has become a vital task in ionospheric study. Hence, in Malaysia two different techniques, namely TEC dual frequency technique and TEC Map based on the Bernesse software and precise point positioning (PPP) technique were explored to estimate the ionospheric TEC on 8 November 2005 using the Malaysia data (Ya'acob et al., 2009a; Ya'acob et al., 2009b). The Malaysian ionospheric research also includes the study on the validity of the optimized ionospheric layer for vertical TEC measurements at equatorial region (Jusoh et al., 2009).

In recent years, the Virtual Reference station (VRS) has become a great technique in providing instant access to real-time kinematic (RTK) corrections utilizing a network of permanent and continuously operating reference stations. In Malaysia, a few groups studied the ionospheric research using the VRS technique. The RINEX (Receiver Independent Exchange Format) VRS data format provided by JUPEM is used to analyse the ionospheric behaviour based on TEC data. Leong et al. (2009) used the dual frequency GPS measurements from the local Malaysia RTK network (MyRTKnet) and few International GNSS service (IGS) to investigate the variations in ionospheric TEC by generating a local TEC maps over Peninsula Malaysia for six months during the period of minimum solar activity (2007-2009). On the other hand, Ya'acob & Idris (2012) and Ya'acob et al. (2013) studied the concept of VRS technique in Malaysia and applied the levelling process technique in the dual frequency VRS receivers to compute the VRS-based TEC. The slant TEC retrieved from the VRS measurements are converted to vertical TEC using two different mapping functions, namely single layer model (SLM) and modified single layer model (M-SLM). Besides, Idrus et al. (2013) used the TEC data from the MyRTKnet network to study and observe the propagation of large-scale travelling ionospheric disturbances over Peninsula Malaysia during moderate magnetic storm.

Other than the aforementioned studies, Abdullah et al. (2007) have investigated the possibility of using a statistical Holt-Winter technique to forecast the ionospheric delay using a short period of data (i.e. from August 2005 to October 2005) based on the GPS TEC measurements over Parit Raja station in Malaysia. Knowing the importance of a forecasting model in ionospheric research and the suitability of Holt-Winter method to forecast a time series with seasonal patterns and repeated trends, Elmunim et al. (2013) adopted the work done by Abdullah et al. (2007) and used the Holt-Winter Multiplicative model to forecast the ionospheric delay on a monthly basis for a particular time period of (0800-1200 LT) and (1500-2100 LT) using GPS Ionospheric Scintillation and TEC Monitor (GISTM) at Universiti Kebangsaan Malaysia, (UKM) receiver station over short period from June to December 2010. Continuously, Elmunim et al. (2015) has extended the work for a longer period, from October 2009 to December 2010 to forecast the ionospheric delay based on the Additive and Multiplicative Holt-Winter models using the GPS TEC data at the same receiver station.

From the summary of the above-mentioned studies, it can be deduced that even though numerous ionospheric research based on TEC data have been done in Malaysia, yet an ionospheric TEC model to estimate and forecast the Malaysian TEC are still in its infancy stage. Therefore, in this work, two different techniques, namely NN and hybrid SARIMA-NN are implemented on the GPS TEC to estimate and forecast the ionospheric TEC over Parit Raja, Malaysia station, respectively. The issues that have initiated this study are listed out in the following section.

1.3 PROBLEMS STATEMENT

The GPS has served as a valid instrument to study the behaviour of the ionosphere. The TEC is an important descriptive quantity for ionosphere because it affects the radio signals that propagate through this layer. With the advent of GPS ground based stations within Malaysia, the researchers in this region now have an opportunity to comprehend the physical behaviour of the equatorial ionosphere. Following are the problems that have initiated this research work:

i. Lack of an optimum local ionospheric model to estimate the TEC variations in Malaysia.

   a. The variation of the Earth's ionosphere is complex and affects the propagation of the radio waves especially in the EIA (equatorial ionization anomaly) region. The equatorial ionosphere differs significantly in the characteristics and dynamic structures compared to other latitudes. The EIA or the Appleton anomaly, usually hosts large electron density irregularities, which cause rapid fluctuations in the GPS signals. This may lead to pronounced signal degradation and cause inaccuracies or errors in GPS measurements. Since Malaysia lies in the EIA region, the measurements are more prone to this anomaly (Zain & Abdullah, 1999; Zain & Abdullah, 2000; Hassan et al., 2002; Zain et al., 2005; Ya'acob et al., 2007; Abdullah et al., 2009).

   b. The adverse condition of the near-Earth space, e.g. solar and geomagnetic storms may severely impacts on the space-borne and ground based technological systems. For instance real time applications such as radio communications and satellite navigations are disrupted due to loss of lock occurrences (Jakowski et al., 2005). Besides, electrical power line is also vulnerable to strong geomagnetic storms which induced high currents. Such effects can cause complete power blackout and infrastructure failures (Kappenman, 2010). During this period, missing and erroneous signals are a common and crucial problems in GPS measurements. This may degrade the accuracy and reliability of the GPS system, where the measurements unable to produce accurate ionospheric parameters e.g TEC data. This may also indirectly affect the post-processing application which highly depends on accurate database. For instance, in a time series analysis, the models mostly depend on the historical data. Poor data quality due to wider gaps and errors in the database, may adversely affect such analysis and the end result.

c. Besides, the discrepancy between GPS TEC measurements and IRI-based TEC at the equatorial region is also a vital issue in the ionospheric research. According to Bhuyan & Borah (2007) and Abdu et al. (2008), the global model such as the IRI (International Reference Ionosphere), a joint cooperation of the Committee on Space Research (COSPAR) and the International Union on Radio Science (URSI) prediction, is most accurate at the mid-latitude regions compared to the other latitudes (i.e. low- and high-latitude) because of high density data sources from this part of the globe (Bilitza & Reinisch, 2008). Furthermore, the lack of consecutive long term ionosphere measurements in the equatorial region due to the general scarcity of GPS observations in this region causes significant discrepancy between the observed TEC and global model data (Bhuyan & Borah, 2007; Obrou et al., 2009; Kenpankho et al., 2011; D'ujanga et al., 2012; Olwendo et al., 2012).

Knowing the importance of ionospheric TEC, the characteristics and issues in this region, it creates a need to develop an estimation model over Malaysia to overcome the above issues.

ii. Lack of a local forecasting model to forecast the ionospheric TEC several days ahead.

a. Severe disturbance from the upper atmosphere may affect the radio waves that propagate through this medium, which causes the satellite-to-ground radio link to become completely severed. For instance, the magnetic storm-driven ionospheric density disturbances interfere with the short wave radio communication for long distance and the radio signals used in satellite communications, positioning and navigation systems (Jakowski et al., 2004; Jakowski et al., 2005). Furthermore, during extreme events, the high frequency (HF) communication is disrupted and may even completely black out. Severe ionospheric perturbations may even damage spacecraft, cause satellite disorientation, and increase the positioning error.

b. Besides, the effect of natural hazards (e.g. earthquake, tsunami , etc.) in the earth can be devastating and can cause the largest annual death due to the collapse of structure and building. In recent studies, (Liu et al., 2000; Liu et al., 2004; Ya'acob et al., 2007; Akhoondzadeh et al., 2010; Hasbi et al., 2011) have observed anomalies in the ionosphere electron densities a few day prior to some strong earthquakes using the ground based GPS stations. The acoustic-gravity waves generated from the pre-seismic interact with the ionospheric plasma cause anomalous variations in the ionospheric plasma densities. These studies have also reported and emphasized that the affected area before some large earthquakes extends over a distance of 1500 km in latitude and 4000 km in longitude.

c. In addition, the length of period to forecast the ionospheric TEC ahead is still an open subject in ionospheric research (Garcia-Rigo et al., 2011). It still attracts and motivates many space science researchers to works on the length of the forecasting duration ahead.

Taking into account the impacts of severe threats and earth natural hazards, a reliable local ionospheric TEC forecasting model is required in order to trace these threats earlier via the TEC variations. Mitigating the impacts and effects of these threats can be enhanced by developing an ionospheric TEC forecasting model.

1.4 RESEARCH OBJECTIVES

The aim of this thesis is developing an ionospheric TEC estimation and forecasting models over Malaysia. The above aim will be accomplished by fulfilling the following research objectives:

i. To identify the space weather parameter(s) that contributes in TEC modelling over Malaysia.

ii. To develop a local ionospheric TEC estimation model based on neural network (NN) and evaluates the NN's interpolation and extrapolation capabilities to estimate the missing TEC data.

iii. To investigate the predictability of TEC using NN over Malaysia for seasonal variation and disturbed conditions. Validate the accuracy of the developed model with an established (classical) model.

iv. To design a new hybrid SARIMA–NN technique to forecast the ionospheric TEC ahead over Malaysia during the medium solar activity.

1.5 RESEARCH SCOPES

The research leads towards the development of estimation and forecasting TEC models over a station that lies at the equatorial anomaly region and the work only concentrated at a single station. The study is carried out at Wireless and Radio Science Centre (WARAS), Parit Raja, Malaysia (geographic coordinate (1.86˚N, 103.8˚E) and geomagnetic coordinate (8.11˚S, 175.98˚E) during the medium solar activity of the solar cycle (SC) 23, in 2005 and 2006. The estimation model is based on certain parameters only. They are the solar, geomagnetic and the periodic indices; the hour(s) represent the diurnal variation and day(s) to represent the seasonal variation.

1.6 RESEARCH CONTRIBUTIONS

This thesis provides a comprehensive guide on the development of TEC models for estimating and forecasting the ionospheric variability over the Malaysia and forms a significant contribution to ionospheric modelling in Malaysia. The models contribute to attain a reliable ionosphere monitoring and forecasting system in Malaysia. The estimation model offers an opportunity to recover lost data in order to generate a complete picture of the Malaysia's ionospheric behaviour. Furthermore, the forecasting model contributes essentially to monitor and detect the ionospheric perturbations earlier. The model serves an as early warning system to trace the space weather and natural hazards effects and can be a mitigation technique to reduce the impacts of these threats on human technologies

1.7 THESIS OUTLINE

This thesis comprises six chapters. Chapter 1 gives the overview of the GPS, TEC and ionospheric research over Malaysia. The chapter discusses the problem statement, objectives, scopes and the contributions of this research.

In Chapter 2, the formation of the ionosphere and its layered structure are described. Furthermore, the factors that influence the ionospheric variability and irregularities are explained. The ionospheric TEC, its effect on radio waves and technology-based activities, along with a brief description of the existing ionospheric models to estimate and forecast the TEC variations are discussed. The chapter also describes the theory and concept of the neural network and seasonal autoregressive integrated moving average techniques along with their algorithms used for modelling the TEC in this study. Besides, the chapter provides a brief description on the Global Positioning System (GPS) and its contribution to the ionospheric studies. At the end of the chapter, the ionospheric effects on the electromagnetic waves are explained along with their algorithms.

Chapter 3 describes the overall methodologies of the ionospheric TEC modelling. Firstly the method used to derive TEC data from the GPS Ionospheric Scintillation and TEC Monitor (GISTM) receiver is presented in this chapter. Then, the chapter is divided into two sections; the first section explains the estimation model based on the artificial neural networks in detail. A comprehensive discussion on the proxies which influence the TEC variations is discussed as well as the NN technique which comprises the architecture and training algorithm are also included. In the latter section, a forecasting ionospheric TEC model based on a hybrid model is explicitly described. The overall method and architecture of the hybrid SARIMA-NNs model is explained with the aid of diagrams.

Chapter 4 presents the ionospheric TEC modelling results. In the first part, the possibility of NN model in estimating the missing ionospheric TEC data via interpolation and extrapolation techniques is presented. In order to access the predictability of the model more rigorously, the extrapolation technique is used to estimate the seasonal and disturbed TEC variations. The performance of the model is validated via a global model, IRI. In the second part, the feasibility study of the hybrid SARIMA-NN model in forecasting the GPS TEC values ahead for different condition days are evaluated and the results are presented. The configuration and the outcomes of these models, which can approximate and forecast the TEC variations, are the novelty of this study.

The overall idea of the work and the findings are summarized in Chapter 5. Besides, the future plans and the improvement of this research are also given in this last chapter.