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Impact of Different Tropospheric Models on GPS Baseline Accuracy: Case Study in Thailand

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Abstract. It is generally known that the atmospheric effects on the GPS signals are the most dominant spatially correlated biases. The atmosphere causing the delay in GPS signals consists of two main layers, ionosphere and troposphere. The ionospheric bias can be mitigated using dual frequency receivers. Unlike the ionospheric bias, the tropospheric bias cannot be removed using the same procedure. Compensation for the tropospheric bias is often carried out using a standard tropospheric model. Most standard tropospheric models were experimentally derived using available radiosonde data, which were mostly observed on the European and North American continents. In order to determine the best-fit standard tropospheric model with the GPS data collected in Thailand, investigations on the impact of different standard tropospheric models on GPS baseline accuracy are therefore needed. This paper aims to compare the GPS positioning results derived from the use of three different standard tropospheric models, namely the Saastamoinen model, Hopfield model and Simplified Hopfield model. In this study, both short and medium length baseline data sets were tested. In addition, each baseline data set is further divided into two scenarios, flat terrain and rough terrain. Overall results indicate that there are no statistically significant differences in the performance of the three tropospheric models. However, the use of the Saastamoinen and the Hopfield models tends to produce more reliable results than the use of the Simplified Hopfield model.

Key words: Tropospheric effect, Hopfield model, Saastamoinen model, Simplified Hopfield model, GPS baseline accuracy

1 Introduction

One of the factors limiting the GPS baseline accuracy is due to the atmospheric delay. The atmosphere causing the delay in GPS signals consists of two main layers, ionosphere and troposphere. The ionosphere is the band of the atmosphere from around 50km to 1000km above the earth's surface (Hofmann-Wellenhof et al., 1997; Langley 1998; Rizos, 1997). The ionospheric delay is a function of the total electron content along the signal path, and the frequency of the propagated signal. With regard to the dual-frequency user, the ionospheric delay is frequency-dependent and the ionosphere-free combination can be formed in order to eliminate this delay (Hofmann-Wellenhof et al., 1997; Leick, 1995; Rizos, 1997). The troposphere is the band of the atmosphere from the earth's surface to about 8km over the poles and 16km over the equator (Langley 1998; Rizos, 1997). The tropospheric delay is a function of elevation and altitude of the receiver, and is dependent on many factors such as atmospheric pressure, temperature and relative humidity. Unlike the ionospheric delay, the tropospheric delay is not frequency-dependent. It cannot therefore be eliminated through linear combinations of L1 and L2 observations. Several standard tropospheric models (e.g. Saastamoinen model, Hopfield model, etc.) are generally used to correct for the tropospheric delay.

All standard tropospheric models are empirically derived from available radiosonde data, which were mostly obtained in the European and North American continents. Global constants within some standard models take no account of latitudinal and seasonal variations of parameters in the atmosphere (Roberts and Rizos, 2001). Furthermore, daily variations of temperature and humidity may cause the tropospheric effects derived from standard models to be in error especially in the height component (Rührnöbl et al., 1998). The high and variable water vapor content, particularly in equatorial regions, may exaggerate this effect further (Mendes, 1999).

Gurtner et al. (1989) also states that tropospheric modelling is only valid for a flat terrain. A large height difference for the baseline points can introduce a bias of the order of 2-5 mm per 100m height difference. Roberts (2002) recommends that the effects of differential troposphere on the height component should be estimated as an additional parameter during a baseline estimation step.

In Thailand, an investigation on the impact of tropospheric delay is still very limited. *What is of particular interest to the GPS surveyors in Thailand is which standard tropospheric model should be used in the baseline processing.* In order to determine the best-fit tropospheric model for processing of the data collected in Thailand, investigations on the impact of different global tropospheric models on GPS baseline accuracy are therefore needed. This paper aims to emphasise an impact of the tropospheric delay on GPS baseline accuracy as well as to compare the GPS positioning results derived from the use of the three tropospheric models, namely the Saastamoinen model (Saastamoinen, 1973), Hopfield model (Hopfield, 1969) and Simplified Hopfield model (Wells, 1977). These models are available in most GPS software packages. This paper is organised as follows. The second section describes data sets used in a subsequent analysis. The third section explains how the data sets are processed. The fourth section presents an analysis of the results, followed by some concluding remarks in the final section.

2 Test data

In this study, both short and medium length baseline data sets were collected. Each baseline length data set is further divided into two scenarios, flat terrain and rough terrain. The details of data sets are given in this section. It should be noted that ground meteorological data (i.e. temperature and air pressure) at each station were also observed every hour.

2.1 Short Length Baseline Case

The short length baseline data were collected in static mode for 24 hours starting from 10:00am on 7th June 2003 to 10:00am on 8th June 2003 with three dual-frequency receivers (Leica SR530) at a 15-second data rate. In order to investigate an impact of standard tropospheric models on different terrains, the first receiver was set up at Station ‘A’ situated on top of the Pra Baht Pluang mountain, while the other two receivers were set up at Station ‘B’ and ‘C’ situated in a flat area. The baseline length between A and B is approximately 17 km and this baseline represents a rough terrain scenario. The baseline length between B and C is about 11 km and this baseline represents a flat terrain scenario. The height difference between A and B is about 950 m while the height difference between B and C is only about 35 m. Figure 1 illustrates the configuration of the short baseline case.

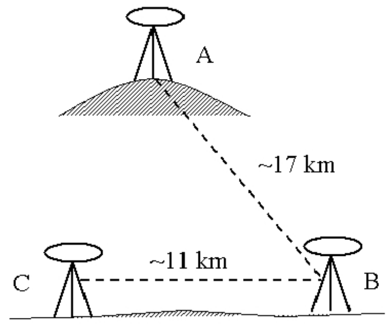

Fig. 1 Configuration of short baseline case

2.2 Medium Length Baseline Case

The medium length baseline data were collected in static mode for 24 hours starting from 8:00am on 14th June 2003 to 8:00am on 15th June 2003 with the same receivers and data rate. The first receiver was set up at Station ‘D’ which is close to station ‘A’, while the other two receivers were set up at Station ‘E’ and ‘F’ situated in a flat area.

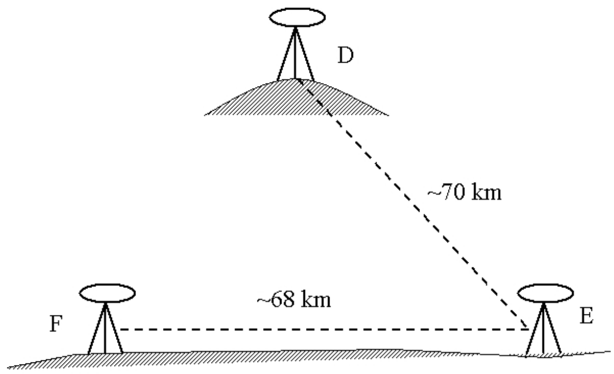

Fig. 2 Configuration of medium length baseline case

The baseline length between D and E is approximately 70 km and this baseline represents a rough terrain scenario. The baseline length between E and F is about 68 km and this baseline represents a flat terrain scenario. The height difference between D and E is about 970 m while the height difference between E and F is only about 25 m. Figure 2 illustrates the configuration of the medium length baseline case.

3 Data processing

3.1 Establishment of Reference Coordinates

Since the coordinates of stations 'B' and 'E' are known, these stations are held fixed in the baseline estimation step for the short and medium length baseline cases respectively. In order to obtain accurate coordinates for stations A, C, D and F, the University of Bern precise GPS data processing software, referred to simply as the 'Bernese software', was used to compute the coordinates of these stations. Table 1 gives a summary of options selected in a baseline estimation step.

Tab. 1 Processing options used in the Bernese software

Baseline	Orbit used	Tropospheric model applied	Solutions
Short length	Broadcast	Estimate as additional parameter	Ionosphere-free fixed double difference
Medium length	Broadcast	Estimate as additional parameter	Ionosphere-free float double difference

The 24-hr data sets were then processed with the Bernese software version 4.2 using the options presented in Table 1. The obtained coordinates are subsequently converted to UTM coordinates and presented in Table 2. These UTM coordinates will be used as references for subsequent analyses.

Tab. 2 Reference coordinates obtained from the Bernese software

Station	Northing (m)	Easting (m)	Height (m)
A	827650.831	1397561.694	-1.855
C	843951.136	1421202.169	980.850
D	735044.696	1487880.450	-17.903
F	843952.151	1421201.949	980.411

3.2 Baseline Processing

For convenience, all data sets are processed with the SKI software version 2.5. Processing options used in the SKI software are the same as the options used the Bernese software except that tropospheric modelling was used rather than the more rigorous parameter estimation approach using Bernese. Data processing strategies for each baseline length are described in this section.

3.2.1 Processing of short length baseline data

For the short length baseline case, the data sets were divided into 12 batches, each of 2 hours length. Each batch was treated as an individual session and processed using the following tropospheric models:

- Saastamoinen model
- Hopfield model
- Simplified Hopfield model
- No model applied

3.2.2 Processing of medium length baseline data

As the baseline length becomes longer, a minimum of 3-hr per observation session is needed. Thus, the data sets were divided into 8 batches, each of 3 hours length. Each batch was again treated as an individual session and processed using the same procedure as in the short length baseline case.

4. Analysis of results

In the following analyses, the discrepancies in the three coordinate components compared to the reference coordinates were firstly calculated. The performance of each standard tropospheric model can be characterised by the Root Mean Square Error (RMSE). Therefore, the RMSE values in both horizontal and vertical components for the stations A, C, D and F were computed and presented in Table 3. It can be seen from Table 3 that by applying any standard tropospheric model in the baseline estimation step, accuracies of coordinates in both horizontal and vertical components are improved. In addition, all RMSE values indicate that the Saastamoinen and the Hopfield models tend to produce more reliable baseline results than the Simplified Hopfield model.

In a further investigation, the hypothesis test was carried out to find out if the differences in performance of each standard tropospheric model are statistically significant. These differences are individually tested for horizontal and vertical components. For each station, the smallest RMSE value in each component was selected as a reference RMSE value. It should be noted that numbers highlighted with red color in the Table 3 indicate the smallest RMSE value for each case. The commonly used two-tailed F-test was chosen to test if the reference RMSE value and the other RMSE values are equal. The F hypothesis test is defined as (Snedecor and Cochran, 1989):

$H_0 : \sigma_1 = \sigma_n$ (Null hypothesis)

$H_a : \sigma_1 \neq \sigma_n$ (Alternative hypothesis)

σ_1 denotes the reference RMSE value calculated from the best-fit tropospheric model, while σ_n is the RMSE value calculated from the other tropospheric model. 5% significance level was used for the hypothesis testing. Table 4 shows a summary of the results obtained from the hypothesis testing.

Tab. 3 Summary of RMSE values of stations A, C ,D and F in horizontal and vertical components

Baseline	Terrain	Station	Tropospheric model Applied	RMSE (m)	
				Horizontal	Vertical
Short Length	Rough	A	Saastamoinen	0.014	0.064
			Hopfield	0.014	0.064
			Simplified Hopfield	0.012	0.083
			No model	0.135	0.835
	Flat	C	Saastamoinen	0.007	0.019
			Hopfield	0.007	0.019
			Simplified Hopfield	0.007	0.023
			No model	0.017	0.020
Medium Length	Rough	D	Saastamoinen	0.058	0.068
			Hopfield	0.058	0.068
			Simplified Hopfield	0.076	0.078
			No model	0.204	0.899
	Flat	F	Saastamoinen	0.060	0.060
			Hopfield	0.060	0.060
			Simplified Hopfield	0.060	0.062
			No model	0.188	0.097

Tab. 4 Summary of results using F-test at 5% significance level

Baseline	Terrain	Station	Tropospheric model Applied	Null hypothesis (H_0)	
				Horizontal	Vertical
Short Length	Rough	A	Saastamoinen	Accept	Reference
			Hopfield	Accept	Reference
			Simplified Hopfield	Reference	Accept
			No model	Reject	Reject
	Flat	C	Saastamoinen	Reference	Reference
			Hopfield	Reference	Reference
			Simplified Hopfield	Reference	Accept
			No model	Reject	Accept
Medium Length	Rough	D	Saastamoinen	Reference	Reference
			Hopfield	Reference	Reference
			Simplified Hopfield	Accept	Accept
			No model	Reject	Reject
	Flat	F	Saastamoinen	Reference	Reference
			Hopfield	Reference	Reference
			Simplified Hopfield	Reference	Accept
			No model	Reject	Accept

In relation to the results presented in Table 4 the following can be noted

- Neglecting the use of a standard tropospheric model in the baseline estimation step leads to unreliable baseline results especially in the case of the rough terrain.
- The three standard tropospheric models produce baseline results that are not statistically different.

An analysis of the relationship between the obtainable baseline accuracies and the ground meteorological data was further carried out. This analysis aims to find out if correlations between the obtainable baseline accuracies and the ground meteorological data are statistically significant. The results revealed that there is no statistically significant correlation between the obtainable baseline accuracies and the ground meteorological data. Hence, it implies that the weather conditions have no significant impact on the baseline results.

5. Concluding remarks

This paper has demonstrated the impact of tropospheric effect on GPS baseline accuracy. The omission of applying a standard tropospheric model in the baseline processing leads to unreliable baseline results especially in the case of large changes in height between stations. The testing procedure for determining the best-fit tropospheric model has also been presented in this paper. Based on the F hypothesis test performed in this study, the three standard tropospheric models, Saastamoinen, Hopfield and Simplified Hopfield models, produce baseline results that are not statistically different. However, the use of the Saastamoinen model and the Hopfield model tends to produce the most reliable baseline results, and hence they are recommended to be used in the baseline processing.

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