NETWORK-BASED REAL-TIME KINEMATIC IONOSPHERIC RESIDUAL MODELLING AND INTEGRITY MONITORING SYSTEM

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To my dearly loved family

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ABSTRACT

The Earth's ionosphere, which is among the major error contributor in Global Positioning System (GPS), is sensitive to level of solar activities. During this study, the concern is on the peak of upcoming Solar Cycle 24 expected in May 2013, which will induce severe disturbance to the ionosphere. This phenomenon raises the question of how will this affect the equatorial ionosphere and real-time GPS positioning. This research helps to understand the geomorphology and climatology of equatorial ionosphere in the Malaysian sector. A combination of local and global GPS network with abundant data has been employed to map the Total Electron Content (TEC) of equatorial ionosphere over Malaysia. The results show that dynamic morphological characteristics of ionosphere induce spatially- and temporally-correlated errors to GPS positioning. A significant amount of these effects can be mitigated with Network-based Real-Time Kinematic (NRTK) technique by generating network correction. This network correction can be tuned to output dispersive correction in order to better model the ionospheric residuals. Dispersive correction approach has been implemented in ISKANDARnet NRTK system for NRTK service enhancement. Extensive tests conducted within ISKANDARnet coverage under undisturbed ionosphere condition found that dispersive correction approach outperformed conventional lump correction with: (i) mean improvement of 20% in ambiguity resolution success rate, (ii) positioning accuracy was two-fold better with all error components lay within ±10 cm, and (iii) 21% improvement in mean ambiguity resolution validation ratio was achieved. However, imperfect ionospheric modelling due to rapid ionospheric irregularities leads to the need of establishing a near real-time ionospheric outburst monitoring system. Thus, the ISKANDARnet Ionospheric Outburst MOnitoring and Alert System (IOMOS) is developed to effectively quantify ionospheric disturbances, translate into indices and disseminate nowcast alert to users in near real-time. The IOMOS mainly serves as NRTK integrity monitoring system to ensure reliable NRTK solutions are delivered to users. It also functions as a near real-time space weather monitoring system to probe ionospheric perturbations. Overall, this research will ultimately benefit the GPS positioning and space weather communities.

ABSTRAK

Ionosfera bumi merupakan antara penyumbang selisih utama dalam Sistem Penentududukan Sejagat (GPS) sensitif kepada tahap aktiviti suria. Kajian ini berkisar tentang Kitar Suria ke 24 yang dijangka memuncak pada Mei 2013 akan menyebabkan gangguan teruk terhadap ionosfera. Fenomena ini menimbulkan persoalan bagaimana ia memberi kesan kepada ionosfera di kawasan khatulistiwa dan penentududukan GPS masa hakiki. Penyelidikan ini membantu pemahaman mengenai geomorfologi dan klimatologi ionosfera khatulistiwa di sektor Malaysia. Gabungan jaringan GPS tempatan dan global digunakan untuk memetakan kandungan total elektron (TEC) di Malaysia. Hasil menunjukkan bahawa sifat morfologi ionosfera yang dinamik memberi selisih ruang dan masa kepada penentududukan GPS. Sebahagian besar selisih ini dapat dikurangkan melalui teknik Jaringan Kinematik Masa Hakiki (NRTK) dengan menjana pembetulan jaringan. Pembetulan jaringan ini boleh dilaraskan supaya membentuk pembetulan serakan untuk memodelkan reja ionosfera dengan lebih baik. Pembetulan serakan ionosfera telah dilaksanakan dalam sistem NRTK ISKANDARnet untuk penambahbaikan sistem perkhidmatan NRTK. Ujikaji terperinci yang dijalankan dalam liputan jaringan ISKANDARnet semasa keadaan ionosfera yang tiada gangguan menunjukkan bahawa pendekatan pembetulan serakan ionosfera menandingi pembetulan gumpalan konvensional dengan: (i) purata penambahbaikan sebanyak 20% dalam kadar penyelesaian ambiguiti, (ii) ketepatan penentududukan dua kali ganda lebih baik dengan semua komponen selisih dalam lingkungan ±10 cm, dan (iii) 21% penambahbaikan dalam nisbah pengesahan bagi penyelesaian ambiguiti dapat dicapai. Namun demikian, permodelan ionosfera yang tidak sempurna disebabkan perubahan ionosfera yang pantas menimbulkan keperluan untuk menubuhkan sistem pemantauan letusan ionosfera masa hakiki. Justeru itu, Sistem Pemantauan dan Amaran Letusan Ionosfera (IOMOS) untuk ISKANDARnet dibangunkan dengan menghitung kuantiti gangguan ionosfera dalam bentuk indeks ionosfera dan menyebarkan amaran semasa kepada pengguna. IOMOS kini digunapakai sebagai sistem pemantauan integriti NRTK untuk memastikan hasil teknik NRTK boleh dipercayai untuk disalurkan kepada pengguna. IOMOS juga berfungsi sebagai sistem pemantauan cuaca angkasa pada masa hakiki untuk meneliti gangguan ionosfera. Secara keseluruhannya, hasil penyelidikan ini dapat memanfaatkan komuniti penentududukan GPS dan cuaca angkasa.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

I_P	Ionospheric delay in pseudo-range
I_Φ	Ionospheric delay in carrier phase
f	Carrier frequency
P	Code observation
Φ	Carrier phase estimation in metric unit
λ	Wavelength
N	Integer ambiguity (in cycle)
c	Speed of light
DCB_A	Differential inter-frequency hardware delays of the receiver A
DCB^i	Differential inter-frequency hardware delays satellite i
$F(z)$	Single-layer mapping function
z	Geocentric zenith distances at the height of the station
z'	Geocentric zenith distances at the height of the single-layer
R	Radius with respect to the station considered
R_0	Mean radius of the Earth
H	Height of the single-layer above the Earth's mean surface
$\mathbf{E}$	Electric field
$\mathbf{B}$	Geomagnetic field
$\Delta\nabla$	DD operator
$\Delta\nabla\Phi_{L4}$	DD L4 observation

$\Delta\nabla\Phi_1$	DD L1 carrier phase measurement
$\Delta\nabla\Phi_2$	DD L2 carrier phase measurement
$\Delta\nabla I_{L1}$	DD ionospheric delay on L1
$\Delta\nabla I_{L2}$	DD ionospheric delay on L2
t_{i}	Epoch i
$\Delta\nabla\phi_k$	DD carrier phase observable in unit of cycles
$\Delta\nabla\rho$	DD geometric range between satellites to receiver
$\Delta\nabla N_k$	DD carrier phase ambiguity
$\Delta\nabla T$	DD tropospheric delay
α_k	Scale for ionospheric delay
$\varepsilon(\Delta\nabla\phi_k)$	DD carrier phase observation noise
$\Delta\nabla\phi_{1,-1}$	DD WL observation in unit of cycles
$\lambda_{1,-1}$	Wavelength of WL combination
$\Delta\nabla N_{1,-1}$	DD WL ambiguity
$\varepsilon(\Delta\nabla\phi_{1,-1})$	DD WL observation noise
$\Delta\nabla\phi_{77,-60}$	DD IF observation in unit of cycles
$\lambda_{77,-60}$	Wavelength of IF combination
$\Delta\nabla N_{77,-60}$	DD IF ambiguity
$\varepsilon(\Delta\nabla\phi_{77,-60})$	DD IF observation noise
$\Delta\nabla N_1$	DD L1 ambiguity
$\Delta\nabla N_2$	DD L2 ambiguity
MF	Mapping function
ε^x	Elevation angles for satellite x
ε^y	Elevation angles for satellite y
V_k	Observation noise
W_k	System noise

R_k	Covariance matrix of observation noise
Z_k	Observation vector
X_k	State vector
H_k	Design matrix
$\Phi_{k,k-1}$	State transition matrix
Q_k	Covariance matrix
q	Variance of RTZD process noise
τ	Correlation time
Δt	Sampling interval
$X_{k,k-1}$	Predicted state vector
$P_{k,k-1}$	Covariance matrix of the predicted state vector
$X_{k,k}$	Estimated state vector
$P_{k,k}$	Covariance matrix of the estimated state vector
J_k	Gain matrix
V_{L1}	DD L1 residual
V_{L2}	DD L2 residual
ΔX, ΔY	Plane coordinate difference between the master station and reference stations
a, b	Coefficients for ΔX and ΔY, respectively
A	Design matrix
W	Weight matrix
I	Identity matrix
V_{1u}	DD combined correction from master station to rover station
$\Delta X_{1u}, \Delta Y_{1u}$	Plane coordinate difference between master station and rover station
ρ_v^s	Geometric distance between satellite and VRS
ρ_m^s	Geometric distance between satellite and master station
x^s	Satellite position vector

x_m	Master station vector
x_v	VRS position vector
$\Delta\rho_{mv}$	Geometric displacement between master station and VRS
$C1_v$	C1 pseudorange observation for VRS
$C1_m$	C1 pseudorange observation for master station
$L1_v$	L1 carrier phase observation for VRS
$L1_m$	L1 carrier phase observation for master station
$L2_v$	L2 carrier phase observation for VRS
$L2_m$	L2 carrier phase observation for master station
$P2_v$	P2 pseudorange observation for VRS
$P2_m$	P2 pseudorange observation for master station
T_v	Tropospheric delay correction for VRS observation
T_m	Tropospheric delay correction for master station observation
ϕ_m^i	Master station observation from satellite i
ϕ_v^i	VRS observation from satellite i
ϕ_m^j	Master station observation from satellite j
ϕ_v^j	VRS observation from satellite j
$\Delta\nabla Corr_{mv}^{ij}$	DD combined correction between master station, VRS and satellite i, j
$CorrL1$	VRS correction on L1
$CorrL2$	VRS correction on L2
$\Delta\nabla N_{L4}$	DD L4 ambiguity
V_{L4}	DD L4 residual
$\Delta\nabla I_{k_{12}}$	DD ionospheric delay between master and reference station
Hz	Hertz
ΔD	Position error in terms of distance
ΔN	Position error of north component (dNorth)

ΔE	Position error of east component (dEast)
ΔU	Position error of up component (dUp)
n_s	Number of satellites
t	Time
$\Delta IR_s(t)$	Differential ionospheric residual for each satellite s at epoch t
IOT_{lim}	Ionospheric Outburst Threshold limit
$\sigma_b^{\Delta IR}$	Standard deviation of differential ionospheric residual for baselines
D_{st}	Disturbance storm time index
K_p	Planetary K_p-index of the geomagnetic activities for every 3 hours
A_p	Daily planetary A_p-index of the geomagnetic activities
nT	Nanotesla

LIST OF ABBREVIATIONS

AR	Ambiguity Resolution
BEHR	Behrang MASS station
CMR	Compact Measurement Record
CODE	Centre for Orbit Determination in Europe
CORS	Continuously Operating Reference Station
CTIP	Coupled-Thermosphere-Ionosphere-Plasmasphere model
DCB	Differential Code Bias
DD	Double-Difference
DGPS	Differential GPS
DoY	Day of Year
DTEC	Differential Total Electron Content
EIA	Equatorial Ionization Anomaly
EOP	Earth Orientation Parameters
EUV	Extreme Ultra-Violet
FKP	Flächenkorrekturparameter or Area Correction Parameters
G&G	GNSS & Geodynamics Research Group
GDM2000	Geocentric Datum of Malaysia 2000
GIM	Global Ionosphere Maps
GNSS	Global Navigation Satellite System
GNSMART	GNSS − State Monitoring And Representation Technique

GPS	Global Positioning System
GSM	Global System for Mobile
IF	Ionosphere-Free
IGS	International GNSS Service
IOMOS	Ionospheric Outburst Monitoring and Alert System
IONEX	IONosphere Map EXchange format
IOT	Ionospheric Outburst Threshold
IOX	Ionospheric Outburst Index
IPP	Ionospheric Pierce Point
ISKANDARnet	Iskandar Malaysia CORS network
ISK1	ISKANDARnet1
ISK2	ISKANDARnet2
ISK3	ISKANDARnet3
KKPG	Pasir Gudang Community College
L4	Geometry-Free linear combination
L6	Melbourne-Wübbena linear combination
LIM	Linear Interpolation Method
LT	Local Time
MAC	Master-Auxiliary Concept
MASS	Malaysian Active Satellite System
MF	Mapping Function
MRS	Multi-Reference Station
MyRTKnet	Malaysian GNSS Real-Time Kinematic network
NOAA	National Oceanic and Atmospheric Administration
NRTK	Network-based Real-Time Kinematic
NTUS	Nanyang Technological University of Singapore IGS station
PDOP	Position Dilution of Precision
POP3	Post Office Protocol 3
PPP	Precise Point Positioning

PTP	Port of Tanjung Pelepas
QIF	Quasi Ionosphere-Free
RINEX	Receiver INdependent EXchange format
RMS	Root Mean Square
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-Time Kinematic
RTQC	Real-Time Quality Control
RTZD	Relative Tropospheric Zenith Delay
SEGA	Segamat MASS station
SLM	Single-Layer Model
SMS	Short Messaging Service
SNAP	Satellite Navigation and Positioning Laboratory
SSIS	School of Surveying & Spatial Information Systems
SSR	State Space Representation
STEC	Slant Total Electron Content
SUPIM	Sheffield University Plasmasphere Ionosphere Model
SWPC	Space Weather Prediction Centre
SydNET	Sydney Network
TEC	Total Electron Content
TECU	Total Electron Content Units
UNSW	University of New South Wales
UTC	Universal Time Coordinated
UTM	Universiti Teknologi Malaysia
UTMJ	UTM Johor Bahru MASS station
VRS	Virtual Reference Station
VTEC	Vertical Total Electron Content
WDC	World Data Centre
WL	Wide-Lane
ZD	Zero-Difference

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Motivation

In the last two decades, Global Positioning System (GPS) applications have been growing rapidly, proving the availability and reliability of the GPS. However, the GPS positioning accuracies are affected by different error sources. A major error source affecting GPS positioning accuracy are the propagation delays as signals pass through the ionosphere layers. This error source can be the dominant bias during periods of disturbed ionospheric conditions. These periods are usually characterised by a significant degradation of positioning accuracy, and reduction of receiver tracking performance. In particular, the ionospheric free electrons, quantified as Total Electron Content (TEC) are strongly affected by the number of the sunspots (Figure 1.1). During this study, the concern is on the onset of the next solar cycle, Solar Cycle 24 (Figure 1.2) which is underway after the past 11-year sunspot cycle in 2000/2001. This cycle's peak, which is called solar maximum, is expected in May 2013 (NOAA-SWPC, 2009).

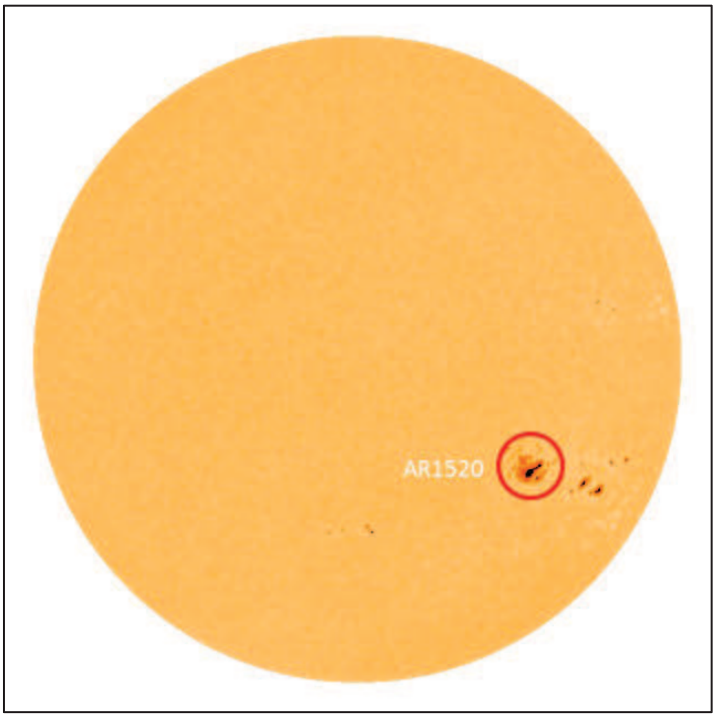

Figure 1.1: Sunspots with Active Region 1520 on 16 July 2012.

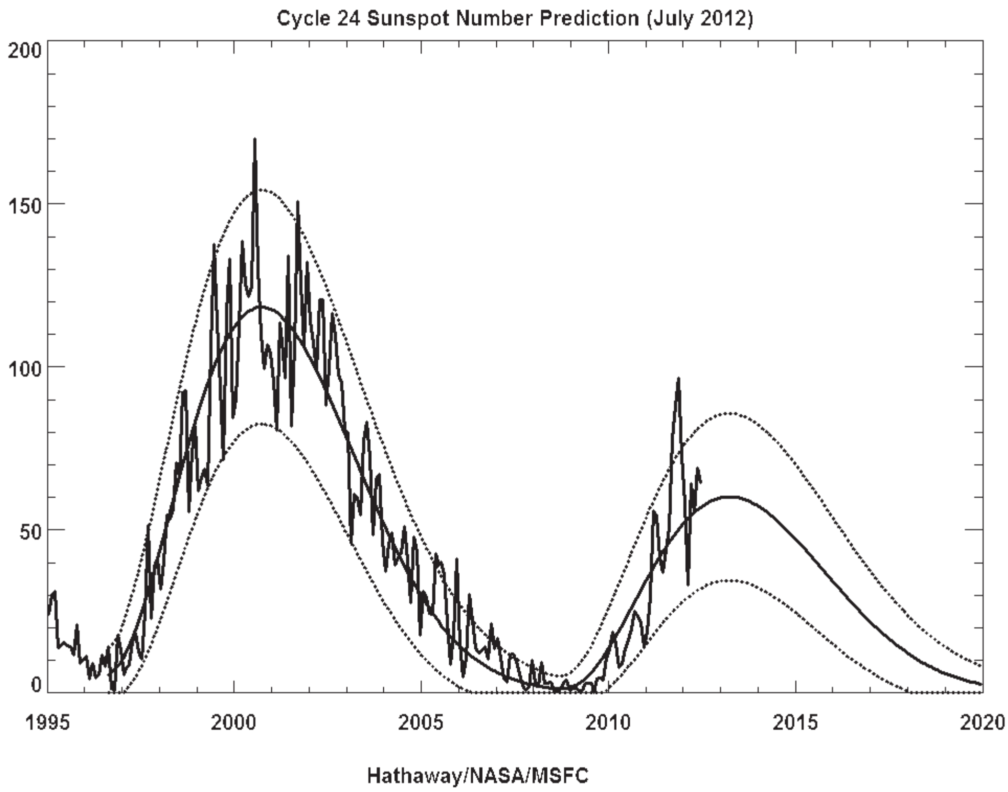

Figure 1.2: Sunspot Number Prediction (Hathaway, 2012).

During this stage, the mean TEC value is expected to increase as shown in Figure 1.3. The green curve shows the interpolated (and 30-day predicted) mean TEC based on a least-squares collocation. In addition a 7-parameter trend function - extrapolated for one year - is plotted in yellow. The daily averaged mean TEC values, namely the zero-degree coefficients of the spherical harmonic expansion used to represent the global TEC, are indicated by black dots. As a result, the performance of (absolute and relative) positioning, navigation and timing will experience degradations during these periods of high ionospheric activity. Moreover, the GPS receiver may lose lock on phase and/or amplitude of the signal when local irregularities in electron contents are present in the ionosphere (Chen *et al.*, 2008). Hence, these phenomena will have direct impact on GPS users in equatorial region since the size and variability of the ionospheric free electron density is usually the largest in this region (Odijk, 2002; Musa, 2007).

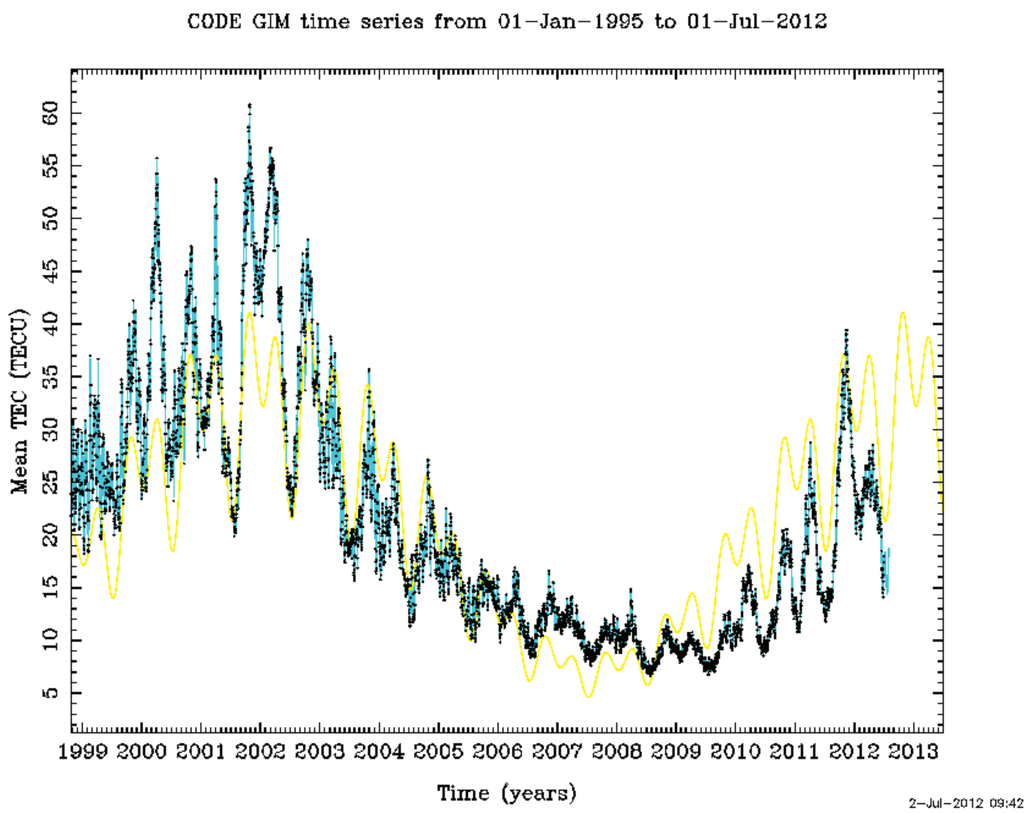

Figure 1.3: Mean TEC value (After CODE, 2012).

1.2 Research Rationale

One possible approach to ameliorate GPS positioning accuracy is Network-based Real-Time Kinematic (NRTK). In recent years, NRTK has been proven to be an efficient way to mitigate ionospheric effect (Lachapelle and Alves, 2002; Rizos, 2002; Musa, 2007). This technique uses a network of GPS Continuously Operating Reference Station (CORS) to model the atmospheric (ionosphere and troposphere) conditions over the region of network coverage, and then to provide users with network corrections. Applying these corrections can reduce a substantial amount of spatially- and temporally-correlated errors related to atmospheric effects, thus improving the accuracy of the rover's position. Moreover, GPS CORS which operates continuously supports the understanding of equatorial ionosphere and thus greatly helps ionospheric modelling in NRTK.

NRTK by nature is for atmospheric modelling enables the detection of local ionopheric irregularities. Ionospheric irregularities affect GPS users by degrading the quantity and quality of measurements; and in the case of NRTK, it worsen the quality of the network correction. Hence, disruption and rapid fluctuation in network correction may signify ionospheric disturbances. Subsequently, NRTK system administrator can inform roving users about potential positioning quality deterioration and/or expected difficulties in network positioning. As a sole university-based NRTK provider in the region, the Iskandar Malaysia CORS network (ISKANDARnet) is utilised as an operational platform for this research. Collectively, understanding and continuously monitoring the spatio-temporal variations of equatorial ionosphere together with delivering reliable NRTK correction can effectively quantify ionospheric disturbances and improving user positioning solution.

1.3 Research Aim and Objectives

The **aim** of this research is rooted in the concept of mitigating ionospheric residual and improving the performance of the NRTK with enhanced network correction and reliability assurance via ionospheric monitoring. Specific **objectives** to achieve the aim of this research are outlined below:

i. ***To quantify equatorial ionosphere over Malaysia using GPS measurements.***

   High-resolution TEC maps derived from GPS CORS are used to study both spatial and temporal variations of ionosphere. The magnitude of ionospheric error to GPS positioning is also investigated.

ii. ***To implement dispersive network correction algorithm in ISKANDARnet NRTK system.***

   The ISKANDARnet NRTK system is enhanced with implementation of dispersive network correction to better mitigate ionospheric effects.

iii. ***To develop an ionospheric residual monitoring and alert system for ISKANDARnet.***

   The ISKANDARnet Ionospheric Outburst Monitoring and Alert System (IOMOS) is developed and integrated with ISKANDARnet system. The IOMOS monitors the quality of NRTK correction and derives ionospheric outburst indicator as part of NRTK integrity monitoring. It also serves as an operational platform for space weather monitoring system.

1.4 Research Scopes

Three limitations were identified during this research:

i. The inter-distance between ISKANDARnet CORS is restricted since ISKANDARnet is a medium-scale CORS network in the equatorial region with maximum baseline length less than 50 km.

ii. This research focused on dispersive component (ionospheric residuals) for NRTK correction enhancement and integrity indicator since ionosphere has rapid variations and contributes the largest error in GPS observables. However, the same approach can be applied for the non-dispersive part (troposphere) too.

iii. The approach in this research is concentrated in the equatorial region; possible adaptation and test have not been considered for other regions.

1.5 Research Strategy

In order to achieve research aim and objectives, the research approach for ionospheric residual modelling involves developing and implementing three components in ISKANDARnet processing core: (i) GPS ionoscope for quantifying equatorial ionosphere over Malaysia, (ii) dispersive network correction for enhancing NRTK correction, and (iii) NRTK integrity monitoring via IOMOS. The model for overall research approach and integral relationship between components are illustrated in Figure 1.4, respectively.

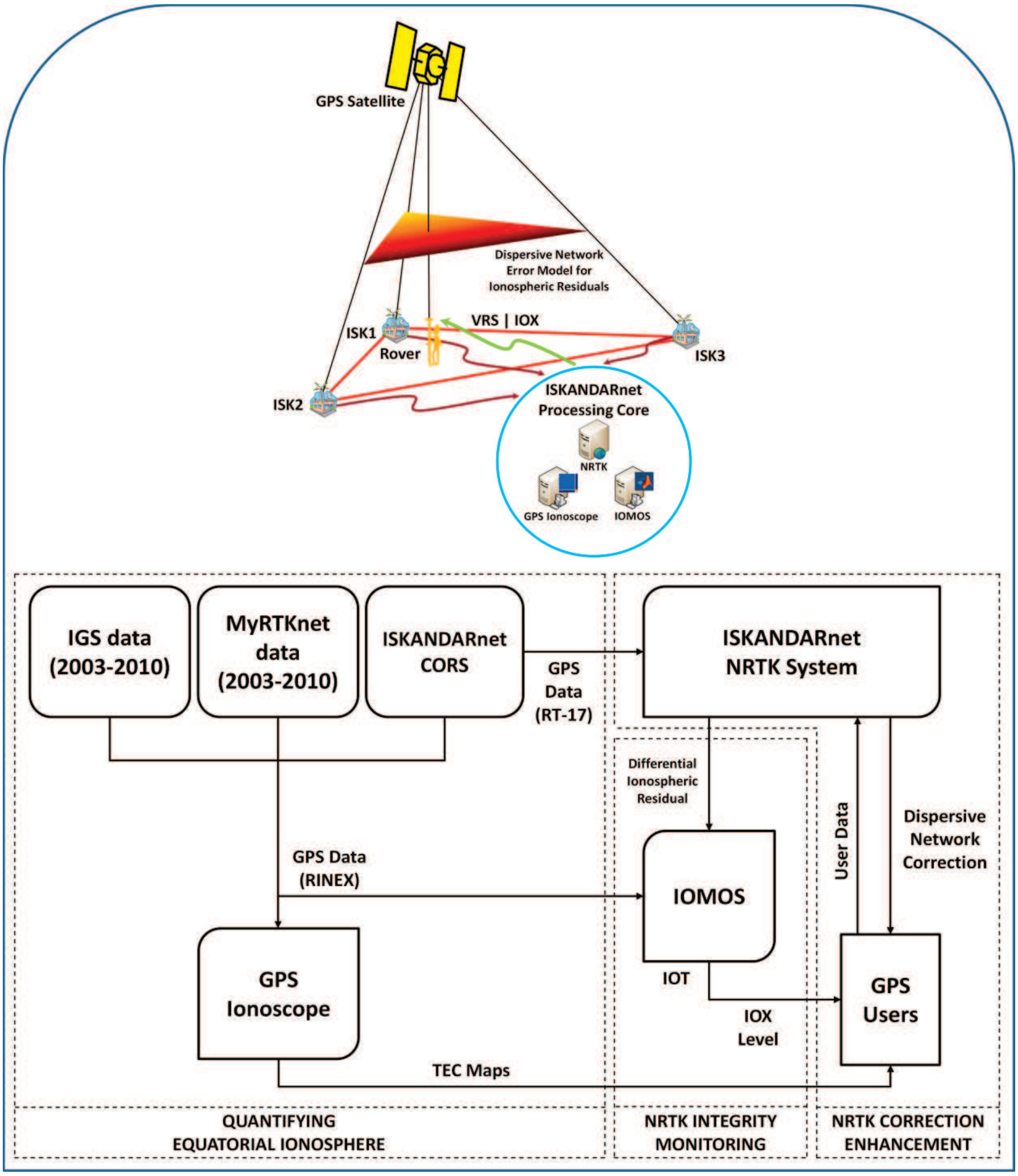

Figure 1.4: Model-based design and schematic design workflow of integral components for research approach.

The research was conducted in five phases:

Phase I: Research Plan and Literature Review

- Critical research planning and literature review were carried out to get detailed insight and research methodology.

Phase II: Quantifying Ionosphere via GPS Ionoscope

- GPS data from local and regional CORS were utilised to map TEC over Malaysia.
- The magnitude of ionospheric error to GPS baseline was analysed.
- First research objective is accomplished upon the completion of this phase.

Phase III: NRTK Correction Enhancement

- The current implementation of NRTK in ISKANDARnet system is clarified.
- The algorithm to generate dispersive network correction is implemented.
- Preliminary test and analysis were conducted to assess dispersive correction compared to conventional lump correction.
- The second research objective is achieved from this phase.

Phase IV: NRTK Integrity Monitoring

- IOMOS is developed and implemented as NRTK integrity monitoring for ionosphere in ISKANDARnet system.
- The algorithm and workflow of IOMOS are explained.
- Test case and analysis are presented.
- This phase fulfils the third research objective.

Phase V: Overall Performance Evaluation

- The output of each component in research approach was integrated and undergone a performance evaluation.
- Test campaigns were conducted in two modes: post-kinematic and NRTK to evaluate overall performance of ionospheric modelling.
- Comparison between dispersive and lump corrections approach was analysed in ambiguity and position domain.
- Conclusion and recommendation are drawn from results and analysis.

1.6 Research Contributions

The main contributions of this research can be summarised as follows:

i. The morphology and climatology studies of equatorial ionosphere in bridging behavioural knowledge of ionosphere over Malaysia. Ionospheric studies via GPS ionoscope also facilitate the development of space-based industry in Malaysia, for example satellite-based navigation, surveillance and communication systems. The understanding of the ionosphere layers helps in modelling signal propagation for abovementioned space-based systems. More importantly, it can be useful for monitoring the incoming Solar Cycle 24, which is expected to reach maximum in May 2013.

ii. Enhancing NRTK performance with implementation of dispersive network correction in ISKANDARnet NRTK processing core. Dispersive correction provides better ionospheric residuals modelling, which in turn higher quality of NRTK corrections can be obtained. Consequently, precise positioning is reliably possible, especially during the period of disturbed ionosphere.

iii. Development and implementation of IOMOS as NRTK integrity monitoring system and operational ionosphere probing system. IOMOS utilises ionospheric residuals to serve as ionospheric network integrity indicator without additional cost and fully covers the network. Ionospheric indicator is a useful tool to inform users about expected difficulties in NRTK positioning. It also provides statistical information on the expected size of residual ionospheric biases that affects positioning accuracy.

1.7 Thesis Outline

This thesis consists of six chapters and summarised as follows:

Chapter 1 describes the motivation, rationale, and objectives of the research. The strategy for meeting these objectives are provided. Major contributions of this research are also highlighted.

Chapter 2 investigates morphology and climatology of equatorial ionosphere over Malaysia. The methodology of estimating the ionospheric TEC values from GPS observables via combination of local and global GPS network is described. Spatial and temporal characteristics of ionospheric error are analysed. Information from this chapter is applied as both a priori information and empirical observation for data analysis in subsequent chapters.

Chapter 3 gives brief introduction about ISKANDARnet. The chapter examines algorithms used in ISKANDARnet software, and clarifies implementation method of dispersive correction in order to better model the ionospheric residuals. The chapter concludes with an initial test and analysis on the performance of dispersive correction.

Chapter 4 presents the need of network integrity monitoring system. The chapter describes the development and implementation of IOMOS as ionospheric perturbation monitoring module in ISKANDARnet. The core components in IOMOS, i.e. IOX and IOT are introduced. Some case studies are included to verify the proposed system.

Chapter 5 describes the design of the tests and analysis on the performance assessment of dispersive correction approach compared with conventional lump correction. Analysis on ionosphere condition via TEC maps and IOMOS during test duration is presented. Results from performance assessment conducted in both post-kinematic and NRTK mode are presented. The efficiency of the proposed approach is discussed.

Chapter 6 summaries major conclusions on main contributions of this research and make some recommendations for future research.

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