MODELING THE *F* REGION IONOSPHERIC PEAK HEIGHT VARIATIONS OVER MALAYSIA BY ANTENNA PATTERN SYNTHESIS TECHNIQUE

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ABSTRACT

The ionospheric F region over Malaysia is still an issue to many radio communication enthusiasts. The actual height of this layer is not well defined. Models available are mostly reliable for temperate zones. This thesis describes the determination of the actual F layer height and proposed a unique model to represent the height variations. The ionospheric F region is observed via ionograms, produced by the ionosonde operated at Parit Raja (2^oN, 103^oW, dip 14.3^o), Batu Pahat, Malaysia. The ionogram gives the virtual height representation of the ionosphere. POLAN ionogram inversion program is used to determine the real height of the ionospheric layer. The observations are held during period of moderate to low solar activity of solar cycle 23 (2005 to 2010). However, in this work, only hourly data of March, June, September, and December, 2006 and 2007, are examined. The data are statistically analysed to summarize their main characteristics. The actual height of the F layer is determined from the median values and the coefficient of variability quantifies the height deviations. To derive the mathematical representation of the variations, the least-squares regression technique is used to fit functions to the median data. The best fit function is the descriptive model that describes the variations. A new model of ionospheric height variations is also proposed on the same basis. The ionospheric height time variation which is a cyclic event is re-represented in polar coordinate form. The cyclic representation which approximates an antenna radiation pattern allows the development of antenna equivalent model of peak height variations. The association of ionospheric height variations to the radiation pattern of antenna array is the novelty idea of this study. The observation results indicate that the median height of peak electron density, h_{max}, varies from 420 km in June to 550 km in other months during noon time. The night-time average heights rest around 300 km for all months. The daytime peak is found highest in December solstice season and lowest in June season while post sunset peaks are not seen during this period. The descriptive mathematical model of diurnal variations shows that the variations fit well into a four-term Fourier series model. The two-element arrays with array spacing in the x-direction of $\lambda/8$, and phase of $\pi/3$, and with element spacing in the y-direction of $\lambda/4$, and phase of zero, is the optimal array configuration which signifies the variations. The results show that an array of two-element arrays antenna is suitable to represent the ionosphere peak height variations over Malaysia during moderate to low solar activity period.

ABSTRAK

Rantau *F* ionosfera merentasi Malaysia masih menjadi isu kepada kebanyakan pengguna komunikasi radio. Ketinggian sebenar lapisan ini belum dapat dipastikan. Model-model yang ada pula cenderung untuk kegunaan di zon bersuhu. Tesis in menjelaskan penentuan ketinggian sebenar lapisan *F* dan mensyorkan sebuah model unik sebagai paparan kepelbagaian ketinggian. Rantau *F* ionosfera diperhatikan melalui ionogram, hasil cerapan yang diperolehi daripada '*ionosonde*' yang beroperasi di Parit Raja (2^{o}N, 103^{o}W, dip 14.3^o), Batu Pahat, Malaysia. Ionogram mempaparkan ketinggian maya lapisan ionosfera. Perisian POLAN digunakan untuk menukar kepada ketinggian sebenar lapisan ini. Pencerapan telah dilakukan dalam tempoh aktiviti solar sederhana hingga rendah, pada kitaran solar 23 (2005-2010). Bagaimanapun, untuk kajian ini, hanya ionogram dalam sela masa jam bagi bulan Mac, Jun, September, dan Disember, 2006 dan 2007, diteliti. Analisa statistik digunakan untuk menentukan ciri penting data tersebut. Ketinggian lapisan ionosfera diperolehi daripada nilai median manakala pekali variasi menentukan corak kepelbagaian. Pembangunan model matematik menggunakan teknik 'least-squares regression'. Sesuatu fungsi matematik akan disesuaikan kepada nilai median tersebut. Model matematik diperolehi apabila fungsi matematik tersebut memberikan penghampiran terbaik. Atas dasar yang sama, pembangunan model bagi menggambarkan kepelbagaian ketinggian ionosfera juga dilaksanakan. Kepelbagaian ketinggian lapisan ionosfera terhadap masa adalah suatu keadaan yang silih berulang. Ia boleh dipaparkan dalam koordinat polar. Paparan sebegini menghampiri paparan corak radiasi antenna tatasusun justeru pembangunan model kepelbagaian ketinggian lapisan ionosfera adalah perlu. Kesinambungan di antara kepelbagaian ketinggian lapisan ionosfera dan corak radiasi antena tatasusun merupakan idea terbaru yang terhasil dari kajian ini. Keputusan pemerhatian menunjukkan ketinggian ionosfera, h_{max} berubah dari 420 km pada bulan Jun kepada 550 km pada bulan-bulan yang lain semasa waktu tengahari. Purata ketinggian pada waktu malam pula berada pada paras 300 km. Puncak tertinggi dicapai pada bulan Disember dan terendah dalam bulan Jun. Model matematik untuk kepelbagaian harian menunjukkan bahawa model jujukan Fourier 4-terma sangat bersesuaian dengan kepelbagaian ini. Antena tatasusun dua-elemen dengan jarak susunan $\lambda/8$ dalam arah-x dan fasa $\pi/3$, dan jarak elemen $\lambda/4$ dalam arah-y dengan fasa sifar, adalah konfigurasi tatasusun yang paling optimum untuk menggambarkan kepelbagaian ketinggian ionosfera. Keputusan kajian menyatakan tatasusun dua-elemen tatasusun adalah paparan yang paling sesuai untuk kepelbagaian ketinggian ionosfera untuk tempoh aktiviti solar sederhana hingga rendah.

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LIST OF SYMBOLS

f_oE	Critical frequency of the *E* layer
f_oF1	Critical frequency of the *F1* layer
f_oF2	Critical frequency of the *F2* layer / Ordinary wave
f_xF2	Extraordinary wave
f_N	Plasma frequency
f_c	Critical frequency
f_o	Critical frequency of ordinary wave
f_x	Critical frequency of extraordinary wave
f	Frequency
h	Real height
h'	Virtual height
h_o	Base of the ionosphere
h_r	Reflection height
$h_{\max}$	Height of peak electron density
$hmF2$	*F2* layer height of peak electron density
H	Scale height
N, N_e	Number of electron (per meter^3)
$N_{\max}$	Peak electron density
$NmF2$	*F2* peak electron density
$B0$	Thickness of the *F2* region
$B1$	Shape of the *F2* region
$M(3000)F2$	Propagation factor
Rz_{12}	12 month running-mean sunspot number
IG_{12}	ionosphere-effective solar index
A_p	Daily magnetic index
K_p	3-hour Planetary
c	Speed of light
t	Time
T	Time of flight
χ	Solar zenith angle

μ	Refractive index
μ'	Group refractive index
a_0, a_n, b_n	Fourier coefficients
n	Number of term (harmonics)
E	Electric field
N	Number of element
d	Element spacing
d_x	Array spacing
d_y	Element spacing
α	Progressive phase shift
θ	Elevation angle
k	wave number
r	Far field distance
ψ	Array phase
λ	Wavelength
O	Oxygen
N_2	Nitrogen
NO	Nitrogen Oxide

LIST OF ABBREVIATIONS

ACE	Advanced Composition Explorer
ARTIST	Automatic Real Time Ionogram Scaler with True Height
CADI	Canadian Advanced Digital Ionosonde
CCIR	International Radio Consultative Committee
COSPAR	Committee on Space Research
CTIP	Coupled Thermosphere-Ionosphere-Plasmasphere
EEJ	Equatorial Electrojet
EIA	Equatorial Ionization Anomaly
EITS	Equatorial Ionosphere-Thermosphere System
ESF	Equatorial Spread *F*
EUV	Extreme Ultra-violet
FAIM	Fully Analytical Ionospheric Model
GIRO	Global Ionospheric Radio Observatory
GPS	Global Positioning System
HF	High Frequency
HWM	Horizontal Wind Model
ICED	Ionospheric Conductivity and Electron Density
IONCAP	Ionospheric Communication Analysis and Prediction
IRI	International Reference Ionosphere
ISR	Incoherent Scatter Radars
LT	Local Time
MSIS	Mass Spectrometer and Incoherent Scatter
MUF	Maximum Usable Frequency
NASA	National Aeronautics and Space Administration
NHPC	*N(h)* on PC
NOAA	National Oceanic and Atmospheric Administration
PARIM	Parameterized Regional Ionosphere Model
PIM	Parameterized Ionospheric Model
POLAN	Polynomial Analysis
RCS	Radar Cross Section

RMSE	Root Mean Squared Error
SID	Sudden Ionospheric Disturbance
SLIM	Semi-Empirical Low-Latitude Ionospheric Model
SOHO	Solar and Heliospheric Observatory
SPIDR	Space Physics Interactive Data Resource
SSE	Sum of Squares due to Eerror
SSN	Sunspot Number
SUPIM	Sheffield University Plasmasphere-Ionosphere Model
TEC	Total Electron Concentration
THO	Tun Hussein Onn
UHF	Ultra High Frequency
URSI	International Union of Radio Science
UTC	Universal Time
VHF	Very High Frequency
VIS	Vertical Incidence Sounding

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The knowledge on the state of the upper atmosphere, in particular its ionospheric part, is very important in several applications affected by space weather. The radio frequency communications and the satellite positioning and navigation systems are the most affected ones by ionospheric disturbances. In particular, ionospheric disturbances can cause drastic changes of large-scale to the usable range of high frequency (HF) or below high frequency bands affecting the standard ground-to-ground and submarine communication systems. The effects are recognized as loss of communications, change in area of coverage, low signal power, fading, and error rate change. Fading and error rate change are also the effect of very high frequency (VHF) or ultra high frequency (UHF) band, causing disturbances in ground-to-satellite communication systems. Ionospheric scintillation and dispersion could lead to loss of phase lock and position errors, which strongly affects the advanced navigation systems. Therefore, to keep different technical systems functioning in spite of all these effects, specification and prediction of the state of the upper atmosphere is of significant important and valuable.

The most important property in the ionosphere is the electron density. This parameter varies considerably with time (sunspot cycle, seasonally, and diurnally), geographical location (polar cap, auroral zones, equatorial regions), and with certain solar disturbances (Davies, 1990). Over the last 60 years, continuous and automatic monitoring of the state of the ionosphere has been carried out extensively with the worldwide network of ionosonde stations. The ionospheric electron-density profiles are modeled and their characteristic parameters are presented through global maps. These models are widely used for effective ionospheric study and forecasting. However, in some regions the discrepancies are highlighted. The models had under or overestimated densities that may lead to wrong interpretation of the state of the ionosphere. The accuracy of the data-based model is highly dependent on the availability of reliable data for the specific region and time (Bilitza et al., 1993). Inadequate comparisons are obviously seen in particular at low- and equatorial latitudes regions due to scarce distribution of ionosonde stations. This scenario had raised interest for researchers and scientists to extend studies over these regions. More ionosonde stations are installed in equatorial region and their results are valuable inputs to the improvement of these models. Readers are referred to Chapter 2.2 for further deliberations on this issue.

The ionosphere over this region was described by Rishbeth (2000) as unique as it exhibits the well-known equatorial ionization anomaly (EIA). This is characterized by an ionization trough at the magnetic equator and crests on either side at latitudes around $\pm 16^{o}$ (Appleton, 1946). The cause of the anomaly is by the equatorial plasma fountain that transfers ionization from around the equator to higher latitudes (Appleton, 1946). Peculiar features over this region such as the appearance of an additional ionization layer above the *F2* peak, namely the *F3* layer during morning-noon period and the post-sunset peak are results of the above mentioned mechanism (Bailey and Balan, 1996; Jenkins et al., 1997; Balan et al., 1998). Located in between the geographical equator at the south and geomagnetic equator in the north, the location of Malaysia is found to be very strategic to explore such interesting phenomena. The operational of Parit Raja ionosonde station is a substantial beginning of this exploration. The station was in operation in December 2004. It is the only ionosonde station in Malaysia that provides ionosonde data for region close to magnetic equator.

The ionosonde data is a viable resource to describe the vertical profile of the ionosphere. The data is analysed to determine the actual *F* layer height and produce better description of its variations. The height of peak electron density, h_{max}, is the height where maximum electron density occurs. Along with the peak electron density, N_{max}, these parameters made up the electron-density profiles. Thus, ionospheric observation is a vital step in understanding of the ionospheric behavior. This will be further elaborated in the subsequent chapters. A model that characterised the *F* region peak density height variations is the outcome of the study.

1.2 PROBLEM STATEMENT

The ionosphere *F* region, being the most important region of the ionosphere exist in the upper atmosphere at an altitude range of 200 km to about 1000 km (Davies, 1990). This region is primarily responsible for most skywave propagation of radio waves, facilitating high frequency, or shortwave radio communications over long distances as it has the densest electron density and most important exists at all time (Davies, 1990; Rishbeth and Garriot, 1969). This layer may also cause signal attenuation to most space related applications, deteriorating the performance of satellite radio systems. The equatorial *F* region is also known to be highly variable corresponds to the processes which control its production, loss, and transport of electrons, especially at the altitude range above 250 km (Rishbeth and Garriot, 1969; Rishbeth, 2000). The greatest electron density, $N_{\max}$, occurred at higher altitude and the corresponding height is referred as the height of maximum electron density, $h_{\max}$ (Rishbeth and Garriot, 1969).

Studies on the *F* layer height of peak electron density, $h_{\max}$, received less attention compared to other ionospheric parameters. Unlike critical frequencies, the actual height determination process is more complex as the electrons are easily drifted. This thesis reports on three main problems associated with the actual height of maximum electron density, $h_{\max}$, which had inspired research on this parameter, as below:

i) To enhance the actual height analysis studies in Malaysia.

All ionospheric sounding processes provide only virtual height information. When Zain et al. (2008) observed the appearance of *F3* layer over Parit Raja, the demand for a precise value of actual height of peak electron density becomes apparent. The *F* region peak electron density is assumed to occur at 300 km, as observed in mid-latitude regions, whereas, in equatorial latitude regions, the height of peak electron density has been reported high, between 350 and 500 km (Bilitza, undated). The assumptions need further justification considering that Malaysia is located in the vicinity of equatorial ionization anomaly. The actual height of peak electron density over Malaysia is still unknown. Varying height is expected in the diurnal pattern of h_{max}.

The assertion on varying height of the ionosphere over Malaysia requires research on the height deviation of h_{max}. The F region h_{max} variability study is important to determine the extent of the height deviation from the mean value under different ionospheric conditions. The dependence of electron density on solar radiation is known as the main cause of the h_{max} variability. The effects are greater under severe solar activities and geomagnetic storms. Any occurrence of ionospheric disturbances may change the physical properties of the ionosphere. The F layer may become unstable, fragmented, or even disappear completely. The electron-density profile is very significant to illustrate the variation of electron densities with heights. Different shapes of day and night profiles are observed to gauge better understanding of the physical mechanisms that control the processes and behavior of the equatorial ionosphere.

Furthermore, the International Reference Ionosphere (IRI) model verification for Malaysia has not been extensively reported. The IRI model is the most widely used empirical model for effective ionospheric study and forecasting globally. The model becomes the first adopted standard specification of ionospheric parameters by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) in 1990. The accuracy of IRI model in presenting equatorial region densities have been reported elsewhere (Jesus et al., 2011; Yadav et al., 2010; Wichaipanich et al., 2010), however for Malaysia, there is no activities conducted related to IRI model verification.

ii) The classical way of representing $h_{\max}$ temporal variation in the Cartesian coordinate system is too conventional

In this study, trend analyses are used to illustrate the characteristic variation patterns. Appropriate mathematical functions are then used to represent the temporal variations; for a repetitive function, the Fourier series approximation is suitable to describe the variations. This is a classical way of representing temporal variations which is usually represented in a rectangular coordinate system. An alternative representation is introduced where the diurnal height variation, which is cyclic in nature, can be represented using polar representation. By using appropriate formulation, the time variation model is transformed into polar representation.

iii) Lack of a model to signify the ionospheric height variations

A suitable model representing the characteristic parameter is anticipated at the end of this study. Equivalence antenna pattern model of ionospheric height of peak density variations based on antenna radiation characteristics is possible considering the underlying principle of polar representation. This is a novel approach introduced in this study by parameterization of the ionospheric height variation using the attributes of array antenna.

In general, further specifications on the actual height of *F* layer over equatorial region require thorough studies in this domain. The Parit Raja ionosonde data may provide good insight into this anonymous scenario. The experimental data sets are analysed to obtain concrete justifications to the above statements. In addition, characterisation of this parameter helps to describe the scenario in a more appropriate manner.

1.3 OBJECTIVES

The quest for actual *F* region height of peak electron density over Malaysia instigates studies in this domain. Important attributes of the *F* region height of peak electron density are used to explain the dependency in the actual behavior of this parameter to the variations in solar activity, and other geographical constraints. The objectives of this work in addressing the problem statements described in section 1.2 are:

i) To determine the actual ionospheric F region height of peak electron density, $h_{\max}$, overhead, describes its variability (diurnal, seasonal, annual) corresponding to different ionospheric conditions, and investigate the adequacy of IRI model in explaining the observed densities in equatorial regions.

   The actual heights of ionospheric F region during moderate to low solar activity period are deduced from hourly ionograms of March, June, September, and December, 2006 and 2007. The representations are based on median data. The typical behavior of the F region ionosphere is explained and statistical analyses are used to quantify the expected deviations from that typical behavior. The variability of ionospheric characteristics with local time, season, and solar indices, as a result of known changes in ionising sources and atmospheric composition are clarified. The results of IRI prediction model will be compared with observational data to establish an empirical correction to the current model, if exists.

ii) To develop a descriptive model that represents the diurnal characteristics of the ionospheric F region height of peak electron density over Malaysia and further enhanced the classical representation.

   A simple, numerical model that can be used to calculate approximate profiles under any required conditions are derived based on experimental evidence using data sources from the ionosonde. The descriptive model should give fully smooth and physically realistic variations at all times. The cyclic nature of the variations would enable new representation in polar form. Enhancement in the classical way of representing $h_{\max}$ temporal variation is feasible by using appropriate transformation of the time domain.

iii) To model an antenna equivalences of peak height variation.

A signature of ionospheric height of peak density variations in this manner may represent appropriately the ionospheric *F* region height variations over Malaysia. The variations can be described by antenna array design parameters such as number of elements, element separation, and current and phase in each element.

1.4 SCOPE OF WORK

The scope of work is divided into three main categories according to the research approach. The description for each of the stages is as follows:

1.4.1 Ionospheric Observation

Ionospheric observation is the most fundamental step in preliminary understanding of the ionosphere. The ionosonde used to probe the ionosphere is located at Parit Raja (2^oN, 103^oW, dip 14.3^o), Batu Pahat, Malaysia. Radio soundings are carried out daily at 5 minutes interval to monitor the state of the ionosphere. The recorded tracings of reflected high frequency radio pulses are observed regularly to examine the present ionospheric condition. These ionograms, generated by the ionosonde, shows the virtual height, *h'*, of the ionospheric layers as a function of plasma frequency. Proper inversion method is required to obtain the real height, *h*. Several programs arise to facilitate this inversion, among which the polynomial analysis (POLAN) program and NHPC are widely used at present (Liu et al., 1992). Depending on the instrument type, the POLAN program developed by Titheridge (1985) is used extensively in this study. The inversion process is manually performed on individual ionogram. The tediousness of the inversion process is highly vulnerable to error especially when there are occurrences of ionospheric disturbances (e.g. spread *F* and sporadic *E*). These disturbances may mislead the ionogram interpretation. Knowledge in physics and chemistry of ionosphere are necessary to facilitate this process. The output of POLAN is in text file where in this context, it is still considered as raw data.

1.4.2 Data Analysis and Trending

The peak electron density, $N_{\max}$, and height of peak electron density, $h_{\max}$, are two important parameters derived from the ionograms using POLAN. Together with the solar and geomagnetic data, these data are arranged to form a solid database. The data assimilation process also involves some pre-processing procedures which categorised the data according to event types and subsequently extract any geomagnetic dependency data in the final output. The idea is to produce a database which will produce an ideal approximation of the ionosphere behavior. The 'processed data' are also used to draw the median $N_{\max}$ and $h_{\max}$ trends. Different conditions could be considered; diurnal variations (sunrise, noon time, sunset, midnight), seasonal variations (spring, summer, autumn, winter), and solar activity (high, low) variations. These are various type of variability that can weigh up any investigation on the ionospheric behavior. This stage requires high computational skills and MATLAB program is utilized for this purpose.

1.4.3 Modeling

A numerical model of the diurnal trends of median height of peak electron density variations is needed to calculate approximate variations at all times. In this case, appropriate mathematical function is used to represent the characteristic variation patterns. As for a periodic function, Fourier series approximation is the most suitable fit. The empirical models are then remodeled into suitable representation before a final model which constitutes to ionosphere height of peak electron density variations can be established. The configuration of this new model is the novelty of this study.

1.5 THESIS OUTLINE

This thesis is divided into six main chapters. Chapter 1 introduces the main idea of the research project. The introduction describes the importance of ionospheric studies in communication aspects which involves either terrestrial or satellite communication systems. The idea of having comprehensive global ionospheric profiles is also addressed which then highlights the equatorial ionosphere as one of the challenging region to