UPORABA KODE L2C ZA DOLOČITEV UPORABNIKOVEGA POLOŽAJA

UTILIZATION L2C CODE FOR DETERMINATION OF USER'S POSITION

Kamil Krasuski, Damian Wierzbicki

UDK: 528.2
Klasifikacija prispevka po COBISS.SI: 1.01
Prispelo: 17. 2. 2015
Sprejeto: 12. 11. 2015

DOI: 10.15292/geodetski-vestnik.2015.04.789-808
SCIENTIFIC ARTICLE
Received: 17. 2. 2015
Accepted: 12. 11. 2015

SI | EN

IZVLEČEK

V članku je opisanih nekaj primerov določanja položaja v sistemu GPS (angl. Global Positioning System) z novo kodo L2C. Za matematični izračun določitve položaja je bila uporabljena metoda absolutnega določevanja položaja s stohastično obdelavo. Predstavljeni so primeri rezultatov določevanja položaja sprejemnika, pri čemer smo uporabili metodo absolutnega določevanja položaja, vključno z vplivi pogreška položaja satelita z uporabo Lagrangejevega polinoma ter rotacije in plimovanja Zemlje, Sagnacovim vplivom, vplivi pogreška ure satelita, vplivi ionosfere in troposfere ter drugih pogreškov oddajnika in sprejemnika. Izvorna programska koda je bila napisana v programskem jeziku Scilab 5.4.1. v 64-bitnem sistemu Windows. Kodna opazovanja v obliki zapisa RINEX (angl. Receiver Independent Exchange Format) so bila za časovni interval med 20:00:00 in 23:59:30 na dan 6. 1. 2015 pridobljena s permanentne postaje WROC v Wroclawu na vzhodnem Poljskem. Izračun je bil opravljen za štiri serije z intervalom registracije opazovanj 30 sekund. Rezultati ocene položajne točnosti v geocentričnem referenčnem sistemu kažejo, da je srednji pogrešek določitve koordinat manjši od 8,5 metra, kar je primerljivo s točnostjo, ki jo zagotavlja koda L1C. Praviloma bi morali biti rezultati boljši, toda število satelitov GPS s kodo L2C je bilo nestabilno. Dodatno je treba poudariti, da je znašal srednji pogrešek ure sprejemnika nekaj manj kot 8 metrov, kar ustreza 2,7•10-8 s.

ABSTRACT

The article describes a few tests of standalone positioning in Global Positioning System (GPS) with the utilization of a new L2C code. Single Point Positioning (SPP) method in stochastic processing was applied as a mathematical formulation in computations. Measurement models of the SPP method such as interpolation satellite position using Lagrange polynomial, Earth rotation effect, Sagnac effect, satellite clock bias, ionosphere delay, troposphere delay, satellite and receiver instrumental biases are discussed based on study cases. The source code of the program was written in Scilab 5.4.1 software language under the 64-bytes Windows system. Code observations in Receiver Independent Exchange format (RINEX) file (between 20:00:00 – 23:59:30) for 06.01.2015 were taken from WROC station in Wroclaw in eastern Poland. Adjustment processing was carried out over 4 sessions with a time interval of 30 seconds. The preliminary results of positioning accuracy in geocentric frame, presented by mean errors of each coordinate, are less than 8.5 meters and they are comparable to the accuracy of L1C code. Generally, positioning accuracy in experiments is expected to be higher but the number of GPS satellites with L2C code was very unstable. Additionally, mean errors of the receiver clock were shown in the paper with a maximum value of less than 8 meters, which equals about 2.7•10-8 s.

KLJUČNE BESEDE

GPS, metoda absolutnega določevanja položaja, koda L2C, sistematični pogreški, točnost določanja položaja

KEY WORDS

GPS, single point positioning method, L2C code, systematic errors, positioning accuracy

1 INTRODUCTION

The fundamental conception of the GPS system is developed to determine the user's position in each point on the Earth over 24 hours. Currently, beside the GPS system, also GLONASS, BEIDOU and GALILEO satellite systems are utilized in positioning across the whole world. The basic idea of positioning based on coordinates estimation (usually XYZ in geocentric frame or BLH in geodetic frame) uses code and phase observations. Carrier phase data (L1/L2) are very precise observations (with an accuracy of about 1÷3 mm) and should be applied in precise positioning method such as PPP (Precise Point Positioning) method, DGPS (Differential GPS) technique or RTK (Real Time Kinematic) method (Abdel-Salam, 2005; Zheng, 2006). Code observations (C1/P1/P2) are greater noisily but they are very popular in many applications in post-processing and near real time. Especially, SPP (Single Point Positioning) method is a universal solution for estimation of coordinates in standalone positioning and navigation. The SPP method prefers C1 or P1 code as an input data for numerical computations. The C1 code is an acquisition code with a standard deviation of between 3 and 30 meters.

In contrast to C1 code, P1 code is more precise (about 1÷3 m), but it is very hard to reconstruct, because the same sequence is repeated after 266 days (Seeber, 2003). Significantly, P1 code has got an encrypted version as a P(Y) code with a chipping rate of 10.23 MHz, but P(Y) code is designed only for military users. In civil applications, the relation between P1 and C1 code is called instrumental biases and marked as a DCB P1-C1. It also is very important for receivers with cross-correlation (e. g. C1/P2), without access to P1 code (Dach et al., 2007). In this way, the accuracy of the new P1 code is similar to C1 code, but the precision of pseudorange was changed. In practice C1 code is still more preferable and beneficial for civil users in the SPP method.

Generally, the SPP method is used into two modes (static and kinematic). Moreover, the static mode is utilized in absolute positioning of a single receiver in post-processing. Kinematic mode is preferred in real time applications for determining vehicle (such as car of aircraft) coordinates. In static mode for single measurement epoch 4 parameters are estimated, it means 3 coordinates (XYZ) and one receiver clock as a parameter of time transfer. Of course, geocentric coordinates can be also applied for obtained temporary velocity (or temporary acceleration) and attitude angles (e. g. in kinematic mode). The minimal number of measurements in a single epoch for position estimation is equal 4, but one freedom degree is needed for the adjustment processing of GPS observations. In the case of all measurement epochs in all sessions unknown numbers of estimated parameters will be equal $3 + 1 \times S \times NT$ (in static mode) and $3 \times S \times NT + 1 \times S \times NT$ (in kinematic mode), where S is number of all sessions, NT is number of measurements epochs in single sessions. The least square method is recommended as a mathematical model for solving user's position, but Kalman filter can be also applied. For GNSS dual-frequency receivers, C1 code observations from other navigation systems are utilized in the SPP method. In this case the receiver clock parameter should be estimated for each GNSS system as information about the difference of time scale between GNSS systems. It is called an inter-system bias of the receiver clock. Currently the SPP method can be applied in GPS, GLONASS, BEIDOU and GALILEO systems. The typical accuracy of the SPP method is less than 10 m with a probability of 95% using C1 code observations (Kaplan et al., 2006).

The GPS system is still being modernized and new satellites have been launched on the orbital plans. Actually, the GPS system is divided into 4 generations, e. g.: Block II-A, Block II-R, Block II-RM and

Block II-F. Among these generations, only two blocks (II-RM and II-F, exactly now 15 satellites) can transmit the new L2C code on the 2nd frequency (1227.6 MHz) in the GPS system (Leandro et al., 2008). The L2C code consists of two codes, these are known as L2 CM (Civil Moderate) and L2 CL (Long). The L2 CM code is 20 ms long and includes 10230 chips, while L2 CL code is repeated every 1.5 s and has got 767250 chips. The relation of times longer between L2 CL and L2 CM codes is close to 75. Each code (L2 CM and L2 CL) is generated by MRSRG (Multiple Return Shift Register Generator) with a chipping rate of 511.5 kbps and it can described using 27-degrees polynomial. The final frequency of L2C code is the same as L1 C/A code (when CM and CL codes are combined), but the spectrum power is less than 2.3 dB, which causes the SNR value to be higher than L1 C/A code. Additionally, civil navigation messages (CNAV) are modulated on the L2 CM with bit rate 25 bps (Fontana et al., 2009; Iswariya et al., 2013, Kwon et al., 2011; Wang, 2010; Yao, 2007).

In this paper the possibilities of L2C code for GPS standalone positioning are presented. For this purpose raw observations from RINEX file from WROC reference site were utilized. Station coordinates were estimated using the SPP method and the code source of program was written in Scilab 5.4.1 software. The other attributes of the SPP method such as systematic and geometric errors with examples were shown also. The mathematical formulation of the SPP method (e. g. least square method) has been described in detail. The paper is organized in 4 sections: 1. Introduction, 2. Mathematical model of SPP method for L2C code, 3. Experiments and Results, 4. Conclusions.

2 THE MATHEMATICAL MODEL OF THE SPP METHOD FOR L2C CODE

2.1 Observations modelling

2.1.1 Geometric range term

The basic equation of the SPP method can be described as follows:

$$p = d + C \cdot (dto - dts) + Ion_2 + Trop + SDCB_{C2} + RDCB_{C2} \quad (1)$$

where:

p - pseudorange L2C from RINEX file,
d - geometric distance between satellite and receiver,
C - speed of light,
dto - receiver clock,
dts - satellite clock,
Ion_2 - ionosphere delay on 2nd frequency in the GPS system,
$Trop$ - troposphere delay,
$SDCB_{C2}$ - satellites instrumental biases for L2C code,
$RDCB_{C2}$ - receiver instrumental bias for L2C code.

At first, raw observations L2C from RINEX file (usually in 2.10 or 2.11 format) must be annexed as input data for adjustment processing. Information such as pseudoranges, time interval, time of measurement epoch, number of observations and Satellite Vehicle (SV) number should be read from RINEX file to Scilab 5.4.1 software. These parameters are converted from string character to numerical format. Now, the reception time from RINEX file, it means measurement epoch, and pseudorange value are utilized for the determination time of signal transmission (Sanz Subirana et al., 2013), as below:

$$t_S = t_{RINEX} - \frac{p}{C} - dts \tag{2}$$

where:

t_S - time of signal transmission,

t_{RINEX} - measurement epoch from RINEX file.

Equation (2) is the basic solution for providing information about the time of the signal travelling through the atmosphere (without iterative computations) and it is utilized in gLAB software. The time t_S is also applied for estimating satellite position using 9-degrees Lagrange polynomial based on 10 nodes. Mathematical formulation for interpolation satellite position can be written (Bidikar et al., 2014):

$$r(t_S) = \begin{bmatrix} X(t_S) \\ Y(t_S) \\ Z(t_S) \end{bmatrix} = \frac{(t_S - t_2)(t_S - t_3)...(t_S - t_{10})}{(t_1 - t_2)(t_1 - t_3)...(t_1 - t_{10})} \cdot \begin{bmatrix} X(t_1) \\ Y(t_1) \\ Z(t_1) \end{bmatrix} + ... + \frac{(t_S - t_1)(t_S - t_2)...(t_S - t_9)}{(t_{10} - t_1)(t_{10} - t_2)...(t_{10} - t_9)} \cdot \begin{bmatrix} X(t_{10}) \\ Y(t_{10}) \\ Z(t_{10}) \end{bmatrix} \tag{3}$$

where:

$X(t_1),..., Z(t_{10})$ - satellite coordinates from Precise Ephemeris file,

$X(t_S),..., Z(t_S)$ - satellite coordinates estimated on the epoch t_S.

Equation (3) is repeated for each satellite in iterative scheme in sequential process for all measurement epochs from RINEX file. Satellite coordinates in Precise Ephemeris file (with abbreviation „*.SP3" or „*.EPH") are expressed in geocentric frame (e. g. IGS or ITRF) with interval 15 minutes. The 1-hours data of „*.SP3" file includes four epochs of SV position and for the whole day (for 24-hours data) it will be equal to 96 epochs. The typical precision of satellite coordinates in „*.SP3" file is about a few millimeters, but the basic unit of „*.SP3" format is 1 km. Together with satellite coordinates, in „*.SP3" file, precise clocks for each satellite are available also. Sometimes velocity components with clock rates are implemented in „*.SP3" file as additional information about SV position (Hilla, 2010). Currently „*.SP3" file is produced by the Analysis Centers (AC are a part of IGS service, a list of the AC is available at: http://igs.org/about/analysis-centers) as a final, rapid and ultra-rapid product. Similar to the GPS system, GLONASS, GALILEO and QZSS satellite positions are provided and distributed in Precise) Ephemeris format.

Satellite coordinates in equation (3) should be also corrected for Earth rotation effect (Schüler, 2001), as below:

$$r = \begin{bmatrix} Xs \\ Ys \\ Zs \end{bmatrix} = \begin{bmatrix} X(t_S) \cdot \cos\Omega + Y(t_S) \cdot \sin\Omega \\ -X(t_S) \cdot \sin\Omega + Y(t_S) \cdot \cos\Omega \\ Z(t_S) \end{bmatrix} \tag{4}$$

where:

Ω - rotation angle during the signal travel, $\Omega = \omega \cdot \left(\frac{p}{C} + dts \right)$,

ω - angular velocity of the Earth, $\omega = 7{,}2921151467 \cdot 10^{-5}$[rad/s].

Table 1: Influence of Earth rotation effect on the satellite position at epoch 20:00:00 GPS Time (06.01.2015).

SV Number	$r_x = Xs - X(t_S)$ [m]	$r_y = Ys - Y(t_S)$ [m]	$r_z = Zs - Z(t_S)$ [m]
1	78.479	80.854	0.000
12	-57.829	-136.991	0.000
15	-3.964	-112.820	0.000
17	102.573	-50.969	0.000
24	-49.950	-73.850	0.000

Results of Earth rotation effect on the satellite position for the study cases are presented in Table 1. Especially the differences between two vectors r and $r(t_S)$ are visible for r_x and ry component and these values can reach up to more than ±100 m. From the other side r_z component is 0 and its influence is negligible for Z coordinate. An alternative solution of r vector is described in paper (Zhang, 2007), where Sagnac effect is added as follows:

$$d = \|R - r\| = \|R - r(t_S)\| \pm \delta R \quad (5)$$

where:

$\| \, \|$ - vector norm, R - vector with receiver coordinates, $R = [x_R, y_R, z_R]^T$,

$\|R - r\|$ - geometric distance between satellite (after Earth rotation correction) and receiver, $\|R-r\| = \sqrt{(x_R - Xs)^2 + (y_R - Ys)^2 + (z_R - Zs)^2}$,

$\|R - r(t_S)\|$ - geometric distance between satellite (without Earth rotation correction) and receiver, $\|R - r(t_S)\| = \sqrt{(x_R - X(t_S))^2 + (y_R - Y(t_S))^2 + (z_R - Z(t_S))^2}$,

δR - Sagnac effect, $\delta R = \dfrac{\omega \cdot (X(t_S) \cdot y_R - Y(t_S) \cdot x_R)}{C}$.

Sagnac effect has a major significance for the determination of geometric distance between each satellite and receiver. If equation (5) is applied to the obtained interpolated satellite position and Sagnac effect is omitted, then d parameter is not a true value (see Table 2). Generally Sagnac effect is classified as a geometric error and it is a very important bias in precise positioning (e. g. PPP method).

Table 2: Influence of Sagnac effect on the satellite position at epoch 20:00:00 GPS Time (06.01.2015).

SV Number	$\|R - r\|$ [m]	$\|R - r(t_S)\|$ [m]	δR [m]
1	25021404.561	25021420.396	-15.832
12	23374077.089	23374060.700	16.444
15	20880163.182	20880156.093	7.066
17	21949529.442	21949544.633	-15.160
24	21386663.719	21386650.696	13.016

2.1.2 Satellite clock error

The satellite clock should be modelled in the SPP method as a parameter of time transfer. Each GPS satellite is equipped in a few stability atomic clocks, e. g. Cesium, Rubidium or Hydrogen Maser. Onboard satellite clocks (with Allan deviation better than 10^{-14} s) are still monitored and corrected by a control segment and their values are compared with GPS Time (GPST) scale in the US Naval Observatory (USNO) in the USA. Usually twice per day, clock biases are calculated and uploaded to GPS satellites. The 2-degree polynomial function can be applied to determining the approximate value of satellite clock error (de Jonge, 1998), as below:

$$dts_{BRD} = a_0 + (t_S - t_0) \cdot a_1 + (t_S - t_0)^2 \cdot a_2 \tag{6}$$

where:

a_0 - clock offset in [s],
a_1 - clock drift in [s/s],
a_2 - clock drift rate in [s/s^2],
t_0 - reference time of ephemeris data in broadcast message.

Polynomial coefficients are available in sub-frame one in broadcast navigation message, but these parameters enable the recovery of clock error with an accuracy of more than 5 ns (about 1.5 m). Perhaps a better solution can be utilized satellite clock data from „*.SP3" file (accuracy of clock error less than 1 ns). It is worth mentioning that clock errors in „*.SP3" file are expressed in microsecond unit and the magnitude of satellite clock accuracy is less than 3 ns (in case of ultra-rapid product). Similar to satellite coordinates, clock biases are estimated using 9-degrees Lagrange polynomial function, as follows:

$$dts_{SP3} = \frac{(t_S - t_2)(t_S - t_3)\ldots(t_S - t_{10})}{(t_1 - t_2)(t_1 - t_3)\ldots(t_1 - t_{10})} \cdot dts(t_1) + \ldots + \frac{(t_S - t_1)(t_S - t_2)\ldots(t_S - t_9)}{(t_{10} - t_1)(t_{10} - t_2)\ldots(t_{10} - t_9)} \cdot dts(t_{10}) \tag{7}$$

where:

dts_{SP3} - interpolated clock biases at epoch t_S.

Information about precise satellite clock bias is available in „*.CLK" file with sample rate 30 seconds or higher. In this case satellite clock error (with accuracy close to few cm) can be modelled using 1st or 2nd order of polynomial function. In the submitted paper, satellite clock values are estimated based on data only from „*.SP3" file.

Example comparison results of satellite clock offsets were shown in Table 3. The difference of satellite clock bias between „*.SP3" file and navigation message is called satellite clock shift and it can equal a few meters, while Selective Availability (SA) is turned off. The satellite clock shift depends on polynomial degree for „*.SP3" data and polynomial coefficients in broadcast message. However, the satellite clock parameter is eliminated if differential techniques are applied in processing of GPS observations for receivers' network.

Table 3: Comparison of clock biases based on precise ephemeris file and broadcast data at epoch 20:00:00 GPS Time (06.01.2015).

SV Number	dts_{SP3} [m]	dts_{BRD} [m]	$\delta dts = dts_{SP3} - dts_{SP3}$ [m]
1	-3130.986	-3130.708	-0.278
12	77749.896	77749.375	0.521
15	-67388.932	-67387.994	-0.938
17	-44509.045	-44506.431	-2.613
24	-12394.403	-12394.401	-0.002

2.1.3 Atmosphere delays

The L2C code is delayed and lengthened when the signal travels through atmosphere (e. g. ionosphere and troposphere). Ionosphere is the upper zone of atmosphere with a boundary of between 100 and 1000 km. The structure of ionosphere is divided into four regions: D, E, F1 and F2. These layers are very different, especially in electron density concentration and height coverage. One quality is common for each layer, it means reaction with cosmic and ultraviolet radiations, which causes free electrons to be removed from ionosphere zone. If the electromagnetic wave (e. g. GPS signal) meets with these electrons it can be the beginning of GPS signal degradation. Moreover ionosphere has a dispersive nature and signal delay is a function of wave frequency also. In case of any type of positioning (e. g. standalone, precise, kinematic, navigation etc.), ionosphere delay can change receiver coordinates about a few or more meters. Ionosphere delay (referenced to 1st frequency) is a modelled based on „Geometry Free" linear combination, but instrumental biases DCB should be also determined (Bosy, 2005; Schaer, 1999). Ionosphere delay in „Geometry Free" linear combination is expressed using VTEC (Vertical TEC) term, which is evaluated from „IONEX" file. Currently, Analysis Centers (such as the JPL, the CODE, the ESA/ESOC, the NRCan) and the UPC in Spain provide ionosphere maps in „IONEX" format in temporal resolution 2 hours or higher. In practice, VTEC parameters from „IONEX" file can reduce ionosphere delay to 80÷90%, and typically they are applied in precise positioning (e. g. differential technique) using phase observations. In standalone positioning and navigation (where code observations are a basic measurements), the Klobuchar model is utilized for single frequency (L1) receivers. The parameters of the Klobuchar model are transmitted in broadcast message and reduce ionosphere delay only to 50÷60%. For observations on 2nd frequency in GPS system, ionosphere delay can be obtained as follows (Klobuchar, 1987):

$$Ion_2 = \left(\frac{f_1}{f_2}\right)^2 \cdot Ion_1 \quad (8)$$

The Ion_1 term in equation (8) expresses ionosphere delay referenced to L1 frequency in GPS system based on the Klobuchar model, as below:

$$Ion_1 = \begin{cases} F \cdot \left[5 \cdot 10^{-9} + A \cdot \left(1 - \frac{x^2}{2} + \frac{x^4}{24} \right) \right], & if \quad |x| < 1.57 \\ F \cdot 5 \cdot 10^{-9}, & if \quad |x| > 1.57 \end{cases} \quad (9)$$

where:

F - mapping function, $F = 1 + 16 \cdot (0{,}53 - El)^3$,

El - elevation angle, $A = \begin{cases} \sum_{j=1}^{4} \alpha_j \cdot \phi_j, & if \quad A \geq 0 \\ 0, & if \quad A < 0 \end{cases}$,

α_j, β_j - coefficients from navigation message,

ϕ_j -geomagnetic latitude, $x = \frac{2 \cdot \pi \cdot (T_0 - 50400)}{P}$,

T_0 - local time, $P = \begin{cases} \sum_{j=1}^{4} \beta_j \cdot \phi_j, & if \quad P \geq 72000 \\ 72000, & if \quad P < 72000 \end{cases}$.

In contrast to ionosphere layer (where ionosphere refraction index for group delay is always higher than 1, $n_{gr} > 1$ and ionosphere refraction index for phase delay is always less than 1, $n_{ph} < 1$), troposphere layer is an independent zone related to GPS electromagnetic waves and the troposphere refraction index is always higher than 1, $n_{trop} > 1$. In addition, troposphere delay cannot be eliminated using linear combination and only empirical or theoretical models are applied to reduce this effect. Usually troposphere delay consists of two components: hydrostatic and wet. The hydrostatic term is a major part of troposphere delay (approximately 90%) and it is easy to estimate, because it is a function of air pressure on the Earth surface. The wet component (about 10%) is very hard to modelling, because it is a function of water vapour in the atmosphere (Bosy et al., 2006; Cai, 2009). The total troposphere delay is a sum of hydrostatic and wet components and can be described as follows:

$$Trop = m_h \cdot Trop_h + m_w \cdot Trop_w \tag{10}$$

where:

$Trop_h$ - troposphere zenith delay for hydrostatic component,
m_h - mapping function for hydrostatic component,
$Trop_w$ - troposphere zenith delay for wet component,
m_w - mapping function for wet component.

In the SPP method two troposphere models are preferred: Hopfield and Saastamoinen. In submitted paper, simple troposphere model is utilized from gLAB software (Sanz Subirana et al., 2013):

$$Trop = m_{el} \cdot (Trop_h + Trop_w) \tag{11}$$

where:

$m_{el} = m_h = m_w = \dfrac{1,001}{\sqrt{0,002001 + \sin^2(El)}}$,

$Trop_h = 2,3 \cdot \exp(-0,116 \cdot 10^{-3} \cdot H_{el})$,
$Trop_w = 0,1$,
H_{el} - ellipsoidal height.

Ionosphere delay as well as troposphere delay has a positive value for code measurements, because the refraction index for each delay (n_{gr} and n_{trop}) is higher than 1. Therefore these delays are subtracted from code observations as systematic errors. In the SPP method, both delays can be modelled from 5^0 of elevation angle. Example results of ionosphere and troposphere delays as a function of elevation angle were visualized in Figure 1. The troposphere delay for lower elevation angle can reach more than 20 m. In case of ionosphere delay value, the magnitude of error is less than 5 meters in minor solar activity (epoch of calculation is 20:00:00 GPS Time). In connection with the elevation angle, the troposphere delay should be respected as symmetric bias and ionosphere delay as asymmetric bias. The symmetric bias has an impact on the vertical coordinate in GPS positioning, but asymmetric bias can change the baseline between two receivers, which causes horizontal coordinates displacement.

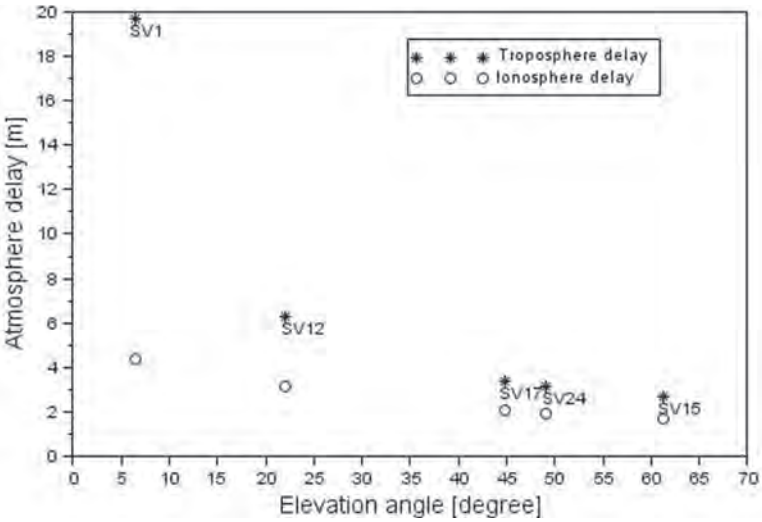

Figure 1: Atmosphere delays in elevation function at epoch 20:00:00 GPS Time (06.01.2015).

2.1.4 Instrumental biases

Different electronic hardware in satellites and receivers was the reason that systematic errors such as instrumental biases must be applied in adjustment processing. Instrumental biases of satellite are defined as a time delay between generation and transmission of each code observation. On-board atomic clocks have the most significance in determining a true value of satellite instrumental biases. Receiver instrumental bias is called the travel time from antenna channel to receiver hardware (Hong, 2007; Lin, 2001). For L1 users in the GPS system, total group delay (e. g. TGD) is utilized in standalone positioning and navigation. TGD parameters are contained in navigation message in sub-frame seven and they have been calibrated and provided by the Jet Propulsion Laboratory (JPL) since 1999. The magnitude order of TGD is between 6 and -21 ns, with an accuracy of about 0.5 ns (Spits, 2011). The other role of TGD is based on satellite clock correction (Witchayangkoon, 2000), as below:

$$dts_{L1P} = dts_{BRD} - TGD, \quad for \quad L1$$
$$dts_{L2P} = dts_{BRD} - \left(\frac{f_1}{f_2}\right)^2 \cdot TGD, \quad for \quad L2 \tag{12}$$

where:

dts_{L1P}, dts_{L2P} - satellite clock biases for code observations on 1st and 2nd frequency in GPS system.

Equation (12) is preferred only for P-code observations, so it cannot be adequate for L2C measurements. Instrumental biases for L2C code are estimated using „Geometry Free" linear combination as follows:

$$L1C - L2C = STEC + SDCB_{C1C2} + RDCB_{C1C2} \tag{13}$$

where:

$L1C$, $L2C$ - raw code observations,

$STEC$ - ionosphere delay at 1st frequency, $STEC = Ion_1$,
$SDCB_{C1C2}$ - Satellite Differential Code Bias,
$RDCB_{C1C2}$ - Receiver Differential Code Bias.

```
GPS C1-C2 DCB ESTIMATION BY TST FOR DAY 6, 2015                06-JAN-15 15:30
-------------------------------------------------------------------------------

DIFFERENTIAL (C1-C2) CODE BIASES FOR SATELLITES AND RECEIVERS:

PRN / STATION NAME        VALUE (NS)  RMS (NS)
***   ****************    *****.***   *****.***
G01                         -2.588      0.324
G03                         -4.058      0.317
G05                          3.264      0.104
G06                         -5.933      0.117
G07                          5.448      0.142
G09                         -0.750      0.174
G12                          4.454      0.082
G15                          3.450      0.199
G17                          6.414      0.170
G24                         -5.186      0.082
G25                         -5.762      0.073
G27                         -3.697      0.279
G29                          1.993      0.055
G30                         -2.730      0.169
G31                          5.681      0.153
G     WROC                  13.968      0.260
```

Figure 2: DCB C1-C2 for WROC station for 06.01.2015.

Example results of DCB C1-C2 are presented in Figure 2, which includes instrumental biases for each satellite and receiver in universal „*.DCB" format. The magnitude order of SDCB C1-C2 is about ±7 ns with an accuracy of less than 0.4 ns. SDCB delays depend on themselves because the reference sum of SDCB amounts to 0 and SDCB delays can translate relate to the gravity center of SDCB. RDCB C1-C2 parameter is respected as an average bias and it should be stable over a day of measurements. DCB C1-C2 term contains only differential relation between absolute hardware delay on 1st and 2nd frequency for L1C and L2C code in the GPS system. For the purpose of hardware delay reconstruction for individual code observations, equation (14) must be applied (Gao, 2008):

$$\begin{aligned} DCB_{C1} &= SDCB_{C1} + RDCB_{C1} = \frac{DCB_{C1C2}}{1-\gamma} \\ DCB_{C2} &= SDCB_{C2} + RDCB_{C2} = \frac{\gamma \cdot DCB_{C1C2}}{1-\gamma} \end{aligned} \tag{14}$$

where:

$\gamma = \left(\frac{f_1}{f_2}\right)^2$.

2.2 Adjustment processing

After the measurements modelling process, unknown parameters in equation (1) should be separated from other terms, as follows:

$$p + C \cdot dts - Ion_2 - Trop - SDCB_{C2} - RDCB_{C2} = \sqrt{(x_R - Xs)^2 + (y_R - Ys)^2 + (z_R - Zs)^2} + C \cdot dto \qquad (16)$$

Receiver coordinates (x_R, y_R, z_R) on the right side of equation (16) can be expressed using approximate coordinates (x_0, y_0, z_0) from RINEX file and vector with corrections of coordinates (δx, δy, δz):

$$\begin{cases} x_R = x_0 + \delta x \\ y_R = y_0 + \delta y \cdot \\ z_R = z_0 + \delta z \end{cases} \qquad (17)$$

If receiver coordinates are replaced by terms from equation (17), then linearization process based on Taylor series is carried out for parameter d (Xu, 2007):

$$d = d_0 + \frac{\partial d}{\partial x} \cdot \delta x + \frac{\partial d}{\partial y} \cdot \delta y + \frac{\partial d}{\partial z} \cdot \delta z \qquad (18)$$

where:

d_0 - approximate distance between satellite and receiver, $d_0 = \sqrt{(x_0 - Xs)^2 + (y_0 - Ys)^2 + (z_0 - Zs)^2}$,

$\left(\frac{\partial d}{\partial x}, \frac{\partial d}{\partial y}, \frac{\partial d}{\partial z} \right)$ - partial derivatives.

Now equation (16) can be described as follows:

$$p + C \cdot dts - Ion_2 - Trop - SDCB_{C2} - RDCB_{C2} - d_0 = \frac{\Delta x}{d_0} \cdot \delta x + \frac{\Delta y}{d_0} \cdot \delta y + \frac{\Delta z}{d_0} \cdot \delta z + C \cdot dto \qquad (19)$$

where:

$\frac{\partial d}{\partial x} = \frac{\Delta x}{d_0}, \frac{\partial d}{\partial y} = \frac{\Delta y}{d_0}, \frac{\partial d}{\partial z} = \frac{\Delta z}{d_0},$

$\Delta x = x_0 - X_S,$

$\Delta y = y_0 - Y_S,$

$\Delta z = z_0 - Z_S.$

In matrix form, equation (19) can be expressed as below (Grewal et al., 2000):

$$\begin{cases} \mathbf{H} \cdot \Delta \mathbf{r} - \mathbf{l} = \mathbf{v} \\ \begin{bmatrix} \frac{\Delta x_1}{d_1} & \frac{\Delta y_1}{d_1} & \frac{\Delta z_1}{d_1} & 1 \\ \frac{\Delta x_2}{d_2} & \frac{\Delta y_2}{d_2} & \frac{\Delta z_2}{d_2} & 1 \\ \dots & \dots & \dots & \dots \\ \frac{\Delta x_n}{d_n} & \frac{\Delta y_n}{d_n} & \frac{\Delta z_n}{d_n} & 1 \end{bmatrix} \cdot \begin{bmatrix} \delta x \\ \delta x \\ \delta x \\ C \cdot dto \end{bmatrix} - \begin{bmatrix} l_1 \\ l_2 \\ \dots \\ l_n \end{bmatrix} = \begin{bmatrix} v_1 \\ v_2 \\ \dots \\ v_n \end{bmatrix} \end{cases} \qquad (20)$$

where:

H - matrix with coefficients, matrix is full rank,

$\Delta \boldsymbol{r}$ - vector with unknown parameters, length of $\Delta \boldsymbol{r}$ equals to 4 for single measurement epoch,

l - vector with difference between measurements and modelled parameters, $\mathbf{l} = p + C \cdot dts - Ion_2 - Trop - SDCB_{C2} - RDCB_{C2} - d_0$,

v - residuals vector, sum of residuals is 0.

In the SPP method, equation (20) is solved using least square method in stochastic processing (Petrovski, 2014):

$$\Delta \boldsymbol{r} = (\mathbf{H}^T \cdot \mathbf{P_1} \cdot \mathbf{H})^{-1} \cdot \mathbf{H}^T \cdot \mathbf{P_1} \cdot \mathbf{l} \tag{21}$$

where:

$\mathbf{P_1}$ - weight matrix of the measurements, $\mathbf{P_l} = \frac{m_0^2}{m_l^2}$,

m_0^2 - unit variance a priori, $m_0 = 1$,

m_l - standard deviation of pseudorange, $m_l = \frac{c_x}{\sin(El)}$,

c_x - accuracy of pseudorange L2C.

Mean errors (standard deviations) of unknown parameters are obtained as follows (Hofmann-Wellenhof et al., 2008):

$$\mathbf{Mx} = diag\left(\sqrt{\delta_0^2 \cdot N^{-1}}\right) = \begin{bmatrix} Qx & Qy & Qz & Qdto \end{bmatrix}^T \tag{22}$$

where:

$diag$ - diagonal values of covariance matrix $\delta_0^2 \cdot N^{-1}$,

δ_0^2 - unit variance a posteriori, $\delta_0 = \sqrt{\frac{\left[v^T \cdot P_l \cdot v\right]}{n-k}}$,

n - number of observations for single measurement epoch,

k - number of unknown parameters for single measurement epoch, $k = 4$,

$\mathbf{N}^{-1}$ - cofactor matrix of the adjusted parameters, $\mathbf{N}^{-1} = (\mathbf{H}^T \cdot \mathbf{P_1} \cdot \mathbf{H})^{-1}$,

Qx - standard deviation of coordinate X,

Qy - standard deviation of coordinate Y,

Qz - standard deviation of coordinate Z,

$Qdto$ - standard deviation of the receiver clock.

Adjustment processing is repeated for each measurement epoch according to the time interval in RINEX file. Unknown parameters $\Delta \boldsymbol{r}$, unit variance a posteriori δ_0^2 and mean errors (standard deviations) **Mx** are estimated for each epoch in each measurement session.

3 EXPERIMENTS AND RESULTS

In research tests, GPS observations are taken from WROC station in Wroclaw city in Lower Silesia in western Poland. WROC station is located on the roof of the Institute of Geodesy and Geoinformatics in Wroclaw University of Environmental and Life Sciences and the current station is equipped with receiver LEICA GR25 with antenna LEIAT504GG LEIS. The GNSS permanent station WROC is a part of the IGS service (more information at URL1), ASG-EUPOS system (URL2) and since 2014 it has been utilized in MGEX campaign as a first site in Poland (URL3). The new technical infrastructure of WROC site enables the tracking of signals from GNSS systems such as GPS, GLONASS, GALILEO, QZSS, BEIDOU and SBAS. In the case of GPS observations, receiver LEICA GR25 can collect C1, C2, P2, C5 for code measurements and L1, L2, L5 for phase measurements. The input data- RINEX file, broadcast message („*.NAV" file) and Precise Ephemeris file were downloaded from BKG server (URL4) and from CODE website (URL5) respectively. The RINEX data (with an interval of 30 seconds) includes observations for 4 sessions between 20:00:00 – 23:59:30 for the 6^{th} of January in 2015.

The main options in source code of application, which was written in Scilab 5.4.1 Editor, was configured, as below:

a) RINEX file type: RINEX 2.11;
b) source of ephemeris data: Precise Ephemeris;
c) method of satellite position determination: interpolation using 9-degree Lagrange polynomial;
d) Earth rotation correction: applied;
e) source of satellite clock data: Precise Ephemeris;
f) method of satellite clock determination: interpolation using 9-degree Lagrange polynomial;
g) ionosphere delay: Klobuchar model;
h) source of coefficients in Klobuchar model: navigation message (IONEX file not applied);
i) troposphere delay: Simple model;
j) instrumental biases: applied;
k) method of instrumental biases estimation: „Geometry Free" linear combination based on SciTEC Toolbox 1.0.0 software (Krasuski, 2014);
l) satellite/receiver phase center offset/variation: not applied;
m) multipath effect: not applied;
n) mathematical model of user's position determination: least square estimation in stochastic processing;
o) number of measurement sessions: s = 4;
p) number of measurement epochs in one session: 120;
q) processing mode: static;
r) basic observations: L2C code;
s) accuracy of L2C pseudorange: $c_x = 3 \cdot \gamma = 4.941$;
t) cut off elevation: 5^0;
u) reference frame: IGS08;
v) number of unknown parameters for a single measurement epoch: k = 4;
w) number of observations for a single measurement epoch: n > 4;
x) approximate coordinates of user's position: based on RINEX file;
y) output solution of coordinates: XYZ in geocentric frame;
z) receiver clock: estimated parameter.

3.1 Session 1

In the first experiment, mean errors (standard deviations) of unknown coordinates were estimated and compared in Figure 3. The average value for mean errors of Coordinate X amounts to 2.677 m, with maximum and minimum value between 4.591 m and 0.579 m, respectively.

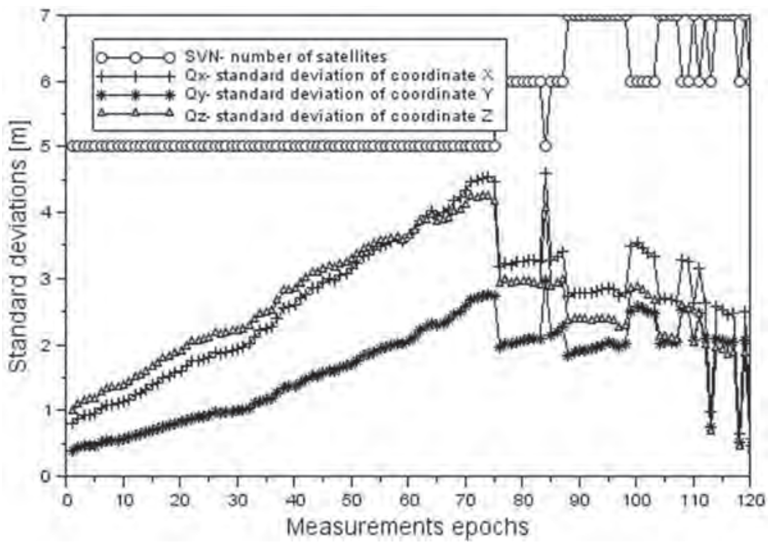

Figure 3: Standard deviations of receiver coordinates for session 1.

From epoch 1 to epoch 75, mean errors Qx are increased with a constant number of available satellites. From epoch 76 to epoch 120, mean errors of coordinate X are still decreased, but very irregularly. The major reason for this problem is the unstable number of GPS satellites (between 5 and 7) in the sky. Moreover mean errors Qx in the final epochs of session 1 are less than 1 m. A similar trend to Qx parameter can be seen for Qz component. The magnitude order of mean errors Qz is between 0.402 m and 4.238 m, with a mean value of about 2.578 m. Quotient Qz and Qx terms for all epochs is very close to 1 (exactly 0.991) with a standard deviation of 0.156. Mean errors Qz are increased between epochs 1÷75, and after that they fall down. In case of Qy parameter, mean errors of this component are the smallest with comparison to Qx and Qz terms. The average result of Qy term equals to 1.649 m with maximum and minimum value between 2.980 m and 0.396 m, adequately. Since epochs 1÷75, mean errors Qy increase between 0.396 m and 2.749 m. From epoch 76, mean errors of coordinate Y are decreased if SV number is still increasing. Sometimes, just like in epoch 84, the mean error of each geocentric coordinate can grow, if 5 satellites are visible in the sky. The relation between Qy and Qx components equals to 0.606 with a standard deviation of 0.102. In the case of a quotient between Qy and Qz terms, this value amounts to 0,645 with standard deviation 0.219.

3.2 Session 2

In the second test the accuracy of each coordinate is very stable over 120 measurements epochs, because SV number is rather constant (between 6 and 7). The average error of X coordinate equals 1.882 m with maximum and minimum result between 2.622m and 0.387m. If SV number amounts to 7, then mean errors Qx are decreased (see Figure 4). From epoch 48, mean errors Qx increase until epoch 120. The mean error for 70 epochs is less than 2 m, which corresponds with about 59% of all mean errors of X coordinate. In the case of Qy term, the mean value of accuracy amounts to 1.598 m and magnitude order between 0.322 m and 2.026 m. Component Qy has a small mean error with comparison to Qx and Qz parameters. The quotient between Qy and Qx terms is exactly 0.862 with a standard deviation of 0.061. The mean value of positioning accuracy of Z coordinate is about 1.841 m, with a tolerance level of between 0.267 m and 3.301 m.

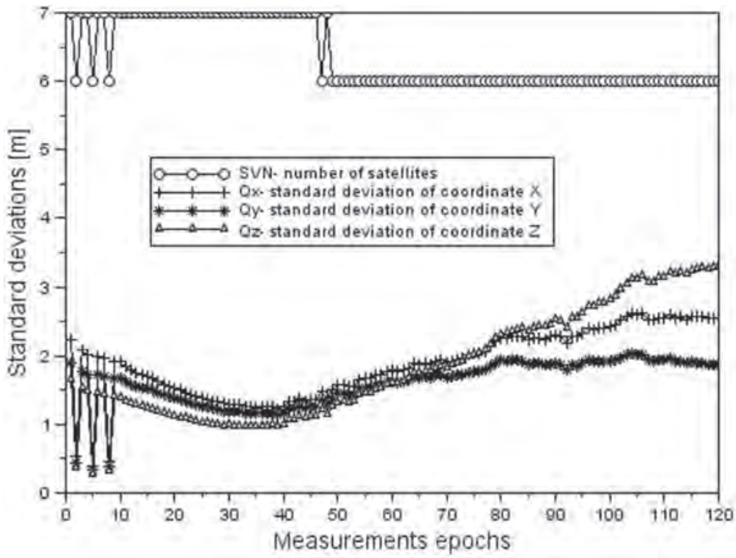

Figure 4: Standard deviations of receiver coordinates for session 2.

The minimum and maximum results of the mean error of each coordinate can be noticed for Z coordinate. The correlation between Qz and Qx is close to 0.937 with a standard deviation of 0.184 (similar results as in session 1). In the case of the relation between Qy and Qz terms, this coefficient equals to 0.965 with a standard deviation of 0.229. Similar quotients of mean errors of each coordinate in session 2 only underline that positioning accuracy is well and less than in session 1.

3.3 Session 3

In the third experiment positioning accuracy changes for the worse in comparison to the first and second tests (see Figure 5). Especially the number of GPS satellites (between 6 and 8) is not a constant which has a major influence on the accuracy of each coordinate.

The average value of mean errors Qx equals to 3.326 m, with an accuracy level of between 2.068 m and 6.152 m. In the case of Qy term, the mean result of accuracy amounts to 2.044 m, with a magnitude order of between 1.383 m and 3.671 m. The average value of mean errors Qz is about 3.513 m, with a tolerance level of between 2.719 m and 5.633 m. The correlation between Qy and Qx terms amounts to 0.623 with standard deviation 0.047 (similar to session 1). In the case of the relation between Qz and Qx parameters, this index is close to 1.111 with a standard deviation of 0.173. The quotient of Qy and Qz components is about 0.572 with a standard deviation of 0.050 (approximate result like in session 1). The general positioning accuracy of each coordinate in session 3 includes many anomalies, e. g. in the same points where SV number is various.

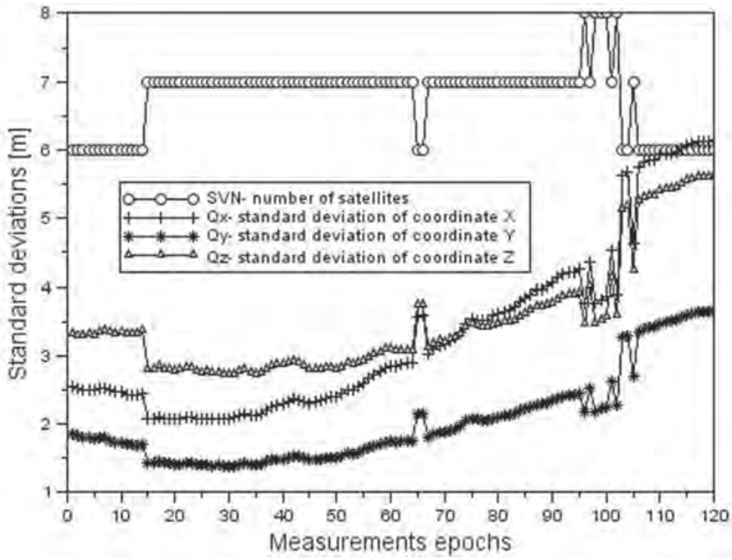

Figure 5: Standard deviations of receiver coordinates for session 3.

3.4 Session 4

The positioning accuracy of geocentric coordinates XYZ is presented in Figure 6. Mean errors of each coordinate are highest in session 4 in comparison to the rest of the experiments. In particular two coordinates (X and Z), have a low level of accuracy. The average value of Qx component is about 6.472 m, whereas the minimum and maximum results equal to 5.123 m and 6.889 m. In the primary phase of session 4 (between epochs 1÷47), mean errors of X coordinate are very variable and irregular, because the number of GPS satellites was unstable. From epoch 48, where the SV number amounts to 6, the characteristic of this error was quite constant (between 6.5 m and 7 m). Between epochs 1÷47, Z coordinate has the same trend as X coordinate. However, from epoch 48, the mean errors of Z term begin to increase to value 8.5 m. General accuracy Qz is between 4.729 m and 8.485 m in session 4, with average value equal to 6.789 m, respectively.

In contrast to X and Z coordinates, mean errors of Y coordinate have better accuracy. The mean result of accuracy amounts to 4.261 m, with a magnitude order of between 3.097 m and 4.611 m. After epoch 48, behaviour of mean errors Qy are more stable, as in the case of X and Z terms. The correlation between Qy and Qx terms amounts to 0.657 with a standard deviation of 0.028 (similar to sessions 1 and 3). The relation between Qz and Qx parameters is exactly 1.045 with a standard deviation of 0.102

and what is important, based on 4 sessions this index is very stable with a magnitude order of between 0.9 and 1.2. The quotient of Qy and Qz components is about 0.632 with a standard deviation of 0.038 (similar to sessions 1 and 3).

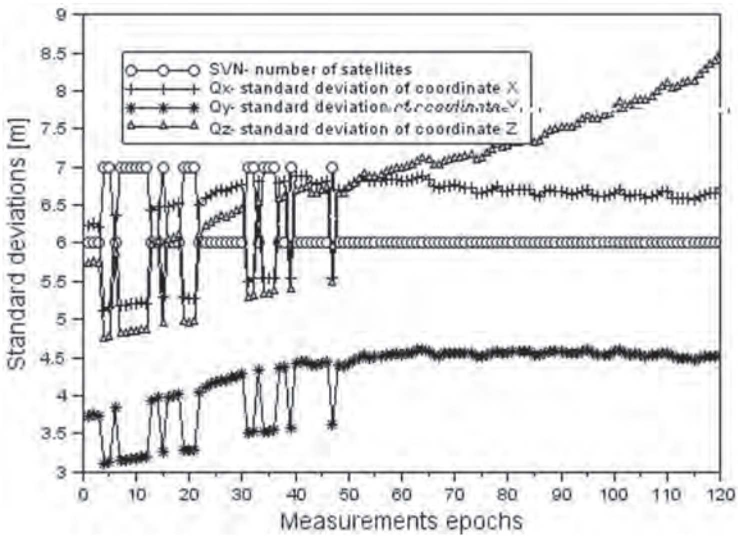

Figure 6: Standard deviations of receiver coordinates for session 4.

3.5 Standard deviation of the receiver clock

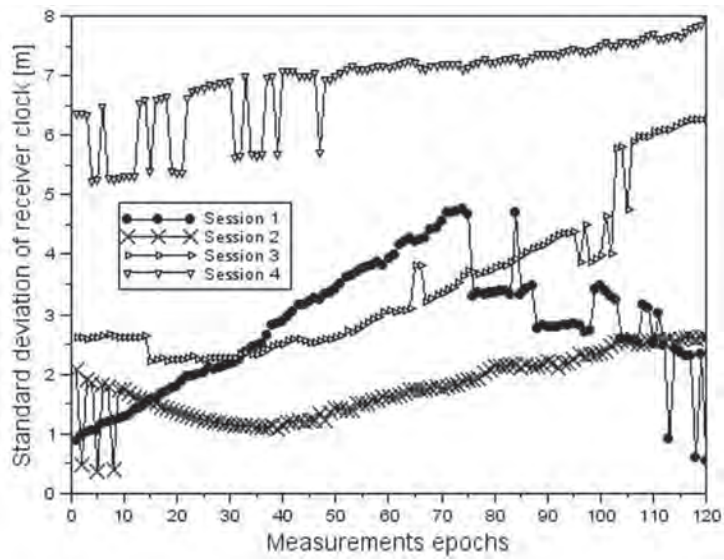

Figure 7: Standard deviation of receiver clock after 4 sessions.

Standard deviation Qdto of the receiver clock has a major significance in time transfer and the SPP method can reconstruct the receiver clock bias on the level 10^{-9} s. The accuracy results of the receiver clock for each session were presented in Figure 7. For session 1, the typical standard deviation of the receiver clock is about 2.799 m, with a tolerance level of between 0.529 m and 4.752 m, respectively. Mean errors of the receiver clock bias are very variable, because SV number is not a constant over the measurement period. In session 2, the standard deviation of the receiver clock is more stable with a magnitude order of between 0.350 m and 2.627 m. The average result of mean errors of the receiver clock is close to 1.766 m, which corresponds with value $5.894 \cdot 10^{-9}$ s in time transfer. The standard deviation Qdto of the receiver clock in session 3 has a growing trend between values 2.226 m and 6.277 m, whereas the average value of mean errors equals to 3.493 m. The worst results of receiver clock accuracy were in session 4. The mean result of receiver clock accuracy amounts to 6,929 m, with a magnitude order of between 5.230 m and 7.958 m. The conclusion of receiver clock accuracy is quite simple- if the number of GPS satellites is constant in session, then the characteristic of mean errors of the receiver clock is very regular without gross error and erroneous measurements.

4 CONCLUSIONS

In the submitted paper, possibilities of utilization L2C code in GPS positioning were presented. The L2C code is a new type of signal in the GPS system and currently it is transmitted by 15 satellites (e. g. SV1, SV3, SV5, SV6, SV7, SV9, SV12, SV15, SV17, SV24, SV25, SV27, SV29, SV30 and SV31). The structure and short characteristic of L2C code was described also. More users will prefer L2C code in standalone positioning and navigation for determining coordinates in geocentric or geodetic frame. A mathematical formulation based on the SPP method was applied in adjustment processing for stochastic approach. The SPP method was characterized in detail, together with systematic and geometric errors. Measurement models such as interpolation satellite position using Lagrange polynomial, Earth rotation effect, Sagnac effect, satellite clock bias, ionosphere delay, troposphere delay, satellite and receiver instrumental biases were presented with example results. Adjustment processing was carried out in iterative scheme for each measurement epoch in each session. The raw observations with L2C code were taken from WROC reference station in eastern Poland. Computations were executed in 4 sessions (between 20:00:00 – 23:59:30) with a time interval of 30 seconds. In the first test, positioning accuracy was less than 4.3 m for each coordinate, but mean errors of Y parameters was the smallest, about 0.6 time with comparison to the rest of the coordinates. In the second experiment the number of GPS satellites was constant (between 6 and 7), which had major significance in that the accuracy of each coordinate was very stable and less than 3.3 m. Achieved positioning accuracies were very irregular and included few anomalies in session 3, because the SV number was still various. Mean errors for each coordinate were increased for all sessions, which is not optimistic for standalone positioning and navigation. Besides, the accuracy of coordinates in session 4 can reach up to 8.5 m (in case of Z term), which is a very large value in GPS positioning at night, whereas the influence of ionosphere delay decreases. From the other side, after 4 sessions the positioning accuracy for each coordinate is less than 10 m. More tests are needed to better understand how L2C code has an impact on the position estimation. The accuracy of the receiver clock must be monitored also within the limits of precise time transfer. Based on 4 experiments, the standard deviation of the receiver clock was less than 8 m, which equals about $2.7 \cdot 10^{-8}$ s.

References:

Abdel-Salam, M. (2005). Precise Point Positioning using un-differenced code and carrier phase observations. Dissertation thesis. Calgary: University of Calgary.

Bidikar, B., Rao, G. S., Ganesh, L., Kumar MNVS S. (2014). Satellite clock error and orbital solution error estimation for precise navigation applications. Positioning, 5, 22–26. DOI: http://dx.doi.org/10.4236/pos.2014.51003

Bosy, J. (2005). Precise processing of satellite GPS observations in local networks located in mountain areas. Wydawnictwo Akademii Rolniczej we Wrocławiu, 522, 155 p.

Bosy, J., Borkowski, A. (2006). Troposphere modelling in local GPS network. EUREF Publication No. 15, Mitteilungen des Bundesamtes für Kartographie und Geodäsie, 38, pp. 356–362.

Cai, C. (2009). Precise Point Positioning using dual-frequency GPS and GLONASS measurements. Dissertation thesis. Calgary: University of Calgary.

Dach, D., Hugentobler, U., Fridez, P., Meindl, M. (2007). Bernese GPS Software Version 5.0. Bern: University of Bern.

de Jonge, P. J. (1998). A processing strategy for the application of the GPS in networks. Publications on Geodesy 46, Delft.

Fontana, R. D., Cheung, W., Novak, P. M., Stansell Jr., T. A. (2009). The New L2 Civil Signal.

Gao, Y. (2008). GNSS biases, their effect and calibration. IGS Workshop 2008, Florida.

Grewal, M. S., Weill, L. R., Andrews A. P. (2000). Global Positioning Systems, Inertial Navigation, and Integration. New York: John Wiley & Sons, Inc. Publication. DOI: http://dx.doi.org/10.1002/0471200719

Hilla, S. (2010). The Extended Standard Product 3 Orbit Format (SP3-c). National Geodetic Survey, Silver Spring, MD 20910-6233, USA. https://igscb.jpl.nasa.gov/igscb/data/format/sp3c.txt, accessed: 15. 2. 2015.

Hofmann-Wellenhof, B., Lichtenegger, H., Wasle, E. (2008). GNSS – Global Navigation Satellite Systems: GPS, GLONASS, Galileo, and more. Wien & New York: Springer.

Hong, C. K. (2007). Efficient Differential Code Bias and ionosphere modeling and their impact on the network-based GPS positioning. Dissertation thesis. The Ohio State University.

Iswariya, B. R., Kumar H. N. (2013). FFT based acquisition techniques of GPS L2C signals. Ictact Journal on Communication Technology, 4(4).

Kaplan, E. D., Hegarty, C. J. (2006). Understanding GPS: Principles and Applications, 2nd edition. Norwood: Artech House, Inc.

Klobuchar, J. A. (1987). Ionospheric time-delay algorithm for single-frequency GPS users. IEEE Transactions on Aerospace and Electronic Systems, AES-23(3), 325–331. DOI: http://dx.doi.org/10.1109/taes.1987.310829

Krasuski, K. (2014). Estimation instrumental biases IFB based on GLONASS observations. Geodesy Review, 12/2014.

Kwon, K. C., Shim D. S. (2011). Rapid acquisition of CM and CL code for GPS L2C software receivers. Journal of Electrical Engineering & Technology, 6(5), 723–730, DOI: http://dx.doi.org/10.5370/JEET.2011.6.5.723

Leandro, R. F., Thirumurthi, T., Sükeová, L., Langley, R. B., Santos M. C. (2008). Analysis of GPS L2C signal quality and its impact on PPP performance. ION NTM 2008, San Diego, CA, 28-30 January 2008.

Lin, L. S. (2001). Remote Sensing of ionosphere using GPS measurements. 22nd Asian Conference on Remote Sensing, 5-9 November, Singapure.

Petrovski, I. G. (2014). GPS, GLONASS, Galileo, and BeiDou for Mobile Devices. New York: Cambridge University Press. DOI: http://dx.doi.org/10.1017/cbo9781139565455

Sanz Subirana, J., Juan Zornoza J. M., Hernández-Pajares, M. (2013). GNSS Data Processing, Volume I: Fundamentals and Algorithms. ESA Communications. Noordwijk: ESTEC.

Schaer, S. (1999). Mapping and predicting the Earth's ionosphere using Global Positioning System. Dissertation thesis. Neunundfünfzigster Band volume 59. Zürich.

Schüler, T. (2001). On ground-based GPS tropospheric delay estimation. Dissertation thesis. Heft 73. München: Universität der Bundeswehr München.

Seeber, G. (2003). Satellite Geodesy. 2nd completely revised and extended edition. Berlin: Walter de Gruyter GmbH & Co. KG. DOI: http://dx.doi.org/10.1515/9783110200089

Spits, J. (2011). Total Electron Content reconstruction using triple frequency GNSS signals. Dissertation thesis. Liège: Universitè de Liège.

Wang, D. (2010). Performance evaluation of GPS L1/L2 positioning with partial availability of the L2C signals. Master thesis. Calgary: University of Calgary.

Witchayangkoon, B. (2000). Elements of GPS Precise Point Positioning. Dissertation thesis. The University of Maine.

Xu, G. (2007). GPS Theory, Algorithms and Applications, 2nd edition. Berlin & Heidelberg & Postdam: Springer-Verlag.

Yao, D. (2007). Interference effects on GPS L2C signal acquisition and tracking. Master thesis. Calgary: University of Calgary.

Zhang, J. (2007). Precise velocity and acceleration determination using a standalone GPS receiver in real time. Dissertation thesis. Melbourne: Royal Melbourne Institute of Technology.

Zheng, Y. (2006). Generation of network-based differential correction for Regional GNSS Services. Dissertation thesis. Queensland University of Technology.

URL1: http://igscb.jpl.nasa.gov/network/site/wroc.html.

URL2: http://www.asgeupos.pl.

URL3: http://igs.org/mgex.

URL4: http://igs.bkg.bund.de/file/rinexsearch.

URL5: ftp://ftp.unibe.ch/aiub/CODE/2015.

URL6: http://igs.org/about/analysis-centers.

Krasuski K., Wierzbicki D. (2015). Utilization L2C code for determination of user's position. Geodetski vestnik, 59 (4): 789-808.
DOI: 10.15292/geodetski-vestnik.2015.04.789-808

Kamil Krasuski, M.Sc.
Team of Satellite Techniques
Zawiszy Czarnego 16, 08-530 Dęblin
Poland
e-mail: kk_deblin@wp.pl

Damian Wierzbicki, Ph.D.
Military University of Technology
Department of Geodesy and Civil Engineering
Sylwestra Kaliskiego 2, 00-908 Warszawa, Poland
e-mail: dwierzbicki@wat.edu.pl