DOI: 10.63550/ICEIP.2025.56.51.095

Application of the Ionospheric Electron Density Calculation Method for the Two-Frequency Method To Detecting Phase Cycles Losses in Radio Navigation

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Keywords: Cycle slip, global positioning system, total electron content, ionosphere, GNSS.

Abstract: A study of the method for determining the total electron content (TEC) in the ionosphere using GPS signals using dual-frequency measurements was conducted for its application in the correction of phase cycle loss (slips). An algorithm for calculating and visualizing the vertical electron concentration in the ionosphere (VTEC) was developed taking into account the correction of phase ambiguity due to slips and the assessment of differential code shifts (DCB). The created software algorithm includes TEC tools based on GPS satellite signals, slip elimination tools, differential code shift calculation tools, vertical VTEC and slant STEC calculation tools of the electron concentration in the ionosphere.

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1 INTRODUCTION

In this paper we continued the topic of research on detection of slips in navigation measurements with a dual-frequency receiver (Tryapitsyn, Dubinko, Fradkin, Parshin, 2025). We also continued the topic of research on algorithms for calculating ionospheric delays (Tryapitsyn, Dubinko, Fradkin, 2023). The total electron density (TEC) in the ionosphere can be easily estimated from a combination of dual-frequency GNSS measurements. However, TEC data obtained from GPS measurements have an uncertainty because the GPS signals have a hardware bias that affects the accuracy of ionospheric TEC estimates.

Hardware biases in GPS signals are caused by transmitters located on satellites and receivers of ground users. TEC can be calculated using the so-called linear combination of two frequencies L_1 and L_2. Differences in hardware biases of GPS code measurements are called differential code biases (DCB) of the receiver, they can be up to several tens of nanoseconds. In this paper, an algorithm was implemented to detect and correct phase losses of phase measurement cycles (slips) in global satellite radio measurement data. We will perform data slip correction using the ionospheric electron concentration (TEC) for the GPS receiver without using differential corrections.

2 MATERIAL AND METHOD

Find the following TEC values, which we need further for slip calculations. From pseudorange measurements, we calculate and designate the slant TEC – STECp. From phase measurements, we calculate and designate STECl.

$STECp_{time,PRN} = k*(P_2-P_1)$

Where:
k is the proportionality coefficient;
time is the moment of measurement;
PRN is the satellite number;

In the same way, we find the pseudorange by phase:

$STECl_{time,PRN} = k*(L_1-L_2)$

Let's take and apply elevation angle cutoff <15˚. That is, we will create a mask for all satellites, if angle cutoff <15˚, then we set 0 in the mask, and if angle cutoff >= 15˚, then one. Next, we multiply all parameters by the satellite mask. This excludes satellites and their parameters with small elevation angles from further calculations.

$STECp = mask*STECp$
$STECl = mask * STECl$

Next, we calculate phase slips using arrays of STEC values for satellites. We obtain the result as an array of all TEC values for a given measurement time interval for all satellites participating in the observations. In this algorithm, we will adjust the electron concentration values taking into account measurement gaps (slips). Next, we create an STEC array and find the DifTres threshold value as an array of differences between adjacent TEC values:

$DiTtres = \{STEC_i - STEC_{i-1}\}$

Next, we calculate an array of values of the differences between the measurements:

$dif\_time = \{T_i - T_{i-1}\}$

Next we find the very first time interval without measurements greater than our threshold and return its index:

$time\_gap\_idx = i, A_i \in \{dif\_time >= tres\_time\}$

where:
tres_time is the time to skip measurements;

Next, we collect and assign the indices of the STEC values to the slip array:

$slip\_idx1 = i, A_i \in \{|STEC| >= 0\}$

We find the very first difference in measurements that is greater than our threshold in absolute value:

$difSTEC_i = |STEC_i - STEC_{i-1}|$

Collect indices of values of the set difSTEC greater than DifTres:

$SlipIdx2 = i, A_i \in \{|difSTEC| >= TECdif\}$

Here we take the current STEC sequence, increasing it towards higher dimensions at each step:

$TECpart1 = STEC\{1:SlipIdx2_{ii}\}$

At each step we take the indices of adjacent slips, forming from them an array of two elements.

$TECpart2 = STEC\{SlipIdx2_{ii} + \{1:SlipIdx2_{ii+1}\}\}$

Bring the time to the initial start of the measurement:

$TECpart_{sm} = \{TECpart1 - \{TECpart1_{end} - TECpart2_1\}\}$

Fill in the set:

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STEC{1:SlipIdx2$_{ii+1}$} = {TEC_part : TECpart2}

Calculate the array of values of the differences between STEC measurements and take these values by module:

dif_STEC_g$_i$ = |difSTEC$_i$|

Next we find the very first difference in STEC measurements that is greater than our DifTres threshold and return its index:

SlipIdx2_g = i,A$_i$Є {|difSTEC_g| >= TECtres}

Here we take the current STEC sequence, increasing it towards higher dimensions at each step:

TECpart$_1$ = {STECg$_k$,...,STECg$_k$ }, 1 <k<= slip2g$_{ii}$

At each step we take the indices of adjacent slips, forming from them an array of two elements.

TECpart$_2$= {STECg$_k$,..., STECg$_k$ }, 1 < k <= slip2g$_{ii}$

In this paper, the method discussed in (Liu, Gao, Skone, 2005) was used to smooth TECp.The smoothed differences for successive measurements,$\delta(TECk)_{sm}$, were calculated using a recursive formula:

$$\delta(TEC_k)_{sm} = \frac{\{(k+1)\delta(TEC_{k-1})_{sm}\} + \{(TEC_p)_k - (TEC_L)_k\}}{k}$$

where:

k — the epoch number at any given point in time;

$\delta(TECk)_{sm}$- this is the smoothed offset, which is then added to TEC_L to produce a smoothed or equalized TEC at each epoch;

Based on the formula, we will build our own, where we will calculate for the total TEC set. In this way, we will reduce the amount of calculations by 4 times.

Here, we subtract the maximum relative excess of STEC on the interval under consideration from the array of boundary indices, i.e., we thus scale the STEC values.

TECpart$_{sm}$= {TECpart1 – {TECpart1$_{end}$-TECpart2$_1$}}

Next, we combine the resulting STEC array with the TECpart2 array. This gives us a value for adjusting the STEC values in the next step.

STEC_g{1:SlipIdx2$_{ii+1}$} = {TECpart : TECpart$_2$}

$$STEC_{adj} = STEC_L + \overline{STEC_P + STEC_L}$$

Ionospheric-free combinations of measurements can be formed from measurements at the initial frequencies. In the literature, it is customary to call the differences in systematic signal delays at one frequency C1C–C1P, C2C–C2P — intersignal differential code offsets (DCB), and the differences at two frequencies C1P–C2P, C1C–C2C — interfrequency differential code offsets (DCB). They include systematic signal delays in the onboard equipment of the satellite and the user equipment (Sharma, Dashora, Galav, Pandey, 2024).

$$\mathrm{D}CB = B_{P1} - B_{P2} = (b_{GS,P1} + b_{P1}^{SC}) - (b_{GS,P2} + b_{P2}^{SC})$$

$B_{P1} = b_{GS,P1} + b_{P1}^{SC}$ - systematic signal delay for coded pseudorange measurements C1P; $b_{GS,P1}$ - systematic signal delay in the receiver equipment for code measurements of pseudorange C1P, which also depends on the satellite;

b_{P1}^{SC} - systematic signal delay in on-board equipment for code measurements of pseudorange P_1;

$$\mathrm{TEC}_{\mathrm{bias\_sat}} = \mathrm{D}CB * \frac{1}{40.3*10^{16}} \frac{f_1^2 * f_2^2}{f_2^2 - f_1^2}$$

where:

f_1, f_2—carrier frequencies of the navigation signal of onboard equipment in the L_1 and L_2 ranges, taking into account the letter dependence.

We read the code offsets DCB from the files for all satellites. In general, the delays P_1, P_2 are individual for each pair of user equipment - satellite equipment and types of measurements in the ionosphere-free combination.

$$\mathrm{STEC_{nobias}} = \mathrm{TEC_{bias}} - \mathrm{DCB_{P_1P_2}}$$

$$SlantFactor = \sqrt{1 - \left(\mathrm{Re} * \frac{\cos(elev)}{\mathrm{Re} + h}\right)^2}$$

$d_{ion} = \dfrac{40.3}{f^2} STEC$— ionospheric delay;

where f stands the frequency of the carrier, and STEC stands for the slant total electron content.

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Find the inclined electron concentration:

$STEC = TEC_{bias} - DCB$

Next we find the vertical electron concentration:

$VTEC = STEC*SlantFactor$

We will use the zero TEC setting (minimum TEC is zero) as an additive to the base TEC value to obtain the resulting VTEC value.

$STEC = STEC_{compl} + tec_{min}$;

Next we plot the ionospheric delay over time for all satellites.

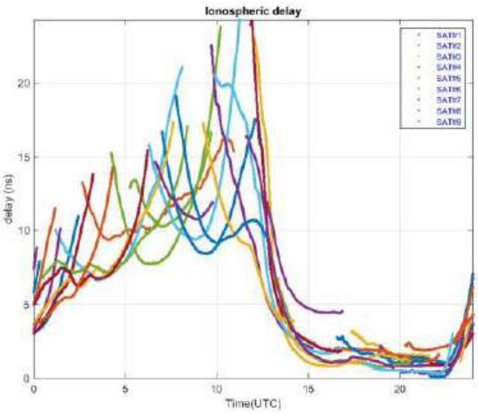

Figure 1: Ionospheric delay values with correction of differential code biases.

We take the tropospheric delay model using the GKAT (Rideout, Coster, 2006) method. We list the parameters used:

Lat- Latitude of a receiver on the earth;
Long - Longitude of a receiver on the earth;

DOY - day of year;
H = Height; Altitude of a receiver on the earth
k_1 = 77.604 - K/mbar
k_2 = 382000 - K^2/mbar
R_d = 287.054 - J/(kg.K)
g_m = 9.784 - m/s^2
g = 9.80665 - m/s^2

P_0– Pressure;
T_0 = 299.65- Temperature;
e_0 = 26.31- Water vapor pressure;
B_0 = 6.30e-3 - Temperature lapse rate;
Lam_0 = 2.77 –Water vapor;

For calculations at a given point on the earth's surface, we need to calculate all the parameters of the algorithm for the given coordinates. We do this using the interpolation formula:

We interpolate each parameter:

$$X = X_{\min} + \left(X_{\max} - X_{\min}\right) * \frac{Lat - Lat_{\min}}{Lat_{\max} - Lat_{\min}}$$

where:

Lat_{min} ,Lat_{max}–minimum and maximum latitude of the point being defined;

X_{min} ,X_{max}–minimum and maximum value of the parameter;

X –interpolated value of the parameter for a given latitude;

Bring the values P_0, T_0, e_0, B_0, Lam_0 to a given geographic location point using the interpolation function described above. We will also transform the parameters using it:

dP, dT, de, dB, dLam, which will mean the offset step for all values in a given area.

$$Y = Y_0 - \mathrm{dY} * \cos\left(2 * \pi * \frac{\mathrm{DOY} - \mathrm{D_{min}}}{365.25}\right)$$

WhereY – one of the substituted values:

P ,T, e, B, Lam.

Let's write formulas for the algorithm for calculating the delay:

Zenith wet delay:

$$Zhyd = \frac{k_1 * R_d * P}{g_m}$$

Zenith dry delay:

$$Zwet = \frac{k_2 * R_d}{g_m * (Lam+1) - B_0 * R_d} * \frac{e}{T}$$

Slant wet delay:

$$dhyd = \left(1 - \left(B * \frac{H}{T}\right)\right)^{\frac{g}{R_d * B}} * Zhyd$$

Slant dry delay:

$$dwet = \left(1 - \left(B * \frac{H}{T}\right)\right)^{\frac{(Lam+1)*g}{R_d * B} - 1} * Zwet$$

Next we find the total tropospheric delay using the formula:

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$$dtropo = (dhyd + dwet) * \frac{1}{\sqrt{0.002001 + \sin^2(elev)}}$$

Next we find the ionospheric delay using the Klobuchar method. In the calculations we will use the following parameters:

φ - latitude of receiver position;
λ - longitude of receiverposition;
elev- elevation angle;
tow - time of week;
dIon -Ionospheric delay;

Find Earth Centered angle:

$$\psi = \frac{0.0137}{elev + 0.11} - 0.022$$

Find Subionospheric lat:

$$lat_i = \varphi + \psi * \cos(a)$$

Find Subionospheric long:

$$long_i = \lambda + \psi * \frac{\sin(a)}{\cos(lat_i)}$$

Find Geomagnetic latitude:

$$latm_i = lat_i + 0.064 * \cos(long_i - 1.617)$$

Find Seconds of day:

$t = 4.32e4*long_i + tow$

Find Slant factor:

$sF = 1 + 16 * 0.053^3;$

Find Period of model:

$PER = \beta_1 + \beta_2*lat\_m + \beta_3*lat\_m^2 + \beta_4*lat\_m^3$

x = 2*π*(t-50400)/PER

Find amplitude of the model:

$AMP = \alpha_1 + \alpha_2 * lat\_m + \alpha_3*lat\_m^2 + \alpha_4*lat\_m^3$

Ionospheric correction:

$dIon = sF * (5e\text{-}9 + AMP*(1 - x^2/2 + x^4/24))$

Using the total tropospheric and ionospheric delays, we construct graphs of the total delay for all satellites.

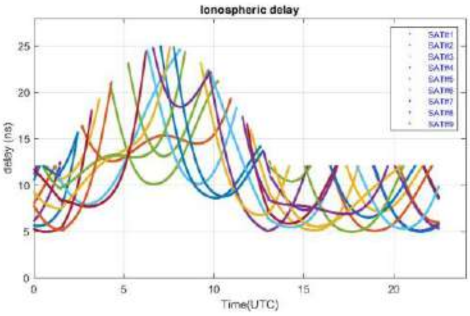

Figure 2: Ionospheric delay values with standard correction.

3 RESULTS

Thus, we have obtained a comparison of two methods for calculating TEC in radio navigation measurements - using the standard method for calculating delays in the atmosphere by the Klobuchar method and the two-frequency method. The SDCM method was used to compensate for the tropospheric delay. We cleaned up the data from slips using the two-frequency TEC method. Comparison of the graphs of ionospheric delays of different methods from time for different satellites showed that the deviation of the values of the calculated ionospheric delays for all available satellites does not exceed 5%. This suggests that the two-frequency method for finding slips using the averaging and alignment algorithm allows calculating slips quite accurately. Its advantages over other methods for detecting slips are that it is not sensitive to single errors in the process of data accumulation with a sufficiently large sample. These algorithms were tested in the equipment for radio navigation measurements of the “Farwater” company and showed their reliability and accuracy of operation comparable to the theoretical part.

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