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Analysis of the Ionospheric Effect for Time Offsets per GPS Code Measurements

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Abstract

This paper shows the analysis results of time offsets using P1, P2 and P3 code in GPS time transfer. The r2cggtts program has been used in GNSS Time Transfer and use the P3 ionosphere free combination of P1 and P2 code measurements. We modified the r2cggtts program in order to calculate and write all kinds of time offsets P3 as well as P1 and P2. The result of the modified r2cggtts program shows that time offsets using P1 and P2 are of wide distribution comparing to time offsets using P3. In order to Figure out the error factors for wide distributions of P1 and P2, we analyze and present the relation between the elevation angle and time offsets in this paper.

Keywords: *GPS time transfer, P1, P2, P3, ionospheric free combination, Klobuchar model*

1. Introduction

This paper introduces the GPS time transfer for TAI (International Atomic Time) using GPS code signals, and presents the effects of ionospheric delay for both time offsets using P3 code, which use ionospheric free model of dual frequency, and time offsets using P1and P2 codes, which use the Klobuchar ionospheric model of single frequency.

The r2cggtts program has been used in time laboratories for TAI generation by BIPM (International Bureau of Weights and Measures). To obtain the comparison result, we modified the legacy r2cggtts software in order to generate each time offset for single frequency P1 and P2 code measurements respectively, using Klobuchar ionospheric delay model and write the 3 kinds of time offset results in the same CGGTTS file.

2. GPS Time Transfer for TAI

The time comparison using GPS code signals starts from the process to obtain the time offsets between each specific satellite clock and a receiver clock of measurement laboratory. Through the comparisons of these time offsets of time laboratories at the scheduled epoch, BIPM generates TAI. Therefore, it is essential to obtain the propagated time from a satellite to a receiver. Then, the time offset between a satellite clock and a

[1] Please note that the LNCS Editorial assumes that all authors have used the western naming convention, with given names preceding surnames. This determines the structure of the names in the running heads and the author index.

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receiver clock is calculated by eliminating error factors added in the propagated time delay.

There are several error sources while the satellite signal is propagated to a receiver [1-3]. Figure 1 shows these error factors. These are the satellite clock error, the satellite orbit error, the tropospheric delay, the ionospheric delay, the multipath, the receiver clock error, the cable delay, the hardware delay, and so on.

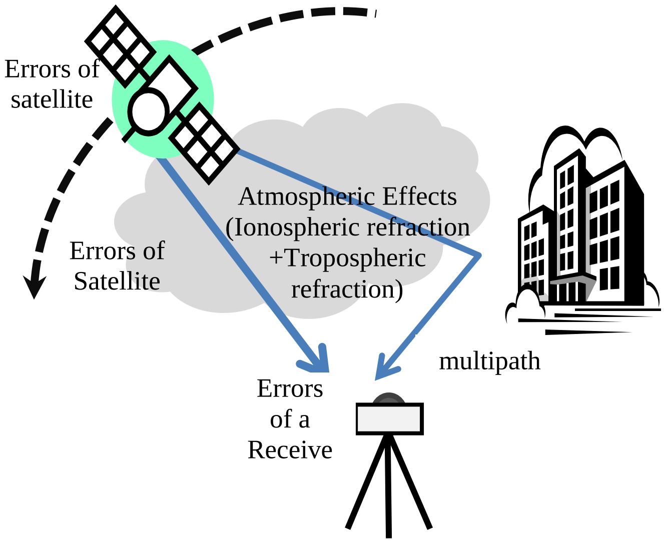

Figure 1. Delay Error Factors while GPS Signal is Disseminated

The ionosphere is the highest source of ranging error for GPS C/A code receivers. Three kinds of elimination methods of ionosphere effects can be adopted. These are to use the dual-frequency technique, to use the ionospheric model for single frequency technique, and to use the augmentation system [4].

The dual frequency technique is the most effective way to eliminate the ionospheric delay by a linear combination of dual frequency. This technique is called ionospheric free combination. GPS uses two frequencies of 1575.42 MHz of L1 frequency for P1 code, and 1227.60 MHz of L2 frequency for P2 code respectively [5]. These two codes are used to make P3 codes of ionospheric free combination, which eliminates the ionospheric delay. Hence, the r2cggtts software, which is used in time laboratories joining the TAI generation, uses the only P3 code.

This paper introduces the additional time offset comparisons using not only ionospheric free combination P3 code measurement, but also P1 and P2 code measurements which applies the Klobuchar ionospheric delay model used in GPS for single frequency receiver in [6]. Also, the relation between the elevation angle and the dispersion of time offsets are compared additionally.

Though the dual frequency receiver is used, the study for characteristics and variations of time offsets for each P1 and P2 with respect to P3 code measurements is important for GNSS time transfer and time synchronization using GNSS.

3. Ionospheric Models

The ionosphere is defined as that part of the upper atmosphere where the density of free electrons and ions is high enough to influence the propagation of electromagnetic radio frequency waves. The ionospheric delay is the amount of additional transmission time by the diffusion while the GPS signal propagates through the ionosphere which is extended in various layers from about 50km to 1,000km above Earth’s surface. The ionosphere, lower than 100km, does not affect the GPS signal.

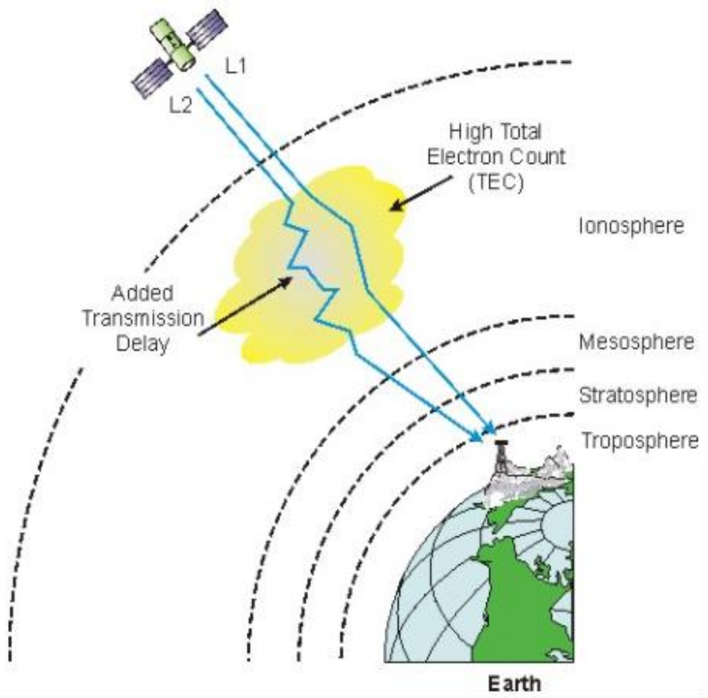

Figure 1. Satellite Ionospheric Delay

Figure 2 shows that the amount of ionospheric delay varies based on the electron density, and that the electron density can vary based on geographic location and sunspot activity. This Figure also shows that the amount of delay is different for the different GPS frequencies [7].

All of ionospheric models start from the evaluation of the electron concentration relative to the path from the satellite to the receiver. The first order ionospheric delay is only dependent from the signal frequency f and the STEC (Slant Total Electron Content) defined as the electron concentration along the path from the receiver to the satellite.

STEC is a function of many variables, including season, time of day, location and azimuth of the GPS receiver, and long and short term changes in solar ionizing flux. The amount of delay through the ionosphere varies with the frequency of the signal that passes through the ionosphere and the zenith angle. According to the zenith angle, the TEC (Total Electron Content) along the signal path varies between the satellite and the receiver.

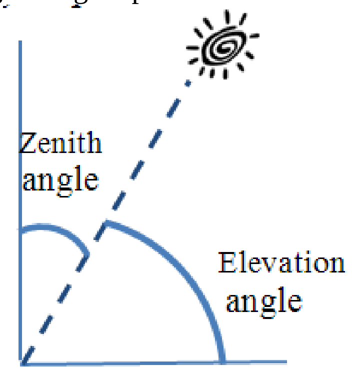

Figure 2. Elevation Angle vs. Zenith Angle

The elevation angle, which is provided in the CGGTTS result file and used interchangeably with altitude angle, is the angular height of the sun in the sky measured from the horizon. The elevation angle varies throughout the day. The elevation is 0° at sunrise and 90° when the sun is directly overhead. It also depends on the latitude of a particular location and the day of the year.

The zenith angle is the angle between the sun and the vertical. The zenith angle is similar to the elevation angle but it is measured from the vertical rather than from the horizontal, thus making the zenith angle = 90° - elevation [8].

The STEC is calculated in a geographic point, IP (Ionospheric Point), which is the intersection between direction of propagation and the average height of the ionosphere. The projection on the surface of the ionospheric point is the SIP (Sub-ionospheric Point) showed in Figure 4. Code delay is obtained from the below equation.

$$\delta_{\rho I}\ (code) = (40.3 \times STEC)\ /\ f^2 \tag{1}$$

Where $\delta_{\rho I}$ is expressed in meters, STEC in TEC units, TECu in electons/m^2 and f in MHz. The value of 1 TECu for the L1 frequency generates a delay of 0.16m. STEC can be estimated using ionospheric mapping function F as follows:

$$\text{STEC} = \text{F}\cdot\text{VTEC} \tag{2}$$

Among these error factors, the elevation angle (zenith angle) of satellites and the location of the GPS receiver are considered in this paper.

3.1 Klobuchar Model

GPS uses the Klobuchar model for the estimation of the ionospheric delay model for the L1 single frequency receiver [9]. The Klobuchar model is supposed to be concentrated in a layer placed at an average altitude of 350km set by the earth's surface in Figure 4.

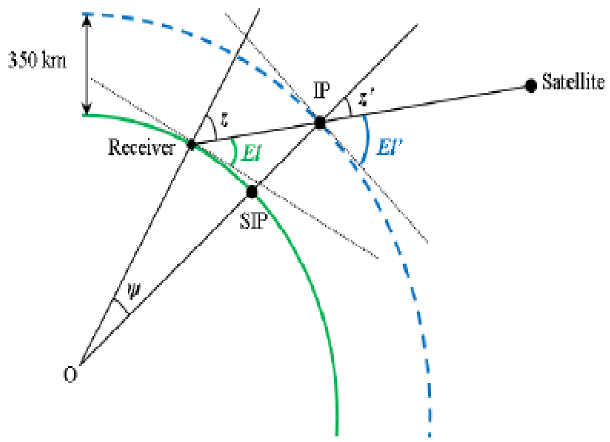

Figure 4. Klobuchar Model

The Klobuchar model provides the different estimation for the daytime and nighttime ionospheric delay in seconds along the SIP vertical direction using eight coefficients transmitted in the navigation message [10].

ΔT_v^{Iono} is the vertical ionospheric delay.

$$\Delta T_v^{Iono} = A_1 + A_2 \cos(2\pi(t - A_3)/A_4) \tag{3}$$

where

$$A_1 = 5 \times 10^{-9} ns$$
$$A_2 = \alpha_1 + \alpha_2 \varphi_{IP}^m + \alpha_3 {\varphi_{IP}^m}^2 + \alpha_4 {\varphi_{IP}^m}^3$$
$$A_3 = 14^h \text{ local time}$$
$$A_4 = \beta_1 + \beta_2 \varphi_{IP}^m + \beta_3 {\varphi_{IP}^m}^2 + \beta_4 {\varphi_{IP}^m}^3.$$

Night time correction is assumed equal to a globally constant value of A_1, while the diurnal vertical delay is modeled as cosine featured by amplitude (A_2), period A_4 and phase A_3 depending from the geomagnetic latitude of SIP.

The values for A_1 and A_3 are constant, the coefficients α_i, β_1, i = 1, .., 4 are uploaded to the satellites and broadcast to the user within the fourth subframe of the navigation message.

In accordance with equation (2), the ionospheric delay of L1 frequency is computed as follows.

$$T_{L1}^{iono} = \mathrm{F} \times \Delta\mathrm{T}_{\mathrm{V}}^{\mathrm{Iono}} \quad (4)$$

$$where\ F = 1 + 16 \times (0.53 - EL)^3, \text{El is elevation angle}$$

Using Taylor series approximation of the equation 1, the expression of Klobuchar model is following.

$$\mathrm{F} \times [5 \times 10^{-9} + A_2(1 - X^2/2 + X^4/24)] \quad if\ |X| \le 1.57 \quad (5)$$
$$\mathrm{F} \times (5 \times 10^{-9}) \quad if\ |X| > 1.57$$

where X is the phase of ionospheric delay and is calulated with $2\pi(\mathrm{t} - A_3)/A_4$.

Although the Klobuchar model is provided to estimate the ionospheric delay in the GPS L1 frequency signal, it can also be used to estimate the ionospheric time delay in the GPS L2 frequency signal, or for the GLONASS and Galileo signals as well. Indeed, taking into account that the ionospheric delay is inversely proportional to the square of the signal frequency, the delay for any GNSS signal transmitted on frequency f is given by

$$T_{L2}^{iono} = (f_{L1}/f_{L2})^2\, T_{L1}^{iono} \quad (5)$$

3.2 Ionospheric Free Combination

The ionosphere term can be eliminated by using the characteristic of that the ionosphere term is inversely proportional to the squared respective carrier frequency. Thus, the P3, ionospheric free combination using dual frequency is obtained like equation (6).

$$P_3 = f_{L1}^2/(f_{L1}^2 - f_{L2}^2) \times P_1 - f_{L2}^2/(f_{L1}^2 - f_{L2}^2) \times P_2 \approx 2.55P_1 - 1.55P_2 \quad (6)$$

P3 ionospheric free combination allows us to remove its effect up to more than 99.9% using two frequency measurements [11].

3. Comparisons

The r2cggtts software requires the GPS observation data and GPS navigation data written in rinex format for the measurement date. In order to evaluate the effects of ionospheric delay, we randomly use two observation and navigation data from May 26, 2014 and December 15, 2013 (MJD 56641) provided by TTS timing receiver of KRISS (Korea Research Institute of Standards and Science). MJD stands for Modified Julian Day.

3.1 Time Offsets for P1, P2, P3 Code Measurements

Figures 4 and 5 show the results of the modified r2cggtts software using P1, P2, and P3 code for MJD 56641 and MJD 56803.

X axis represents the series of the scheduled times from of the observation day in 16 minutes. The middle of X axis is around noon time. Y axis represents the time offsets of all observed satellites in 0.1ns.

According to the number of observed satellites during one day, X axis varies in about 780 results in Figure 4 and about 1,180 results in Figure 5.

These Figures show the ionospheric effects of time offsets using P1, P2 and P3 code measurements. P1 and P2 represent more variations compared to P3 results. P2 results show more variations compared to P1 results.

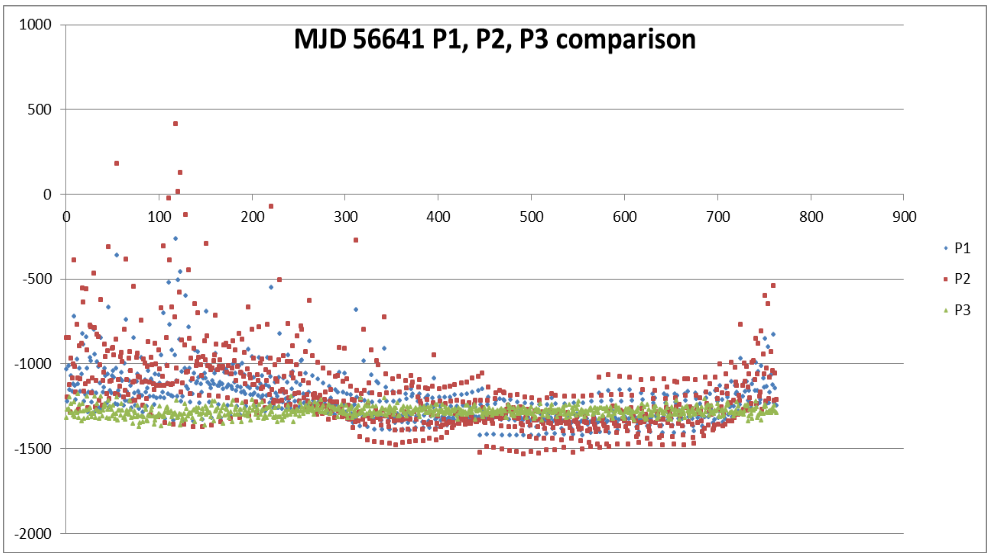

Figure 3. Time Offsets of P1, P2, P3 for MJD 56641

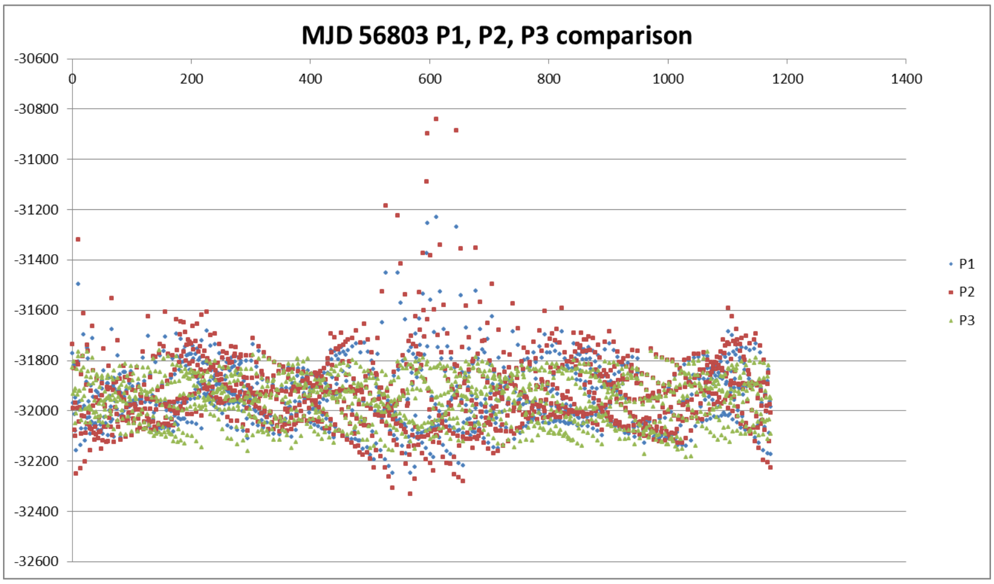

Figure 4. Time Offsets of P1, P2, and P3 for MJD 56803

3.2 Effects of the Elevation Angle on Time Offsets

In order to Figure out the factors for the variations of P1 and P2, we investigate the relation between the elevation angles of satellites and time offsets.

In Figure 6 to Figure 8, X axis represents the elevation angle from 0° to 90° and Y axis represents time offsets in 0.1 ns.

Figure 6 is the graph showing time offsets according to the elevation angle for all P codes. Time offsets of P3 ionospheric free combination are very stable at around 140ns all day while time offsets of P1 and P2 codes show the very large difference in the region of low elevation angles and oppositely, very stable values about high elevation angles above 60°.

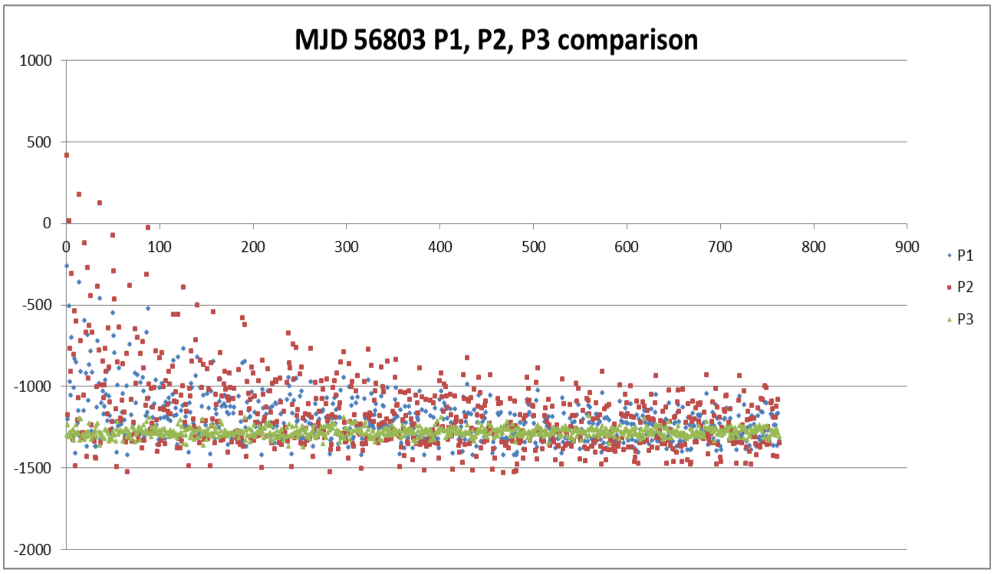

Figure 5. Time Offsets of P1, P2, and P3 According to the Elevation Angle

To recognize the results in detail, time offsets of P1 and P3 code and P2 and P3 code are represented in Figure 7 and Figure 8 respectively.

Time offsets of P2 code measurements are rich in variety in the section of elevation angles from 0° to 40° and especially below 25°.

Also, time offsets of P3 code show some variations below the elevation angle of 10°. It is a well-known fact that the time offsets of low elevation angles below 10° shows the bad quality in atmospheric effects. So the low elevation angles are filtered in GNSS time transfer.

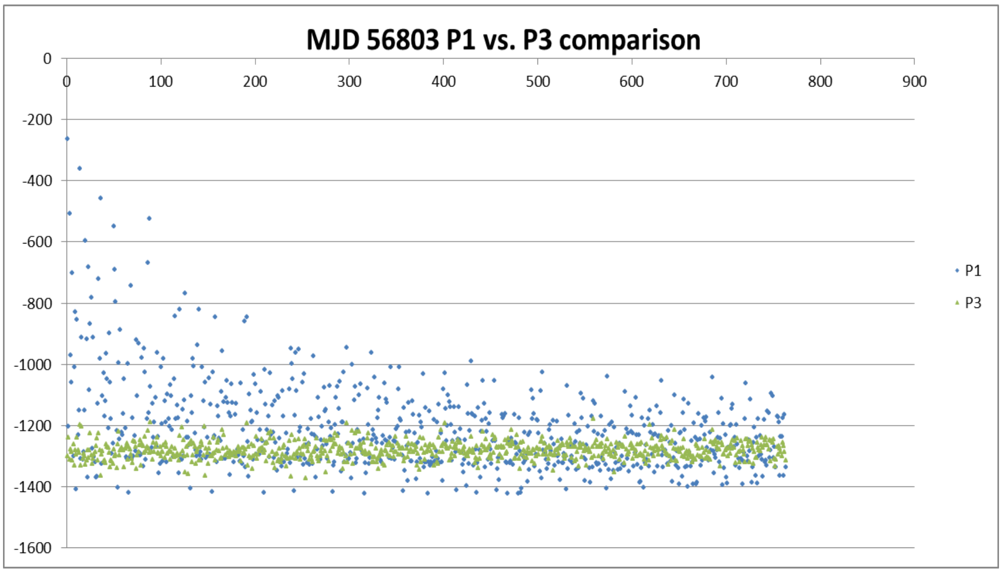

Figure 6. Time Offsets of P1 and P3 According to the Elevation Angle

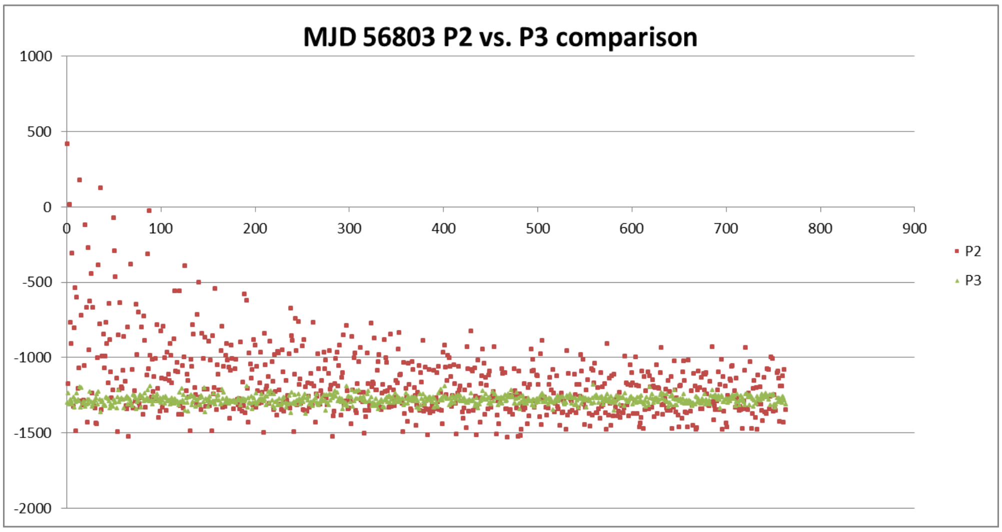

Figure 7. Time Offsets of P2 and P3 According to the Elevation Angle

4. Conclusion

This paper briefly introduces the GNSS time transfer technique in order to generate the time offsets for TAI. There are many steps in the generation of time offsets. This paper handles the ionospheric effects on time offsets. The general method to eliminate the ionospheric delay, P3 ionospheric free combination, is used. The r2cggtts software developed by Dr. Pascale in ORB (Royal Observatory of Belgium) is widely used in time laboratories engaged in GNSS time transfer all over the world in order to generate the time offset.

We modify the legacy r2cggtts software to generate and write the time offsets of P1 and P2 code measurements in addition and then compare the time offsets of P1, P2 and P3 code.

Time offsets of P1 and P2 code use the Klobuchar model to eliminate the ionospheric delay using single frequency. The time offsets using single frequency show more various error conditions during some sections. We figured out the main error source for P1 and P2 time offsets is the elevation angle and analyzed the correlation between the elevation angles and time offsets.

In further studies, we can secure a basic technique for the time-offset generation according to the GPS code characteristics and national competiveness for GNSS time transfer.

5. ACKNOWLEDGEMENTS

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