CHARACTERIZATION OF THE EQUATORIAL F2-REGION PLASMA DRIFT USING DOPPLER INTERFEROMETRY AT PARIT RAJA

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Specially to my wife, Rozana and children, Izzaidah, Izzuddin and Diana

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ABSTRACT

The ionosphere has long been used as a medium for long-distance transmission before the advent of satellites. There has now been a resurgence in its research after events that have occured in Iraq and Aceh where, ground-based infrastructures are destroyed from the effects of war or natural disasters. The bulk of research work in this area of study which uses the ionosphere as a channel medium comes from advanced countries representing the midlatitude regions of the world. It is therefore the objective of this thesis to characterize the behaviour of the ionosphere which is more representative of the equatorial regions. This work presents the measurements of plasma drifts from the ionospheric F2-layer at the equatorial station of Parit Raja (1° 52' N and 103° 48' E) using the technique of Doppler interferometry. Analysis is carried out from data gathered during periods of low solar and geomagnetic activities of 2005 with a view to statistically model or characterize its properties. As a result of plasma drift, Doppler effects are observed on the reflected echoes due to scattering from the irregular and non-uniform reflection layer. An approximation for the ionospheric F2-layer as a non-selective flat Rayleigh channel is first developed using an FIR filter that follows a Jakes' Doppler channel response with the assumptions that multipaths are not resolvable and appear as one at the receiver with uniform Doppler rate. Since the actual ionosphere is non-flat with frequency-selectivity and also exhibits time-variability, a more realistic modelling of the ionospheric structure is needed. This is achieved by subdividing the operating bandwidth of the ionospheric medium into an aggregate of narrowband and orthogonal subchannels, where each is narrowband enough to possess flat Rayleigh fading. By adopting this technique of multicarrier transmission, each subchannel can be considered as flat and uniformly time-varying, which can be practically implemented using an IIR filter. The effect of variable Doppler rates is addressed by employing the techniques of upsampling and interpolation. The channel modelling is based on the Jakes Doppler response for 35 KHz in bandwidth which is more appropriate for equatorial region as opposed to ITU-R F.1487 that adopts the Gaussian spectral response with 10 KHz of bandwidth for midlatitude regions. Empirical simulation of results for the developed models using measured data and the performance measures have been reasonably accurate in characterizing the channel as having a Jakes Doppler response with Rayleigh fading within limits of +/-2 Hz Doppler shifts or +/-100 m/s plasma drifts.

ABSTRAK

Penggunaan ionosfera bagi penghantaran isyarat secara jarak-jauh telah lama wujud sebelum penggunaan satelit. Pengkajian mengenainya di dunia ketiga menjadi lebih rancak susulan bencana di Iraq dan Aceh di mana berlakunya kerosakan besar-besaran infrastruktur komunikasi atas bumi. Walaubagaimanapun, sebahagian besar kerja-kerja penyelidikan yang dilakukan mengenai penggunaan ionosfera adalah hasil daripada negara-negara maju yang terletak di latitud pertengahan dunia. Oleh itu, satu pengamaatan baru diperlukan bagi tujuan yang sama bagi negara-negara berdekatan khatulistiwa. Tesis ini membentangkan ukuran aliran plasma dari lapisan-F2 ionosfera di stesen khatulistiwa Parit Raja (1°52' N dan 103°48' E) menggunakan teknik interferometri Doppler. Analisis data yang dikumpulkan dilaksanakan semasa tempoh aktiviti suria dan kuasa magnet bumi rendah bagi tahun 2005. Ini adalah untuk menentukan struktur ionosfera bagi tujuan pemodelan secara statistik ke atas ciri-cirinya yang mewakili keadaan tempatan negara ini. Disebabkan plasma yang bergerak, kesan Doppler juga dirasakan pada gema pergi balik di tanah. Buat permulaan, satu anggaran bagi lapisan-F2 ionosfera tempatan akan dilakukan dengan tanggapan isyarat yang melalui saluran Rayleigh diajukan dengan andaian yang pantulan berselerak tidak dapat diselesaikan dan kelihatan sebagai satu isyarat di penerima. Ini dilakukan menggunakan tapisan FIR yang bertindak mengikuti saluran Doppler Jakes. Secara praktiknya, saluran ionosfera juga mempamirkan kepelbagaian masa dan pemilihan frekuensi. Untuk itu, satu keperluan bagi menggabungkan faktor-faktor ini harus diambil kira di dalam peragaan sebenar. Untuk peragaan yang lebih realistik, pembahagiaan keseluruhan jalur frekuensi yang melalui medium ionosfera terpilih ke dalam satu agregat jalur sempit dan saluran-saluran ortogonal digunakan, di mana setiap saluran adalah jalur sempit dan mewakili sepenuhnya Rayleigh memudar dalam julat frekuensinya. Dengan ini, saluran ionosfera boleh dianggap sebagai tidak mempunyai kepelbagaian masa, seperti kes di dalam peragaan pertama, kecuali sekarang teknik penghantaran pelbagai karrier digunakan. Ini dilakukan menggunakan tapisan IIR berdasarkan kepada ketumpatan kuasa spektra Jakes. Hasil dari kajian yang dilakukan dengan menggunakan data yang dikumpulkan telah berjaya memodelkan lapisan ionosfera tempatan sebagai mengikuti spektra Jakes yang mewakili saluran Rayleigh di dalam lingkungan +/-2 Hz peralihan Doppler yang bersamaan +/-100 m/s kelajuan plasma.

CONTENTS

CHAPTER I

INTRODUCTION

1.1 Introduction

The ionosphere everywhere is a very dynamic and also disturbed region. It contains irregularities which, on scales much greater than a wavelength may be considered as providing a rough reflecting surface. As a result of this roughness, signals associated with each skywave propagation mode may arrive at the receiver over a range of azimuth and elevation angles.

Furthermore, ionospheric drift velocities and movements close to the F2-layer reflection points often impose large Doppler spreads and Doppler shifts onto the signal. This time-varying behaviour will have an impact on the characterization of the local structure at Parit Raja as a medium for HF transmissions.

Evident also is a variation in the bearing of multipath echoes with Doppler frequency. This is attributed to the reflections from the bottomside ionospheric irregularities drifting across the reflection points. When the drift of the plasma is such as to shorten the path of the received signal, positive Doppler shifts are imposed.

On the other hand, negative Doppler shifts are imposed when the plasma drift is such as to lengthen the path. A good understanding of these plasma drift mechanisms as well as the methods used to analyse their effects are therefore important for the purposes of modem designs and ionospheric propagation predictions. Apart from these, it is important to fully understand the behaviour and limitations of many types of HF communication systems available today so as to facilitate the design of new systems that are representative of local conditions.

1.2 Background

The upper layers of the earth's atmosphere are ionized (ie. electrons are detached from the atmospheric gas atoms) mainly due to ultraviolet radiation from the sun. A state of equilibrium is reached where the free electron density is maintained almost constant with the ionization rate being balanced by the recombination rate of electrons with positive ions.

As the ionization rate is dependent also upon solar radiation, the electron density will vary between day and night times. Because of this, fluctuations in the concentration of electron densities that occur during the day have been observed to happen (Salwa *et. al*. 2000).

In equatorial region like Malaysia, the total electron content (TEC) has its variations based on time of day (diurnal) as well as the solar activity. It is also proportional to the time delay of the wave signal being transmitted as it traverses the ionospheric plasma. Even when the solar is relatively quiet, there is the possibility of a bigger spread of TEC. This spread can be explained by the fact that the occasional occurrences of solar flares tend to push the TEC higher (Zain, A.F.M. *et al.,* 2000). TEC is important as signal propagation via the ionosphere depends on its level.

Previous works in the field of ionospheric simulation models have been proposed and experimentally confirmed by Watterson, *et. al.,* (1970), which is the most widely used approach for HF simulation purposes. However this model is based on the typical mid-latitude regions of the world where, the upper atmospheric weather and solar conditions as well as the earth's rotational speeds are not similar or representative enough of equatorial regions like Malaysia.

Channel characterizations which are used to explain the observed statistical nature and fading of signal propagations via a time-varying multipath channel are generally based on scattering. Among them, Clarke's (1968) and Jakes (1974) models are widely used. It is to be shown in the thesis that propagation via the ionospheric channel at Parit Raja follows similar behaviour where the incident HF signal wavefronts from the transmitting digital ionosonde are scattered by the non-uniform and irregular bottomside plasma reflecting layer.

The isotropic scattering results in random and (equiprobable) reflections of returned echopaths forming a composite multipath signal arriving at the station's receiver interferometer which is to be processed and analyzed. By invoking the central limit theorem (CLT) it is possible to show that the baseband signal received from the multipath fading ionospheric channel is approximately a complex Gaussian random process (i.e. stochastic) when the number of reflected echoes is large.

By the adoption of such an approach, the statistical characteristics of the multipath echoes arriving at the receiver can similarly be deduced from scattering imposed by the drifting or time-varying plasma reflectors. Data measurement carried out on the bottomside ionosphere F2-layer is based on a 5.9 MHz/6 MHz ground-based transmit digisonde with a 50-foot delta antenna and a coherent phase receiver employing fast Fourier transform (FFT) for processing.

1.3 Ionospheric Research in Malaysia

Early equatorial ionospheric research work in this country was carried out by Abdullah M. and Zain, A.F.M. (1999) and Salwa H. *et al*. (2000) which focused principally on the investigation of ionospheric total electron content (TEC) using GPS receivers from the *Jabatan Ukur dan Pemetaan Malaysia (JUPEM)* GPS stations. However, these pioneering research work on the total electron content in Malaysia was mainly carried out using GPS data.

Successive research work in equatorial ionospheric activity in this country involves the determination of ionogram critical frequencies of operation at UTHM's Wireless and Radio Science (WARAS) station by Abdullah S. (2011) using a digital ionosonde beginning with the year 2005.

The present research work however, concerns the measurement of the local equatorial F2-layer ionospheric drifts or motions at Parit Raja station and analyzing its behaviour in relation to drift velocity, Doppler shifts in frequency, returned echoes angles of arrival as well as the roles played by the earth's geomagnetic fields and the sun's solar activity in influencing the ionospheric structure. This is done with a view to study and characterize its behaviour which is representative of the local equatorial conditions at Parit Raja and the surrounding areas. Subsequently, appropriate statistical models using filters will be developed and performance measures quantified by empirical simulation in order to gauge the suitability of the models for use in modem modulation designs for HF transmissions representing the equatorial regions.

1.4 Problem Statements

The world has experienced two world wars previously before satellites were put into orbit. The only means of establishing long-distance and beyond-line-of-sight (BLOS) communications then were by using high frquency or HF transmissions via the ionospheric channel, especially for the military and diplomatic services.

Even though satellite transmissions were subsequently deployed with state-of-the-art technologies, it is now considered insecure to countries at war (and their enemies) since it is vulnerable to sabotage (jamming). In addition, satellites move along predictable orbits and can be shot down by missiles as proven by the Chinese military and the US Navy a few years ago.

It is therefore desirable for commanders of ground forces or infantry platoons and warships to be able to communicate more securely via the ionosphere using HF as an alternative method and rely on it to make strategic decisions. With the security aspects of satellite transmission and also its networks being potentially compromised, it now becomes imperative for field commanders to consider more use of adhoc and mobile HF transmissions to complement satellite links to counter enemy forces.
This is most suited for a country like Malaysia where the land area and sea coverage are quite extensive that range from the Peninsula right up to Sabah and Sarawak.

However, the standard ionospheric model adopted by ITU R-1487 uses the Gaussian Doppler channel model with 68% of confidence interval and represents only the midlatitude regions of the world where advanced countries are located. Since the equatorial regions of the world have higher ionospheric drifts and Doppler shifts and are also not affected by equinox and solstice, it is to be shown in this thesis that the Jakes Doppler channel model with 95% of confidence interval is more representative of the local equatorial Parit Raja station.

1.5 Motivations for Using the Ionospheric Channel

The ionospheric medium is a time-varying channel with an inherent narrow bandwidth. The transmission channel is subjected to unpredictable variations which occur as a product of time of day, seasons, and such occurrences as geomagnetic and sunspot activities. Variations in the ionospheric plasma reflection layer also result in multipath propagation and reception at the ground receiver.

The ionospheric radio channel has also been recognized as a useful and economical medium for signal transmission over long distances. It is considered as a 'gift of nature' whose properties depend much on solar and geomagnetic activities.
The increasing availability of high speed digital signal processing (DSP) techniques in recent decades as well as events that occurred in Iraq and Aceh have resulted in a resurgence and more renewed interest in research work for HF communications within the 3 MHz to 30 MHz range.

Hence, HF transmission via the ionospheric medium has seen increased applications in situations where normal communications are difficult or unreliable. The reason is that the ionospheric channel offers a relatively inexpensive and long range communications link without the need for a third party equipment like a satellite, whose operation can be compromised as well as being prone to sabotage.

1.6 Aims and Objectives of Study

The purpose of this study is to investigate and characterize statistically the dynamics of the ionosphere at UTHM's Parit Raja station under different conditions of Doppler shifts due to the changing plasma drift velocities as well as planetary effects such as the geomagnetic and solar activities.

Specifically, the objectives of this study are:-

i. to analyse the distributions of the ionospheric channel statistical parameters like the autocorrelation function, scattering function, Doppler power spectral density, probability density functions of the phase angles of arrival as well as the amplitude fading due to random echo cancellations

ii. to implement a model for statistical characterization of the behaviour of the local ionospheric reflection layer using a finite impulse response (FIR) filter for flat channel response with uniform Doppler rate and infinite impulse response (IIR) filter for non-flat (frequency-selective) channel response with rapidly variable Doppler rates

iii. to carry out performance measures in order to gauge the validity of the characterized model in terms of its bit error rates (BER) versus signal-to-noise ratios (SNR) for future development of HF modem modulation methods representative of local equatorial conditions like Malaysia

1.7 Scope of Study

This study will only focus on the behaviour of ionospheric plasma drifts and the associated Doppler shifts in frequencies and the angles of arrivals of reflected echowaves at this equatorial station of Parit Raja (latitude 1° 52' N and longitude 103° 48' E) representing the local F2-region with critical frequencies ranging from 5.9MHz to 6MHz. Only ionospheric plasma convection with pronounced cloud of scattering points and moving with bulk flow will be considered.

In addition to that, only the bottomside of the local F2-region ionosphere will be probed using a digital ionosonde employing Doppler interferometric reception technique. Near topside or deep probing are not considered in this research work.

This research topic can be justified by the increasing interest in propagation that affects navigation (eg. global positioning satellite system or GPS), surveillance using over-the-horizon (OTH) radar as well as non-satellite-based remote military communications in the high-frequency band (HF) for the army ground forces as well as the navy in our country. These help complement the existing satellite links.

In this thesis, Matlab programmes are written to model the ionospheric channel medium and empirically simulate its properties using FIR and IIR filters. It also facilitates the graphical plotting of results in order to reflect the characterization of the ionosphere as well as to validate its performance measures in terms of the bit error rate (BER) versus the signal-to-noise ratios (SNR) which is important for modem design.

1.8 Importance and Contributions of Study

HF can be used to establish adhoc remote military networks without much expensive satellite equipments. It is cost-effective for beyond-line-of-sight (BLOS) transmission and can support sources of information that are vital to modern military communications like voice and data as well as the newer traffic types that utilize asynchronous transfer mode (ATM) for narrowband services.

Apart from non-satellite-based skywave communications for the military ground forces (eg. West Malaysia to East Malaysia), this research is also relevant for rural telecommunication services where long-distance repeaterless transmission is a necessity without third-party involvement (like the use of an intermediate satellite link) or in times of disasters (eg. earthquakes and tsunamis) when terrestrial communication infrastructures are destroyed.

Hence, it is considered important to analyze and alternatively characterize the ionospheric plasma drift behaviour at this local equatorial station based on another Doppler model instead, i.e., the Jakes Doppler channel response, as opposed to the conventional Gaussian Doppler channel model adopted by ITU R-1487 for midlatitude regions of the world. This will better predict in a more accurate manner the extent of spectrum spreading that occur in the Doppler channel and hence, the behaviour of the equatorial ionospheric structure, caused by the moving plasma reflectors on the incident HF propagated signals. The effects of employing a model that is designed for the midlatitude region which does not represent the actual conditions of the equatorial region may degrade the effectiveness of equipments requiring precise timing and signal frequency information like those used in navigation and positioning systems.

1.9 Thesis Outline

Chapter two provides a literature review of the current research work on the subject and deals with the typical ionospheric structure and its characteristics as well as the techniques used for probing the bottomside ionospheric reflection layer.

Chapter three presents the research methodology employed during the research work and includes equipment setup at both the transmitter and receiver sides as well as the data measurement and time analysis and frequency analysis methods by fast Fourier transform (FFT) being used. The use of finite impulse response (FIR) and infinite impulse response (IIR) filters with upsampling and interpolation to simulate the behaviour of the local equatorial ionospheric channel medium for different Doppler rates are also included.

Chapter four lays down the research results obtained from the empirical simulation of measured data being analyzed together with an attempt to characterize the Doppler channel for HF transmissions that is more representative enough of the equatorial ionospheric structure at Parit Raja. Performance measures are also carried out in order to validate and gauge the effectiveness of the modelled ionospheric medium using filters.

Finally, chapter five list down the conclusions and recommendations for future work in this ‘forgotten’ but important area of research.

1.10 Summary

This chapter provides a background introduction to the ionosphere and its potential use as a medium for long-distance transmission in this country as well as the problems associated with its use. It is considered important after events that occurred in Iraq and Aceh where ground infrastructures are destroyed due to war and natural disasters which makes long-distance transmission almost impossible.

The realization of this problem led to the motivation to investigate the behaviour and characteristics of the local equatorial ionosphere to be potentially used as an alternative medium for high-frequency (HF) skywave communications, in the event that such disasters do occur in this country. The standard channel model that is currently being adopted is based on the conditions relevant to midlatitude regions of the world which is not representative of the local conditions of Parit Raja. A good understanding of HF transmission mechanisms and its limitations over the equatorial ionospheric channel as well as the techniques used to analyse its effects are therefore important for the purpose of ionospheric propagation. This will then help to facilitate the design of new HF ionospheric modems that reflects more on the equatorial conditions of this country for use in military as well as in civil defence applications.

The next chapter will discuss further the characteristics of the ionosphere together with the techniques being used to probe and measure its drift or convection properties using a digital ionosonde or digisonde.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

As the main area of research for this research study is equatorial ionospheric plasma drift measurement, analysis and modelling using Doppler interferometry, therefore this chapter discusses the characteristics of the ionospheric reflection layer as well as the ionospheric sounding technique that is being employed to probe the properties of the ionospheric medium. This will then form the foundation for channel characterizations which will be used to explain the observed statistical nature and properties of the multipath signal propagations via a time-varying ionosphere.

Basically, the ionosphere is the region of ionised plasma as a result of solar activity. Its height starts at about 50 km and can reach as high as 1000 km. The use of pulse sounding technique for ionospheric investigation has long been practised by radio propagation researchers and is widespread. Sounding to probe the behaviour of the bottomside ionosphere is thus important for scientific purposes, frequency prediction purposes, and for real-time assistance to HF communication systems.

Pulse transmitters are used in conjunction with suitable receivers to vertically sound the bottomside of the ionospheric layer, or to obliquely sound long-distance ionospheric paths between points on the earth's surface. By employing precise timing units for the generation of the pulse repetition rate, as well as for frequency control, the transmitter and receiver are maintained in synchronism as they are swept across a portion of the high frequency spectrum (1 to 20 MHz) as carried out at the Wireless and Radio Science Centre (WARAS) in UTHM.

Generally, the ionosphere is structured into three main layers namely, the D-layer, the E-layer and the F-layer (which is further subdivided into the F1 and F2 layers). Figure 2.1 shows a simplified view of the layers in the ionosphere over the period of one day (Poole, 2006):-

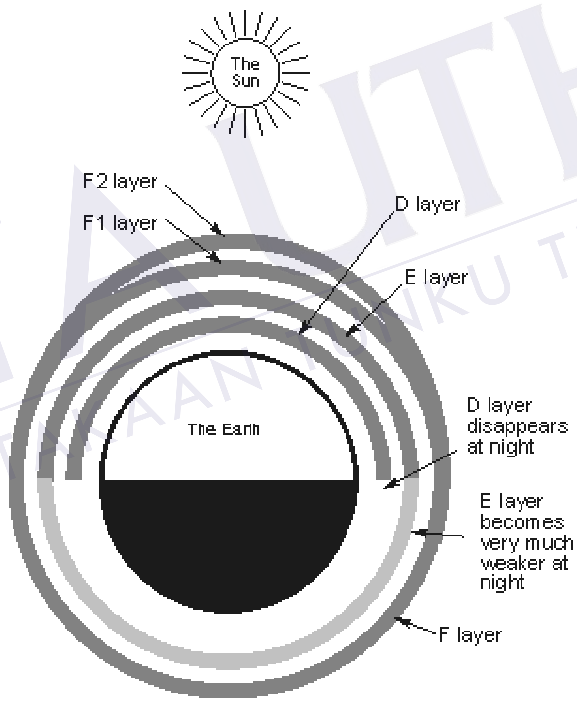

Figure 2.1 Simplified view of the ionospheric layers
(Source: Poole, Adrio Communications Ltd UK, 2006)

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