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Effect of Equatorial Ionospheric Horizontal Gradient to DGPS positioning

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Abstract*— GPS signals always have high ionospheric error as it propagates through the ionosphere especially over the equatorial region. To reduce this error, a method such as DGPS can be used. DGPS or differential GPS involves the cooperation of two receivers, one is stationary and another one is roving around making position measurement. In this paper, four parameters will be investigated to see the effect of ionospheric gradient to DGPS positioning. There are baseline length, solar activity, range measurement from different number of satellites and time durations. Nanyang Technology University Singapore (NTUS) station (1.34°N, 103.7°E) functions as the reference station whereas Universiti Kebangsaan Malaysia (UKM) station (9.92°N, 101.7°E) and ISKANDARnet (ISK) station (1.56°N, 103.6°E) function as the mobile station. Results obtained shows that DGPS positioning improvement can be obtained after the elimination of ionospheric horizontal gradient.

Index Terms—**DGPS positioning improvement, ionospheric horizontal gradient, mobile station, reference station**

I. INTRODUCTION

The ionosphere covers a region between 50 km and 1000 km and is characterized by a significant number of free (negatively charged) electrons and positively charged atoms and molecules called ions [1]. The ionosphere is composed of D, E and F layers, named in the order of increasing height which can enable long-distance radio communication [2]. The Global Positioning System (GPS) signals that are propagating through the atmosphere are affected by varying conditions at different altitudes (height from the surface of Earth), geographical location, diurnal changes, and seasonal changes and also due to the changes in the Sun's solar activity [3]. The main purpose of the GPS is to determine the position and velocity of a fixed or mobile object, placed over or near the Earth surface, using the signals of the satellites [4]. A GPS receiver calculates its position by precisely timing the radio signals sent by the GPS satellites high above the Earth [5]. The receiver measures the transit time of each message and computes the distance to each satellite. It seems 3 satellites are enough to solve for position, since it is 3 dimensions at space (latitude, longitude, altitude).

Although the GPS is clearly the most accurate worldwide navigation system yet developed, but it still can exhibit significant error. The GPS signals always have high ionospheric error as it propagates through the ionosphere especially over the equatorial region. To reduce this error, a method such as Differential GPS (DGPS) can be used. DGPS has been defined as 'the positioning of a mobile station in real-time by corrected and possibly Doppler or phase-smoothed GPS pseudo-ranges [6]. DGPS involves the cooperation of two receivers, one is stationary and another one is roving around making position measurement. The stationary receiver is known as reference station, base station or reference receiver. The second receiver that is roving is known as rover receiver, mobile receiver or navigator [7]. DGPS works by having a reference system at a known location measure the errors in the signals and send corrections to users in the "local" area. These corrections will not be universal, but will be useful over a significant area. The corrections are normally sent every few seconds. The user is generally some mobile platform such as a ship, car, truck or even an aircraft [8]. DGPS provides an additional benefit, the reference station acts as a monitor, and can inform users of problems that might arise in the use of the satellite signals.

By using DGPS, the GPS positioning can be improved by removing the ionospheric horizontal gradient effect especially over the equatorial region. With the DGPS method, a communication link allows the common to be removed by differential processing in real-time, as well as providing an accuracy improvement. The ionospheric horizontal gradient is the variation of electron density with latitude and longitude which could give greater positioning error for a user station in a DGPS system [9].

Trimble Business Center (TBC) office software is ideal for processing and analyzing satellite data recorded in the field and enables the researcher to determine the effect of ionosphere in any GPS data. The software provides

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numerous innovative and unique features, and it is easy to learn and use [10]. Once the ionospheric error is obtained, it will be included in GPS data and by using Trimble Business Center (TBC); the positioning improvement will be shown.

II. METHODOLOGY

For this research purpose, carrier phase measurements on GPS premier carrier signal, L1, from GPS satellites have been used. The observation data was taken at 3 different places for GPS stations; NTUS (1.34°N, 103.7°E) act as the reference station and it is fixed at a location whereas UKM station (9.92°N, 101.7°E) and ISK station (1.56°N, 103.6°E) function as the mobile stations. In this work, corrections are done stage by stage in order to see the improvement in the final user's position. Stage by stage here means, the corrections were done in a sequence. At stage 1, the correction was applied to a single SV. Then at stage 2, the correction was applied to 2 SVs. And the numbers increase and finally, at last stage, the correction was applied to all the satellites' measurements. By doing this, the stages of improvement as the corrections were applied to the different number of satellites can be shown. The period of the analysis is taken on 1st June 2009 and 2nd August 2012 for a time period of 1 hour (from 12:00:00 to 1:00:00 pm) or 3 hours (from 12:00:00 to 3:00:00 pm) depending on the studies. Four comparisons will be shown to see the effect to the DGPS positioning such as baselines length, solar activity, range measurement from different number of satellites and time durations.

In order to avoid estimated positions with poor geometry of satellites, the Position Dilution of Precision (PDOP) equal or smaller than 6 was used, which indicates a good satellite constellation and high-quality data. A low DOP indicates a higher probability of accuracy. A high DOP indicates a lower probability of accuracy. The quality of the data decreases as the PDOP value increases [11].

So, to correct the DGPS positioning improvement there are certain steps to follow. Firstly, get P_1 and P_2 values at 2 different places from both stations; reference station and mobile station. Next, the TEC values will be obtain for both reference and mobile station and the gradient (factor) values using equation below:

$$TEC = \left(\frac{1}{40.3}\right)\left(\frac{f_1^{\,2} f_2^{\,2}}{f_1^{\,2} - f_2^{\,2}}\right)(P_2 - P_1) \qquad (1)$$

Where f_1 and f_2 stands for high GPS frequency (1575.42 MHz) and low GPS frequency (1227.6 MHz) respectively. While P_1 and P_2 are pseudo ranges measured in L1 and L2 respectively. After that, gets the ratio (gradient) using equation below:

$$m = \frac{TEC_{USER}}{TEC_{NTUS}} \qquad (2)$$

Replaced the corrected new value in mobile station data;

$$P_{NEW} = P_{1(USER)} \times m \qquad (3)$$

Lastly, the positioning error also can be calculated using equation below:

$$Improved\ positional\ error = \sqrt{(x_{ori} - x_{new})^2 + (y_{ori} - y_{new})^2 + (z_{ori} - z_{new})^2} \qquad (4)$$

Where *ori* stands for the coordinates of the receiver in x, y and z-axis before the correction and *new* stands for the coordinates of the receiver in x, y and z-axis after the correction. Positioning improvement by removing the effects due to ionospheric horizontal gradient will be shown.

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III. RESULTS AND ANALYSIS

A. DGPS Positioning Improvement between short baseline and long baseline

For both cases, the NTUS station functions as the reference station, whereas the UKM and the ISK is the user station. The baseline distance between NTUS and UKM stations are 275.10 km, while the baseline distance between NTUS and ISK stations are 24.33 km.

Table I. The comparison of the distance after correction for NTUS – UKM data

SV	Distance After Correction (m)
02	274611.52
05	274611.50
10	274611.41
27	274611.36
02,05	274611.07
02,05,10	274610.98
02,05,10,27	274610.97

Table II. The comparison of the distance after correction for NTUS – ISK data

SV	Distance After Correction (m)
02	24201.264
05	24201.261
10	24201.254
02,05	24201.249
02,05,10	24201.247

The differences for all SVs are more or less about 488 m to 489 m for NTUS – UKM data and 128 m for NTUS – ISK data.

Table III. Positioning Improvement Error for NTUS – UKM data

SV	Error in the positioning (cm)
NTUS – UKM (woc)	166.9304
02	126.0852
05	121.3909
10	116.322
27	79.3641
02,05	75.0697
02,05,10	72.2738
02,05,10,27	39.1664

Table IV: Positioning Improvement Error for NTUS – ISK data

SV	Error in the positioning (cm)
NTUS - ISK (woc)	44.4857
02	43.098
05	22.6082
10	22.2326
02,05	13.9664
02,05,10	10.7898

From the table, for the NTUS – UKM data, without correction (woc), the error is about 166.93 cm. Generally, by looking at all these errors, the positioning error could be further reduced from 166.93 cm to 39.16 cm after the positioning error is applied to each of the SVs stage by stage. And then, when the corrections were applied to the NTUS – ISK data, without correction (woc), the error is about 44.49 cm. Then the positioning error could be reduced from 44.49 cm to 10.79 cm.

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B. DGPS Positioning Improvement between low solar activity and high solar activity

For this case, the NTUS station functions as the reference station, whereas the ISK is the user station. Both data was taken on 1st June 2009 (low solar activity) and 2nd August 2012 (high solar activity)

Table V. The comparison of the solar activity after correction for NTUS – ISK (2009) data

SV	Distance After Correction (m)
11	24201.059
19	24201.057
20	24201.051
11,19	24201.004
11,19,20	24200.988

Table VI. The comparison of the solar activity after correction for NTUS – ISK (2012) data

SV	Distance After Correction (m)
02	24201.264
05	24201.261
10	24201.254
02,05	24201.249
02,05,10	24201.247

The differences are not so notable for all SVs are more or less about 129 m during 2009 data (low solar activity) and 128 m during 2012 data (high solar activity). But we can see the difference for positioning improvement error in the table below.

Table VII. Positioning Improvement Error for low solar activity data

SV	Error in the positioning (cm)
NTUS - ISK (woc)	18.5680
11	16.3521
19	15.8827
20	11.5953
11,19	6.7963
11,19,20	6.0967

Table VIII. Positioning Improvement Error for high solar activity data

SV	Error in the positioning (cm)
NTUS - ISK (woc)	44.4857
02	43.0980
05	22.6082
10	22.2326
02,05	13.9664
02,05,10	10.7898

From the table, for the low solar activity data (2009), without correction (woc), the error is about 18.57 cm. Generally, by looking at all these errors, the positioning error could be further reduced from 18.57 cm to 6.10 cm after the positioning error is applied to each of the SVs stage by stage. And then, when the corrections were applied to the high solar activity data (2012), without correction (woc), the error is about 44.49 cm. Then the positioning error could be reduced from 44.49 cm to 10.79 cm.

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C. DGPS Positioning Improvement between 3 satellites and 8 satellites

For this case, the NTUS station functions as the reference station, whereas the ISK is the user station. Both data was taken on 2nd August 2012 at for one hour duration (12:00 pm to 01:00 pm).

Table IX: The comparison of three satellites after correction for NTUS – ISK data

SV	Distance After Correction (m)
02	24201.264
05	24201.261
10	24201.254
02,05	24201.249
02,05,10	24201.247

Table X. The comparison of eight satellites after correction for NTUS – ISK data

SV	Distance After Correction (m)
02	24201.261
04	24201.260
05	24201.257
09	24201.253
10	24201.249
17	24201.249
26	24201.247
27	24201.245
02,04	24201.243
02,04,05	24201.235
02,04,05,09	24201.221
02,04,05,09,26	24201.212
02,04,05,09,26,27	24201.198
02,04,05,09,26,27,10	24201.193
02,04,05,09,26,27,10,17	24201.187

For this condition, we can see the difference in the comparison when different numbers of satellites are used. For three satellites, the different between single satellite and three satellites is 1.7 cm while for eight satellites; the different between single satellite and eight satellites is 7.4 cm.

Table XI. Positioning Improvement Error for three satellites data

SV	Error in the positioning (cm)
NTUS - ISK (woc)	44.4857
02	43.0980
05	22.6082
10	22.2326
02,05	13.9664
02,05,10	10.7898

From the table, without correction (woc), for three satellites, the error is about 44.49 cm. Generally, by looking at all these errors, the positioning error could be further reduced from 44.49 cm to 10.79 cm after the positioning error is applied to each of the SVs stage by stage. And then, when the corrections were applied to the eight satellites, without correction (woc), the error is about 15.56 cm. Then the positioning error could be reduced from 15.56 cm to 5.07 cm. It has been proven that the range measurement from eight satellites do introduce less positioning error.

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Table XII. Positioning Improvement Error for eight satellites data

SV	Error in the positioning (cm)
NTUS - ISK (woc)	15.5631
02	15.3577
04	14.8169
05	14.7641
09	14.2141
10	13.2925
17	13.0683
26	12.6388
27	12.4684
02,04	11.8617
02,04,05	10.8908
02,04,05,09	9.3654
02,04,05,09,26	8.8284
02,04,05,09,26,27	7.7885
02,04,05,09,26,27,10	6.7602
02,04,05,09,26,27,10,17	5.0695

D. DGPS Positioning Improvement between duration of times

The positioning improvement on 2nd August 2012th, for two different duration times was analyzed. One hour period from 12:00 PM to 1:00 PM local time (LT) and three hour period from 12:00 PM to 3:00 PM local time (LT) was chosen. For this case, the NTUS station functions as the reference station, whereas the ISK is the user station. The observed satellites SVs are 2, 4, 5, 9, 26 and 27 from both stations.

Table XIII. The comparison of 12:00 pm to 01:00 pm after correction for NTUS – ISK data

SV	Distance After Correction (m)
02	24201.261
04	24201.260
05	24201.257
09	24201.253
26	24201.247
27	24201.245
02,04	24201.243
02,04,05	24201.235
02,04,05,09	24201.221
02,04,05,09,26	24201.212
02,04,05,09,26,27	24201.198

Table XIV. The comparison of 12:00 pm to 03:00 pm after correction for NTUS – ISK data

SV	Distance After Correction (m)
02	24201.209
04	24201.196
05	24201.195
09	24201.195
26	24201.184
27	24201.182
02,04	24201.181
02,04,05	24201.173
02,04,05,09	24201.171
02,04,05,09,26	24201.166
02,04,05,09,26,27	24201.156

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For this condition, there is no significant difference can be shown. Both in circumstances indicate about the same value.

Table XV. Positioning Improvement Error at 12:00 pm to 01:00 pm

SV	Error in the positioning (cm)
NTUS - ISK (woc)	15.5631
02	15.3577
04	14.8169
05	14.7641
09	14.2141
26	12.6388
27	12.4684
02,04	11.8617
02,04,05	10.8908
02,04,05,09	9.3654
02,04,05,09,26	8.8284
02,04,05,09,26,27	7.7885

Table XVI. Positioning Improvement Error at 12:00 pm to 03:00 pm

SV	Error in the positioning (cm)
NTUS - ISK (woc)	7.91
02	7.39
04	7.07
05	6.91
09	6.79
26	6.70
27	6.50
02,04	5.24
02,04,05	5.14
02,04,05,09	3.73
02,04,05,09,26	3.19
02,04,05,09,26,27	2.67

From the results obtained, it is known that the different range duration does introduce some error in the user positioning. From the table, at one hour period (12:00 pm to 01:00 pm), without correction (woc), the error is about 15.56 cm. Generally, by looking at all these errors, the positioning error could be further reduced from 15.56 cm to 7.79 cm after the positioning error is applied to each of the SVs stage by stage. And then, when the corrections were applied at 12:00 pm to 03:00 pm, without correction (woc), the error is about 7.91 cm. Then the positioning error could be reduced from 7.91 cm to 2.67 cm.

IV. CONCLUSIONS

The effect of the ionospheric horizontal gradient has been shown between the reference station and the user location when four comparisons was analysed to see the effect to the DGPS positioning such as length of baselines, solar activity, and satellites quantity and time durations. Ionospheric gradient value will be added or eliminated (depending on the direction of the gradient) to the GPS range measurement from GPS observation data. The results obtained will be improved further by determining the ionospheric effect to GPS positioning over the equatorial region. However in order to show the improvements in the user positioning, first of all, the range measurements need to be obtained from at least four satellites. To obtain the optimum satellite locations, the PDOP factor needs to be considered. The lower the PDOP, the better the location spread of the satellites used to obtain the range measurements. Using Trimble Business Center (TBC), improvement made by mitigating the ionospheric error and the improvement after the ionosphere correction are shown. For this research work, after the elimination of the ionospheric horizontal gradient and the correction was applied, some distance reducing was obtained. Some improvement can be seen after the correction and this is a noticeable positioning improvement at the user location over the equatorial region. Then, by using equation in (4), the improvement in the final positional error can be found for all these range measurements; considered the cases without and with corrections. The correction then will be included to the more GPS satellites range measurement in order to show better DGPS positioning improvement.

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