Estimations of Ionospheric Properties over Indian Subcontinental region from GPS Signal Analysis

Submitted in partial fulfillment of the requirements
of the degree of

Doctor of Philosophy

by

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In dedication to my parents for making me be who I am

&

my wife for supporting me all the way!

Thesis Approval

This thesis entitled **Application of Dynamic Phasor Models for the Analysis of Power Systems with Phase Imbalance** by **Mahipalsinh C. Chudasama** is approved for the degree of **Doctor of Philosophy**.

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Declaration

I declare that this written submission represents my ideas in my own words and where others´ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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CERTIFICATE OF COURSE WORK

This is to certify that **Sampad Kumar Panda** (Roll No. 09431010) was admitted to the candidacy of Ph.D. degree on 13 Jan 2010, after successfully completing all the courses required for the Ph.D. programme. The details of the course work done are given below.

S.No	Course Code	Course Name	Credits
1	NR 805	Advanced Concepts in Polarimetric SAR Image Analysis	6
2	NR 808	Introduction to Geospatial Technologies	6
3	NR 623	GPS: Principles and Applications	6
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Abstract

The ionosphere is a layer of the earth's upper atmosphere which comprises high concentration of electrons and ions, from the existing atmospheric gases mostly due to the solar radiations. Ionospheric properties such as electron density, ion and electron temperatures, ionospheric composition, as well as dynamics vary with altitude, latitude, longitude, local time, season, solar cycle, as well as geomagnetic activity. There are spatial as well as temporal variations in the number of ionization layers, their heights and ionization intensities in space. Changes in the equatorial and polar ionosphere are known to be high compared to relatively moderate changes in the mid-latitude regions. The variability of the equatorial and low latitude ionosphere is due to the large-scale electrodynamics associated with the equatorial electrojet (EEJ), plasma fountain, equatorial ionization anomaly (EIA), equatorial wind, and temperature anomaly etc. There is strong EIA on a day with strong EEJ, less prominent EIA on a day when CEJ develops, and even absence of EIA crest during certain severe geomagnetic circumstances. All these unique features at the equatorial and low latitude ionosphere are due to the perfect horizontal alignment of the geomagnetic field lines at the dip equator and the shifting between the geographic and geomagnetic equator.

Prevailing free electrons in the ionosphere affect the propagation of electromagnetic wave by introducing delays in the traveling time of the communication and navigation signals, such as the global navigation satellite system (GNSS) signal propagating towards the earth through the ionosphere. As the signals from the constellation of GNSS satellites traverse the dispersive ionosphere, they experience group delay and phase advancement of the signals. Further, a rapid irregular electron density profile may give rise to phase and amplitude scintillations with additional measurement errors. The full constellation of global positioning system (GPS) signals traversing the dynamic ionospheric medium, carry its signatures and thus provides all time, all weather, round the globe opportunity of observing and analyzing the ionospheric conditions

through modeling the group delays and phase advances experienced with the signals. In a dual frequency GPS receiver, differential of carrier phase and pseudorange observations in both the frequencies (L1 & L2) can effectively cancel out all frequency dependent biases highlighting at least the first order estimates of along the ray path total electron content (TEC), which refers to the ionospheric delay error. Through numerous experiments and observations, it is now intrinsically convinced that the characteristics of the ionosphere could be effectively determined by TEC as derived from the redundant GPS observables at almost all parts of the globe. Although there developed many theoretical and analytical ionospheric models, the discrepancies in the robustness of the observations practically varies with geographic distribution of the ionosphere. The peculiarity of the ionosphere above Indian subcontinental region is that, most part of it is situated in the low latitude anomaly (EIA) region with geomagnetic equator passing below the peninsular India, and the anomaly crest straddling through the heart of the subcontinental region. Hence, it is distinctively different from other latitudinal regions due to participation of the driving equatorial electrodynamics which itself varies from day-to-day. As the precisions in GPS positioning accuracies depend on the trustworthy modeling of the attenuating ionospheric parameter, any generalized model may not consequence reliable results unless and until a proper understanding of the background parameters has been realized over the region.

Framework of the present research work is aimed at the comprehensive study of regular diurnal, seasonal and latitudinal variations of ionospheric TEC with a year of data set which pertains the progressive phase of the Solar cycle-24. The international GNSS service global ionosphere maps (IGS-GIM), standard international reference ionosphere (IRI-2012) and standard plasmasphere-ionosphere model (SPIM: IRI + Russian SMI) predictions and their reliability are examined, by comparative analysis with in-situ GPS derive TEC measurements. Reviews of past records do agree with IRI lacking reliable results, but predictability of the SPIM over Indian ionosphere is yet to be explored. The present study has considered these models to characterize their suitability over the region. Results confirm much higher deviations of SPIM model from the in-situ GPS observations as well as IGS-GIM and IRI-2012 estimations, emphasizing in further improvement of the models. Additionally, re-investigations of the much stronger geomagnetic storms during the Solar cycle-23 and their ionospheric responses are evaluated, through a unique approach of suitably selecting the best quiet days on the basis of EEJ strength and normalcy in pattern. It is our belief that an arbitrary consideration of regular quiet days, ignoring the EEJ strength over low latitudes, may yield erroneous interpretations of the results. Although the results of these experiments outcome similar postulates to that of earlier studies, miniature differences are noticeable due to our incomparable way of choosing the best reference days in the analysis. The other study included in this research work is a multi-instrumental study of annular solar eclipse (15 Jan 2010) effect on the equatorial and low latitude ionosphere. We highlight the plausible manifestation of anomalous gravitational tidal enhancement on the eclipse day, probably due to the conspicuous Sun-Moon-Earth alignment during the local ionization peak hours. We support our argument in the outcomes by comparing with dual control days, (1) the preceding CEJ day and (2) the very normal EEJ day with a strong back up of magnetometer recordings and satisfactory explanations of pertaining reports. In connection of the present event we attribute the gravitational tidal forces to be the foremost manipulators of the equatorial electrodynamics, unlikely the temporary interruptions in the eclipse obscured photo-ionization played a minor role in ionization changes over the equatorial and low latitude Indian region. Finally, the first order ionospheric delay error for the single frequency (L1) GPS receivers is deduced by modeling the ionospheric TEC with a single layer ionosphere model. The model estimates of diurnal maximum delay error at a low latitude Indian location (i.e., Mumbai), is investigated for different solar-terrestrial conditions, namely very nominal quiet, strong and extreme geomagnetic storms and day-time annular solar eclipse conditions. Highest estimated error is observed during the Halloween storm of 29 Oct 2003 and the lowest during the solar eclipse condition. The results of these analysis would certainly help in better understanding of the equatorial and low latitude ionosphere over Indian region.

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List of Abbreviations

BRDC . . . . . Broadcast Ephemerides

CEJ . . . . . . Counter Electrojet

DCB . . . . . . Differential Code Bias

D-Day . . . . . Disturbed Day

EEJ . . . . . . Equatorial Electrojet

EIA . . . . . . Equatorial Ionization Anomaly

EMR . . . . . Electromagnetic Radiation

GAGAN . . . . GPS Aided GEO Augmented Navigation

GIM . . . . . . Global Ionosphere Map

GNSS . . . . . Global Navigation Satellite System

GPS . . . . . . Global Positioning System

IEF . . . . . . Interplanetary Electric Field

IGS . . . . . . International GNSS Service

IMF . . . . . . Interplanetary Magnetic Field

IONEX . . . . IONosphere map Exchange

Iono-WG . . . Ionosphere Working Group

IPP . . . . . . Ionospheric Piercing Point

IRI . . . . . . International Reference Ionosphere

IST . . . . . . Indian Standard Time

PCA . . . . . . Polar Cap Absorption

Q-Day . . . . . Quiet Day

RINEX . . . . Receiver Independent Exchange

SPIM . . . . . Standard Plasmasphere-Ionosphere Model

TEC . . . . . . Total Electron Content

TECU . . . . . Total Electron Content Unit

VTEC . . . . . Vertical Total Electron Content

Chapter 1

Introduction

1.1 Background

The ionosphere is a layer of earth's upper atmosphere where high concentration of electrons and ions are produced from the existing atmospheric gases, mostly by the solar radiations (Klobuchar, 1991). It extends from 50 km to more than 1000 km altitude; at the higher altitudes although solar radiation is stronger but there are fewer gaseous atoms to interact with, hence ionization is sparse. The ionospheric properties such as electron density, ion and electron temperatures, ionospheric composition as well as dynamics varies with altitude, latitude, longitude, universal time, season, solar cycle and magnetic activity etc. (Hong, 2008). These variations in ionization at the equatorial and polar regions are known to be high compared to relatively moderate changes in the mid-latitude region (Davies and Hartmann, 1997). Alterations in the equatorial ionosphere is due to large-scale electrodynamic phenomena associated with the equatorial electrojet (EEJ) current, plasma fountain, equatorial ionization anomaly (EIA) etc. The EEJ refers to an eastward electric field due to a strong vertical polarization electric field developed in a latitude band of $\pm 3^{\circ}$ about the dip equator, because of the almost horizontal configuration of earth's magnetic field (Chapman, 1951).

The quiet day regular variation of F-region electron density in the low latitude is dependent on strength of EEJ and thereby intensity of fountain effect over the region. However, the irregular disturbances occur randomly, major source of which are the solar flares resulting sudden ionospheric disturbance (SID), polar cap absorption (PCA), ionospheric scintillations as well as geomagnetic and ionospheric storms. Also solid earth-related phenomena like volcanoes and earthquakes may cause perturbations in the ionosphere, triggered by seismic surface waves but the frequency is less in comparison to solar and magnetospheric activities (Davies and Hartmann, 1997).

1.2 Motivation

As discussed in Section 1.1, the redundancy of GPS signals carrying unique signatures of the dispersive ionosphere, can be effectively used for studying

1.3 Motivation

the ionospheric morphology and variations during different solar and geophysical conditions.

1.3.1 Motiv

It is evident from the literatures that the ionization in the upper atmosphere is the major perpetrator for navigation and satellite communication signals through introduction of delays, an accurate estimation of the ion densities with suitable modeling techniques could improve the transmission accuracies. Moreover, a sudden abnormality in the ionization layers may abruptly effect the traversing signal by introducing errors in the measurements. Efforts have been given by many researchers around the globe, even across the Indian region to use different techniques for probing the ionosphere. However, the modern GNSS observables along with ground-based ionosonde and magnetometer recordings have given importance now a days in studying various aspects of the ionosphere and its properties which would certainly help in improving ionospheric modeling accuracies in the low latitude ionosphere (Komjathy, 1997; Hernández-Pajares et al., 2009). Using different theoretical concepts and external data sources, modeling practices have been attempted by the ionospheric community with subsequent improvements in the predictability. On the other hand, appropriate modeling of the ionospheric constituents give excellent opportunity for studying the temporal and spatial variation of the ionosphere on global/regional basis for learning and implementing the influence of ionospheric structures on electromagnetic propagations. With the establishment of Indian regional GAGAN (GPS Aided Geo Augmented Navigation) and IRNSS (Indian Regional Navigation Satellite System) program, extensive studies have been performed but developing a regional ionospheric total electron content map through distributed GPS receiver network and to conversely model them for providing ionospheric corrections for single frequency navigation, communication and other positioning services on/over the region (Acharya et al., 2007; Sunda et al., 2015).

The remarkable feature of ionosphere over Indian subcontinental region is that a large span of the Indian landmass covers the equatorial and low latitude region with the magnetic equator passing beneath the southern tip of the country through the Indian ocean, and the northern hemisphere EIA crest contour lies over central India straddling the line joining Kolkata and Ahmadabad (DasGupta et al., 1997). Notable to say, the magnetic equator was previously passing through the peninsular mainland of India via Trivandrum, but is now migrating into the Indian ocean at an approximate rate of 0.14 degrees a year. Hence, the spatio-temporal variation in the Indian ionosphere is necessarily controlled by the equatorial electrodynamics, manifestation of which are seen as equatorial electrojet, plasma fountain and equatorial ionization anomaly (EIA). This suggests that the characteristics of ionosphere over Indian region is differs from other regions. The equatorial electrojet is a ribbon of intense eastward electric current flowing eastward in the ionospheric E-layer at about 90-130 km altitude during daytime, within a narrow belt of $\pm 3^{\circ}$ latitude over magnetic dip equator (Chapman, 1951). The main cause of this high current density is the geomagnetic field geometry exhibiting horizontal lines of force at the equator. As earth rotates from west to east, the temperature gradient between the dawn and the dusk terminators results the flow of neutral wind from east to west (westward) on dayside and from west to east on nightside (eastward). This neutral wind develop a polarization electric field pointing in the eastward direction during daytime at the magnetic dip equator where the magnetic field is exactly horizontal. This electric field and the resulting upward $E \times B$ drift of the electrons generate a negative charge at the top and a positive charge at the bottom of the ionospheric E-layer ($\sim 90-130$ km altitude). The resulting electric field boundary prevents the further upward drift of electrons. Rather, they are now forced westward by the eastward electric field. This westward movement of the electrons constitutes an eastward electric current which is called

1.4 Motivation

the equatorial electrojet (EEJ) by Chapman (1951). Its manifestations are observed as the enhancements in the noontime horizontal component of the geomagnetic field (H) in the vicinity of the dip equator. Hence, variation in H acts as a proxy index for EEJ strength over the equator (Egedal, 1947; Forbes, 1981; Rastogi, 1994). In context to Indian region the magnetic data from two stations, an equatorial station Tirunelveli (in the vicinity of EEJ) and an off equatorial station Alibag (outside EEJ effects) are used to estimate the EEJ strength. Studies also confer that the daytime E region eastward electric field may sometimes flow reversely showing negative depression in the magnetic H data, called the counter electrojet (CEJ) which restricts the regular uplifting of equatorial electrons to higher altitude and its subsequent diffusion to higher latitudes through the fountain process (Appleton, 1946; Gouin and Mayaud, 1967). This in turn changes the distribution of electron density across the region. Also, it has been seen that the CEJ may there be present on a quiet day, the strength of EEJ may vary depending on the prevailing electrodynamics over the equator (Deshpande et al., 1977). Hence, multi-instrumental observations may preferably help in understanding different aspects of the low latitude ionosphere during varied electrodynamic conditions. Moreover, the reliability in the estimation parameters with successive improvements in the existing models or newly introduced developed models are need to be tested over different geographic regions to realize their effectiveness. In connection to the above discussion, it can be speculated that comprehensive studies of regular ionospheric variations and abnormalities with multi-instrumental observations are very much essential for better understanding of its physical properties. This would help in relative improvements in the model estimations over the low latitude EIA region. With this motivation, we formulated our research objectives which are discussed subsequently in the next chapter.

1.5 Thesis outline

- ✓ Chapter-1 describes a brief overview of ionosphere and its imaging techniques, particularly the global positioning system (GPS) which provides uninterrupted signals carrying the ionospheric signatures.
- ✓ Chapter-2 elucidates on GPS system, signal structure and error sources during measurements. Additionally, the ionosphere, its layer structure and spatio-temporal variability and different imaging techniques, modeling and major geophysical parameters are discussed. A thorough review of past decades of ionospheric investigations across Indian longitudes and successive improvements on understanding of the effects are included in this chapter.
- ✓ Based on the insight into characteristic of ionosphere in the equatorial region and its effect on GPS signal propagations, the objectives for the present study are formulated and enumerated in Chapter-3, along with requirement of experimental setup, method of treatment and modeling aspects for the processing and analysis of the data.
- ✓ In Chapter-4, a comprehensive study is performed to investigate (i) diurnal, seasonal, and latitudinal total electron content (TEC) variations through the GPS observation data and a comparative analysis of the standard ionospheric models and their suitability during the period of study. In the part (ii) of the work, a set of four extreme geomagnetic storms during the Solar cycle-23 are analyzed with a multi-instrumental study with special reference to the EEJ strength over the equator. In part (iii) an extensive work has been done on the annular solar eclipse over the Indian dip equator and its ionospheric response, particularly the driving electrodynamic parameters are examined in this study. The last part (iv) of the work demonstrates on modeling the ionospheric error on the basis of the TEC retrieved at different solar-terrestrial conditions.
- ✓ Finally in the Chapter-5, the discussions of the results including the important findings of

the studies are summarized. The future scopes of the research work is proposed successively, following the conclusion on the basis of important extracts and understanding of the subject of interest.

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Book Chapter

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2. **S. K. Panda**, S. S. Gedam, and G. Rajaram, 2014, "Study of Ionospheric TEC from GPS observations and comparisons with IRI and SPIM model predictions in the low latitude anomaly Indian sub continental region", *Advances in Space Research*, DOI: 10.1016/j.asr.2014.09.004.

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1. **S. K. Panda**, S. S. Gedam, and G. Rajaram, 2014, “Investigations of Geomagnetic storm effect on the equatorial ionospheric anomaly over Indian region with GPS, Radio occultation and magnetometer observations”, *Proc. of National Conference on Application of Geoinformatics in Rural, Urban & Climatic Studies (Geomatrix’14)*, Indian Institute of Technology Bombay, CD proceedings.

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