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MODELING AND MODIFICATION OF GLOBAL POSITIONING SYSTEM TROPOSPHERIC DELAY MAPPING FUNCTION

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July 2008

Chairman : Associate Professor Mohd Rizam Abu Bakar, PhD

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The accuracy of Global Positioning System (GPS) measurement is determined by the sum of several sources of error, such as orbit error, satellite clock error, multipath error, receiver noise error, selective availability, ephemeris error and also atmospheric error. The principal error source in the GPS technology is a delay experienced by the GPS signal in propagating through the electrically neutral atmosphere, usually referred to as a tropospheric delay. This delay is normally calculated in the zenith direction, and is referred to as a zenith tropospheric delay. The delay consists of a zenith hydrostatic delay, which can be modeled accurately using surface barometric measurements, and a zenith wet delay, which cannot be modeled from surface barometric measurements and depends on atmospheric water vapor. The mapping function is the coefficient for the zenith delay, either hydrostatic (dry) or non-hydrostatic (wet) delay that can be used to increase or reduce the tropospheric delay.

In this research, 3 mapping function models which are known as $UNBab(E)$, $UNBabc(E)$ and Neill (NMF) are selected to be simplified, where as 2 mapping function models which are known as $UNBabc(E)$ and Neill (NMF) are selected to be modified. For the simplification of the mapping function models, regression method has been used to find the suitable equation. The simplified mapping function models for $UNBab(E)$, $UNBabc(E)$ and Neill (NMF), can reduce the computing time by reducing the percentage of number of operations between 71.4% to 92.3% for linear equations and 28.6% to 80.8% for quadratic equations. The calculations of the sum of errors show that the deviation of the simplified model from the original model is not significant. The simplification of the mapping function models can also create better understanding of the models by using hyperbolic, linear and also quadratic equations rather than continued fractions. Results indicate that the modification of the mapping function models can give smaller value especially for less than 5 degree elevation angles. As the coefficient of the zenith delay, it can improve the tropospheric delay directly. The improvement of the tropospheric delay for $UNBabc(E)$ and Neill mapping functions, NMF can be obtained up to 19.1% and 17.8% respectively at 2 degree elevation angle.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMODELAN DAN MODIFIKASI FUNGSI PEMETAAN BAGI KELEWATAN TROPOSFERIK GPS

Oleh

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Kejituan pengukuran sistem penentududukan sejagat (GPS) boleh ditentukan oleh hasil tambah beberapa punca gangguan (error) seperti gangguan pada orbit, gangguan jam pada satelit, gangguan daripada berbilang laluan, ketidaktepatan pada alat penerima, keupayaan pilihan, gangguan daripada efemeris dan juga gangguan daripada lapisan atmosfera. Punca gangguan utama terhadap teknologi GPS adalah kelewatan yang dialami oleh signal GPS semasa merambat melalui lapisan atmosfera yang neutral, yang disebut kelewatan atmosfera. Kelewatan ini dikira dalam arah 'zenith', dan dirujuk sebagai kelewatan troposfera 'zenith'. Kelewatan ini terdiri daripada kelewatan hidrostatik 'zenith', yang boleh dimodelkan dengan jitu menggunakan pengukuran barometrik permukaan dan kelewatan lembap 'zenith' yang tidak boleh dimodelkan daripada pengukuran barometrik permukaan dan hanya bergantung kepada tekanan wap air atmofera. Fungsi pemetaan (mapping function) merupakan pekali kepada kelewatan 'zenith' bagi kedua-dua komponen samada hidrostatik (kering) atau bukan hidrostatik (lembap) yang boleh digunakan untuk menokok atau menurunkan kelewatan troposferik.

Dalam kajian ini, 3 model fungsi pemetaan iaitu fungsi pemetaan $UNBab(E)$, $UNBabc(E)$ dan Neill (NMF) telah dipilih untuk diringkaskan, manakala 2 model fungsi pemetaan $UNBabc(E)$ dan Neill (NMF) telah dipilih untuk diubahsuaikan. Bagi meringkaskan model fungsi pemetaan ini, kaedah regresi digunakan untuk mendapatkan persamaan yang sesuai Model fungsi pemetaan bagi $UNBab(E)$, $UNBabc(E)$ and Neill (NMF) yang telah diringkaskan ini boleh menurunkan masa pengiraan dengan menurunkan bilangan operasi model di antara 71.4% hingga 92.3% untuk persamaan linear dan antara 28.6% hingga 80.8% untuk persamaan kuadratik. Pengiraan jumlah kesilapan menunjukkan sisihan bagi model yang diringkaskan daripada model asal tidak signifikan. Model fungsi pemetaan yang diringkaskan boleh memudahkan kefahaman mengenai operasi model dengan menggunakan persamaan hiperbola, linear dan juga kuadratik berbanding dengan pecahan berlanjar. Keputusan yang diperolehi menunjukkan bahawa, pengubahsuaian model fungsi pemetaan dapat mengecilkan nilai fungsi pemetaan terutama bagi sudut dongakan yang kurang daripada 5 darjah. Selaku pekali kepada kelewatan zenith, nilai kelewatan troposfera telah dapat dikurang secara langsung. Pembaikan nilai kelewatan troposfera bagi fungsi pemetaan $UNBabc(E)$ dan Neill, NMF boleh dicapai sehingga 19.1% and 17.8% masing – masing pada sudut dongakan 2 darjah.

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I certify that an Examination Committee met on 3 July 2008 to conduct the final examination of Hamzah bin Sakidin on his Doctor of Philosophy theses entitled "Modeling and Modification of Global Positioning System Tropospheric Delay Mapping Function" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulation 1981. The Committee recommends that the student be awarded the Doctor of Philosophy.

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APPROVAL

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

HAMZAH BIN SAKIDIN

Date : 5 August 2008

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LIST OF ABREVIATIONS

DOY	Day Of Year
GPS	Global Positioning System
msl	mean sea level
STD	Slant Total (Tropospheric) Delay
ZHD	Zenith Hydrostatic Delay
ZTD	Zenith Total (Tropospheric) Delay
ZWD	Zenith Wet Delay

CHAPTER 1

INTRODUCTION

1.1 Background

The issue of atmospheric delay of Global Positioning system (GPS) signal is now extensively investigated to minimize the positioning error due to atmospheric delay, especially tropospheric and ionospheric delay. The refraction index is a function of the actual tropospheric path through which the ray passes. The ray's path begins at the receiver antenna ending at the last point of the effective troposphere. Tropospheric delay refers to the refraction of the GPS signal as it passes through the neutral atmosphere from the satellite to the earth. The effect causes the distance travelled by the signal to be longer than the actual geometric distance between the satellite and receiver. Hence, there is scope to introduce the mathematical modeling of the tropospheric model to improve the delay.

The signal bends from its original path and experiences velocity variations as it passes through regions of different refractive indices in the troposphere and the ionosphere. An ionospheric delay is caused by the presence of ionized gas molecules in the ionosphere, and it is dispersive at radio frequencies, meaning that the refractive index depends on the signal frequency. The ionospheric delay is dependent on the density of free electrons. The ionospheric delay can be removed using a linear combination of observations on two GPS frequencies (Shresta, 2003).

Various tropospheric delay models have been developed to estimate these delays, as a function of the satellite elevation angle, receiver height, and meteorological parameters, such as temperature, pressure, and humidity. The range delay in the zenith direction is approximately 2.5m however, for an elevation of 5 degrees, it increases to about 25m. This dependence on elevation angle is described by a mapping function, so that the delay near the horizon is three to five times higher than in the zenith direction (Ahn, 2005).

The zenith hydrostatic delay contributes about 90% of the total delay to the tropospheric delay (Skone, 2001). Zenith hydrostatic delay models can be estimated with accuracies better than 1% where the zenith hydrostatic delay is considered to be a function of the surface pressure and hydrostatic equilibrium is assumed. The zenith wet delay contributes about 10% of the total delay, and the zenith wet delay models have accuracies of 10 to 20%. The wet component depends on water vapor, which is highly variable with the space and time and is difficult to model (Shresta, 2003).

The tropospheric delay is measured in distance, and a typical zenith tropospheric delay would be between 2.3 to 2.5m (Misra and Enge, 2001), meaning that the troposphere causes a GPS range observation to have an apparent additional 2.5m distance between the ground based receiver and a satellite at zenith. The delay caused by the troposphere can be separated into two main components: the hydrostatic delay and the wet delay (Saastamoinen, 1972). The hydrostatic delay is caused by the dry part of gases in the atmosphere, while the wet delay is caused solely by highly varying water vapor in the atmosphere. The hydrostatic delay makes up approximately 90% of the total tropospheric delay. The hydrostatic delay is entirely dependent on the atmospheric weather characteristics found in the troposphere. The hydrostatic delay in the zenith direction is typically about 2.3m (Businger et al., 1996; Dodson et al., 1996). The hydrostatic delay has a smooth, slowly time-varying characteristic due to its dependence on the variation of surface pressure; it can be modeled and range corrections applied for more accurate positioning results using measurements of surface temperature and pressure.

However, the wet delay is dependent on water vapor pressure and is a few centimeters or less in arid regions and as large as 35 centimeters in humid regions. The wet delay parameter is highly variable with space and time, and cannot be modeled precisely with surface measurements (Bevis et al., 1992). By measuring the total delay, and calculating the hydrostatic delay from theoretical models using surface measurements, the remaining wet delay signal, caused by water vapor in the atmosphere, may be recovered.

The tropospheric delays are not measured directly to all satellites in view. Instead, there are several mapping functions that take zenith signal delays and map them to all individual GPS satellites in view at a given site. The Lanyi (1984), Herring (1992), Ifadis (1986), and Neill (1996) models are examples of mapping functions that can be used for high-precision positioning applications. The individual satellite-receiver line-of-sight signal delays are termed as slant delays.

The study of atmospheric water vapor is important for two reasons. Firstly, short-term weather forecasting is affected by the content of water vapor in the atmosphere. Water vapor is highly variable both in time and space and sudden changes in water vapor in the atmosphere can result in changes in the local weather. Water vapor is fundamental to the transfer of energy in the atmosphere (Rocken et. al, 1989). This transfer of energy often results in thunderstorms or even more violent atmospheric phenomena. Secondly, long term climate changes are reflected in water vapor content. Water vapor is a greenhouse gas, which traps emitted long wave radiation from the Earth's surface. Scientists may be able to directly measure and model the spatio-temporal manifestations of climate change, such as changes to processes of atmospheric water vapor content. Better predictions of weather can be obtained by measuring water vapor accurately both in time and space using GPS. The use of GPS to measure water vapor in the atmosphere for the application of weather predictions and study of climate change is currently referred to as GPS meteorology (Shresta, 2003).

Tropospheric delay can be divided into hydrostatic (dry) delay and wet delay. At zenith direction, tropospheric delay contributes about 2.5 m. Hydrostatic (dry) delay contributes 2.3m (90%) and wet delay contributes about 0.2 m (10%) of the tropospheric delay (Skone, 2001). This hydrostatic component has a smooth, slow time-varying characteristic due to its dependence on variations in surface air pressure (weather cells). So this part can be modeled and removed with an accuracy of a few millimetres or better using a surface model (including pressure, temperature and humidity). It does not therefore create much of a problem as far as its effect on GPS signals. Although wet delay is much smaller than the hydrostatic component but the uncertainties in wet tropospheric delay modeling do place a great burden on high precision GPS applications.

1.2 Rationale of the research

Many atmospheric models were established by using many approaches. However the difficulty in modeling the tropospheric effect, especially water vapor is the main reason why the researchers are still looking for better model for reducing the tropospheric error. Troposphere behaves like a non dispersive medium, whereby the refraction is independent of the frequency of the signals passing through it, so troposphere effect cannot be eliminated via dual-frequency observations (Leick, 1995).

Nowadays, many modern mapping functions such as *UNBabc*, *UNBab*, Neill and some others have been established in a form of continued fraction, which introduce many operations. The number of operations for those mapping function models should be reduced from continued fraction form into simpler form to allow shorter computing time and better understanding of the models, but at the same time can give similar value for the mapping function scale factor.

Tropospheric delay can be reduced by using smaller mapping function. As a coefficient to the zenith tropospheric delay for both dry and also wet components, the value of mapping function can affect the total tropospheric delay. Mapping function depends on the elevation angle and produce larger value of mapping function by decreasing the elevation angle, especially for the elevation angles less than 5 degree. There is a need to minimize the mapping function in order to improve the total tropospheric delay for GPS signal. Saastamoinen model (1972) is selected for tropospheric delay calculation due to its accuracy about 3cm in zenith and this model is widely used for high accuracy GPS positioning (Mendes, 1999).

1.3 Objectives and contributions

The objectives of this research focus on the simplification and also the modification of the mapping functions that affects the tropospheric delay directly, as given below:

a. To develop a simple mapping function models using simulated data of UNB_{ab}, UNB_{abc} and also Neill mapping function (NMF) models for both hydrostatic and also non-hydrostatic components, as discussed in Chapter 4.

b. To investigate the improvement of the modification of UNB_{abc} and also Neill mapping function (NMF), either for hydrostatic or non-hydrostatic components by comparing its tropospheric delay values using Saastamoinen model as described in Chapter 5.

The research contributions of the thesis are:

a. Simplified UNB_{ab}, UNB_{abc} and also Neill mapping function (NMF) models have been developed for both hydrostatic and also non-hydrostatic models, which can be used to reduce the computing time and better understanding of the model for getting the mapping function scale factor.

b. Modified mapping function models for UNB_{abc} and NMF have been developed for both hydrostatic and also non-hydrostatic models, which can be used to improve the tropospheric delay at arbitrary elevation angles.

1.4 Thesis outline

Chapter 1 states the background of this research, the problems of the GPS signal, motivation and the objectives of the thesis. Chapter 2 will present the mapping functions for the some established model and also mathematical background of the tropospheric delay by using Saastamoinen (1972) model. Basic fundamentals of GPS such as the GPS theory, different error sources, the principles of GPS signal delays in the troposphere and some of the fundamental models for mitigating the tropospheric errors are discussed in Chapter 3.

For Chapter 4, the simplification of mapping function is shown using regression approaches. The comparison between the original and the simplified model is conducted using statistical analysis. The sum of errors is calculated to get the difference between the original and also the simplified models. In Chapter 5, the modification of the mapping function and also the improvement of the tropospheric delay are discussed in detail.

As a conclusion, Chapter 6 discusses the overall result of the thesis. The effect of simplification of the mapping function models and the calculation of the sum of errors which shows the deviation between the original and simplified mapping function are