COMPARING THE HIGHER ORDER IONOSPHERIC REFRACTION EFFECTS ON GPS PRECISE POINT POSITIONING ACCURACIES IN DIFFERENT REGIONS AND SEASONS - A CASE STUDY OF TAIWAN REGION

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ABSTRACT: The precise point positioning (PPP) accuracy can reach centimeter level using global positioning system (GPS) dual-frequency data. However, centimeter level accuracy is insufficient for high accuracy applications, such as control surveying, deformation monitoring, etc. To improve the accuracy of PPP, higher order ionospheric refraction effects must be taken into account. The purpose of this research is to investigate the effects on PPP accuracies caused by higher order ionospheric refraction errors. The first step is to estimate the higher order ionospheric refraction terms of GPS dual-frequency data. And then, correcting the GPS RINEX file accordingly. At last, evaluating the accuracy of PPP accuracies after higher order ionospheric refraction errors are corrected. There are two programs applied in this paper: RINEX_HO and gLAB(global navigation satellite system-LABoratory). RINEX_HO, developed by São Paulo State University in Brazil, can estimate higher order ionospheric refraction terms and produce a corresponding corrected observation file. gLAB, developed by gAGE(Research group of Astronomy and GEomatics Technical University of Catalonia in Spain), can perform precise point positioning and calculate position errors. The following data sets of Taiwan region are tested, including the GPS observation data provided by Civil-NET, precise ephemeris and other data from international global navigation satellite system service (IGS). And the period of these data are a few days before and after the spring equinox, summer solstice, autumn equinox and winter solstice of year 2014. The detailed theory, experiment methods and preliminary result will be presented in this paper.

KEY WORDS: Global Positioning System (GPS), Precise Point Positioning (PPP), Higher Order Ionospheric Refraction Effects, Dual Frequency

1. INTRODUCTION

As global positioning system (GPS) develops, precise point positioning (PPP) accuracy can reach centimeter level nowadays. However, centimeter level accuracy is insufficient for high accuracy applications, such as deformation monitoring. Higher order ionospheric effects have to be considered if high precision is required (Petrie et al., 2011). As a result, the purpose of this research is to estimate higher order ionospheric refraction errors and correct GPS RINEX file through the estimated errors. And then evaluate the accuracy of PPP after higher order ionospheric refraction errors are corrected.

To investigate higher order ionospheric effects on PPP, literatures about higher order ionospheric refraction errors, characteristics and variability of the ionospheric electron content and the software used in the following experiment will be reviewed. In the first section, literatures regarding factors which affect higher order ionospheric refraction errors will be reviewed; the second section will discuss the characteristics and variability of the ionospheric electron content to choose the experiment data; the third section will be about the data and the two programs used in the subsequent experiment; the final section will summarize the previous sections and provide the basis of subsequent experiments.

1.1 Higher Order Ionospheric Refraction Effects

Higher order ionospheric refraction errors are the remaining terms after eliminating the first order refractive index correction term (I1) of ionospheric errors with a linear combination of dual-frequency signals. The largest effect is from the second order term (I2) after I1 is removed, and the magnitude of I2 is about several centimeters. The third order term (I3) is at the level of the errors in modelling I2 (Petrie et al., 2011). Because higher order ionospheric refraction errors are small, they are often ignored when precision requirements are not high. However, higher order ionospheric refraction errors gradually gain importance as precision requirements on GPS data and products increase.

The ionospheric effects on the carrier phase along the signal path are the following equations (with units of meter):

$$\Phi_1 = \rho + N_1\lambda_1 + I1 + I2 + I3 \quad (1)$$

$$\text{I1} = -\frac{40.3 \int N_e dL}{{f_1}^2} \quad (2)$$

$$\text{I2} = -\frac{1.1284 \times 10^{12} \int N_e B cos\theta dL}{{f_1}^3} \quad (3)$$

$$\text{I3} = -\frac{812.47 \int {N_e}^2 dL}{{f_1}^4} \quad (4)$$

where Φ = carrier phase observation
ρ = geometric range between the satellite and the receiver
N = integer ambiguity,
λ = wavelength
N_e = electron density
B = magnetic field vector
θ = angle between the B and signal vector
f = signal frequency
dL = the integral along the signal path

According to the discussion in Petrie et al. (2011), it is better to choose the international geomagnetic reference field as the magnetic model when estimating higher order ionospheric refraction errors. As a result, the following experiments will focus on the variability of ionospheric electron content effects on higher order ionospheric refraction errors.

1.2 Characteristics and Variability of the Ionospheric Electron Content

The ionosphere is that region of the Earth's atmosphere in which ionizing radiation (principally from solar ultraviolet and x-ray emissions) causes electrons to exist in sufficient quantities to affect the propagation of radio waves (Langley, 1998). The characteristics and variability of ionospheric electron content is critical for the investigation of higher order ionospheric refraction errors because ionospheric electron density directly affects the magnitude of signal delay. According to related articles, the characteristics and variability of ionospheric electron content can be categorized into two categories, periodic variability and regional variability.

1.2.1 Periodic Variability: The ionosphere is formed when molecules and atoms in the atmosphere are ionized by radiation and energetic charged particles from the Sun. Hence, ionospheric electron content depends on the magnitude of radiation. The flux of visible solar energy reaching the Earth's surface varies little from day to day or from year to year (<0-5%). However, solar emissions at shorter wavelengths, in the extreme ultraviolet and X-ray wavelengths, vary by orders of magnitude depending on sunspot number and solar activity (Davies, 1990). Therefore, sunspot number and the periodic variability of solar activity directly affect the variation of ionosphere and they have the following periodic variabilities.

1.2.1.1 11 year cycle: The most prominent variability of sunspot is an 11 year cycle (see Figure 1) (Hathaway, 2015). It spends about 11 years to move from one peak to the next peak.

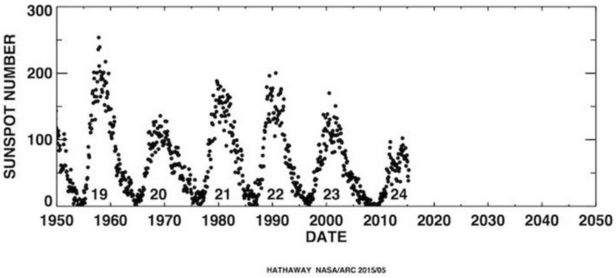

Figure 1. Monthly average sunspot number of each year.
（http://solarscience.msfc.nasa.gov/images/Zurich_Color_Small.jpg）

1.2.1.2 27 day periodicity: Besides 11 year cycle, there is a 27 day periodicity due to the variation of solar emissions caused by solar rotation. Based on relevant research, there is a high positive correlation between ionospheric electron content and the 27- day periodicity (Hocke, 2008; Liang et al., 2008).

1.2.2 Regional Variability: In addition to the association with solar activity, ionospheric electron content varies at different latitudes and heights. For example, the semiannual component predominates over the annual variation in the equatorial regions and at high latitudes in the East Asian and South Atlantic sectors at low altitudes (Liu et al., 2009). The experiments below focus on the effects of ionospheric electron content periodic variability on PPP, so regional variability will not be considered.

1.3 Experiment Programs

1.3.1 RINEX_HO: Developed at the Faculty of Science and Technology of São Paulo State University in Brazil, RINEX_HO is used to correct GPS observables for second- and third-order ionospheric effects and generate a new corrected RINEX file (Marques et al., 2011). Except the corrected RINEX file, RINEX_HO also generates files containing the higher order estimates, and computed total electron content.

Several input files are necessary to run RINEX_HO, observation file, navigation file, ionosphere map, P1C1 bias for satellites, P1P2 bias for satellites and the coefficients of international geomagnetic reference field. The user can choose between calculating total electron content (TEC) from raw pseudoranges, from pseudoranges smoothed by phase, or from global ionosphere maps (GIM). And the geomagnetic field can be chosen from a simple dipolar approximation, a transformation using the corrected geomagnetic model from parameterized ionospheric model, or the international geomagnetic reference field (IGRF) model.

1.3.2 gLAB (global navigation satellite system - LABoratory): Developed by gAGE(Research group of Astronomy and GEomatics Technical University of Catalonia in Spain), gLAB can perform PPP and calculate position errors, and provide PPP capabilities on centimeter level (Sanz et al., 2010).The mode positioning of gLAB includes (standard point positioning) SPP and PPP, and the following experiments perform PPP mode. To run gLAB PPP mode, observation file, antenna file, precise ephemeris and SINEX file (the IGS solution for the receiver coordinates and clock).

1.4 Comment

Due to the characteristics of ionospheric electron content, the comparison of satellite observation data in different year, different month and different regions is important for analyzing the higher order ionospheric refraction effects on PPP. Thus the subsequent experiments will include satellite observation data of different months and different regions and compare the PPP results before and after the correction of higher order ionospheric refraction effects.

2. METHOD

2.1 Experiment Data

CN11, CN14, CN17 and CN18 stations of Civil-NET, a GPS observation network in Taiwan, are chosen as the experiment stations. Besides observation file, P1C1 bias, P1P2 bias file for satellites, ionosphere map, navigation file, antenna file, precise ephemeris and station coordinates are necessary in the following experiments. Since higher order ionospheric refraction errors varies on several timescales because of the solar activity(Petrie et al., 2011), a few days before and after the spring equinox, summer solstice, autumn equinox and winter solstice observation files of year 2014 are chosen to compare the results of PPP using observations in different seasons.

Table 1. The dates of observation data

2014				
season	spring	summer	autumn	winter
date	03/18 to 03/24	06/18 to 06/24	09/20 to 09/26	12/19 to 12/25
day of year	077~083	169~175	263~269	353~359

2.2 Experiment Procedure

First, run RINEX_HO to estimate higher order ionospheric refraction errors and generate the corrected observation file. Then, perform gLAB PPP mode with uncorrected and corrected observation files and calculate position errors. At last, compare PPP results before and after the correction of higher order ionospheric refraction errors and evaluate the precision of PPP after correcting higher order ionospheric refraction errors. In theory, the magnitude of position error before correction should be larger than those after correction. Therefore, after the subtraction, the value should be positive which means the accuracy of PPP improves after correcting higher order ionospheric refraction errors.

3. RESULTS AND DISCUSSION

3.1 PPP Results of Different Stations in four seasons

Due to the limitation of pages, the following tables only present monthly average position errors of each station.

3.1.1 PPP results of station CN11

Table 2. Statistics of station CN11 observation data in 2014 before and after the correction of higher order ionospheric refraction errors

year/month		2014/03		2014/06	
higher order ionospheric correction		before	after	before	after
average position error(m)	X	0.0083	0.0134	0.0059	0.0083
	Y	-0.0018	-0.0019	0.0046	0.0050
	Z	-0.1019	-0.1003	-0.1432	-0.1434
year/month		2014/09		2014/12	
higher order ionospheric correction		before	after	before	after
average position error(m)	X	0.0013	0.0049	0.0051	0.0091
	Y	-0.0044	-0.0050	0.0018	0.0018
	Z	-0.0462	-0.0475	-0.0682	-0.0690

3.1.2 PPP results of station CN14

Table 3. Statistics of station CN14 observation data in 2014 before and after the correction of higher order ionospheric refraction errors

year/month		2014/03		2014/06	
higher order ionospheric correction		before	after	before	after
average position error(m)	X	0.0105	0.0152	0.0012	0.0035
	Y	0.0079	0.0074	0.0156	0.0160
	Z	-0.0997	-0.0987	-0.1222	-0.1224
year/month		2014/09		2014/12	
higher order ionospheric correction		before	after	before	after
average position error(m)	X	0.0034	0.0067	0.0053	0.0091
	Y	-0.0122	-0.0126	0.0031	0.0031
	Z	-0.0706	-0.0717	-0.0817	-0.0831

3.1.3 PPP results of station CN17

Table 4. Statistics of station CN17 observation data in 2014 before and after the correction of higher order ionospheric refraction errors

year/month		2014/03		2014/06	
higher order ionospheric correction		before	after	before	after
average position error(m)	X	0.0157	0.0204	0.0050	0.0073
	Y	0.0064	0.0064	0.0076	0.0078
	Z	-0.0621	-0.0600	-0.1249	-0.1246
year/month		2014/09		2014/12	
higher order ionospheric correction		before	after	before	after
average position error(m)	X	0.0053	0.0084	0.0070	0.0108
	Y	-0.0162	-0.0165	0.0073	0.0075
	Z	-0.0379	-0.0373	-0.0404	-0.0408

3.1.4 PPP results of station CN18

Table 5. Statistics of station CN18 observation data in 2014 before and after the correction of higher order ionospheric refraction errors

year/month		2014/03		2014/06	
higher order ionospheric correction		before	after	before	after
average position error(m)	X	0.0106	0.0158	-0.0014	0.0011
	Y	0.0001	-0.0002	0.0221	0.0224
	Z	-0.1307	-0.1296	-0.0772	-0.0772
year/month		2014/09		2014/12	
higher order ionospheric correction		before	after	before	after
average position error(m)	X	0.0041	0.0075	0.0054	0.0090
	Y	-0.0040	-0.0029	0.0064	0.0065
	Z	-0.0955	-0.0985	-0.0935	-0.0963

3.2 Discussions

3.2.1 Seasonal Variability:

1. Z direction accuracies generally improve after correcting higher order ionospheric refraction errors in spring.
2. The position error differences between uncorrected and corrected data are small in summer.
3. The position accuracies generally get worse after correcting higher order ionospheric refraction errors in autumn and winter.
4. Although Z direction accuracies generally improve in spring using corrected data, Z direction accuracies get worse on March 20th.

3.2.2 Regional Variability: X direction accuracies of station CN14 and CN18 slightly improve after correcting higher order ionospheric refraction errors in summer while station CN11 and CN17 do not have this characteristic.

4. CONCLUSION

According to the experiment results of previous section, the conclusions are as the following:

1. Most of the observation data of year 2014 cannot get better PPP accuracy after correcting higher order ionospheric refraction errors by using RINEX_HO. However, Z direction accuracies generally improve in spring.
2. Unlike other spring observation data, Z direction accuracies get worse after correcting higher order ionospheric refraction errors on March 20th.
3. Y direction accuracies of eastern stations slightly improve after correcting higher order ionospheric refraction errors in summer.

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