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Assessing the Effectiveness of Using Existing Ionospheric Models to Correct Ionospheric Delay

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Abstract: The article discusses methods of existing ionospheric models for correcting ionospheric delay. The results of calculating the ionospheric delay of these models using real navigation measurement data were compared. An assessment of their accuracy and application criteria are given.

1 INTRODUCTION

In this work, calculations of ionospheric corrections were made using various methods. We compare the accuracy and reliability of obtaining ionospheric corrections using four methods:

1). Klobuchar'sglobal ionosphere model

2). Global TEC Mapping Method from Ionex Files.

3). Method using high-precision PPP data.

4). Spherical Harmonics method.

To work as a source of navigation measurements, we take the "observation" file in the Rinex format, compiled from real measurements of the "Helios" navigation receiver. The duration of measurements of this file is 7200 s.

Parameters used for calculation:

El is the satellite elevation angle;

Az is the azimuth of the satellite;

φu is the consumer latitude;

λu is the longitude of the consumer;

t is the local time;

φm is the geomagnetic latitude of the sub-ionospheric point;

Ψ is the central angle between the position of the GNSS receiver and the projection of the ionospheric point onto the Earth's surface (sub-ionospheric point);

Ttr is the Time of observation, (sec of week)

leap_sec is the number of seconds between GPS time and UTC;

UT is the Coordinated Universal Time;

h_SL = 450 is the height of ionosphericlayer, km;

RE is the radius of earth, (km/ 1000);

2 GLOBAL TEC MAPS FROM IONEX FILES

Let us take for analysis and comparison the algorithm based on Ionex files. Let us describe the process of calculating ionospheric corrections through the function of the approximation model. The input parameters for it are:

-The selected point for which the TEC value needs to be estimated is not the location of the receiver, but the location of the sub-ionospheric point. The sub-ionospheric point is the projection of the point of intersection of the satellite signal with the ionospheric layer on the Earth's surface.

-Geocentric spherical coordinates of a sub-ionospheric point can be calculated from the coordinates of the receiver and the azimuth and zenith angles of the satellite (a, z).

The relationship between the vertical and oblique delays of the signal in the ionosphere is determined through the value of the oblique ray function – mf. As a rule, it is taken mf = 1/cos(zi);

Finding the zenith angle, converting from degrees to radians:

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$$z = \frac{(90 - el) * \pi}{180} \quad (1)$$

Zenith angle at pierce point (IPP) in radians:

$$z_i = a\sin\left(\frac{RE * \sin(z)}{RE + H}\right) \quad (2)$$

Where:

H-height of the ionospheric layer, m;

RE – radius of the earth;

We find the value of electron concentration VTEC from the following algorithm for applying the global GIM model. We will interpolate VTEC from the (global) ionospheric map (IONEX format). IONEX maps are given in UTC time, but interpolation is based on GPS time (leapsec time is not taken into account). The result of the calculations will be VTEC is the total interpolated vertical electron concentration. Find the indices of the pierce points on the TEC map. We get the global model map from Ionex:

gim = ionex_map(0,time_index)

TEC distribution maps constructed at JPL (Jet Propulsion Laboratory) and other information can be obtained on the Internet at http://iono.ipl.nasa.gov. Select the time index number from the Ionex file, converting from daily time to GIM interval:

$$time\_index = \frac{Ttr - ionex\_start}{ionex\_Interval + 1} \quad (3)$$

We take data from an ionex file, in which all records of electron concentration are organized in the form of a structure by measurement time and coordinates, and apply interpolation using the BivariateInterpolation method. If the pierce point is outside the GIM map, take the value at the edge of the GIM:

$$\varphi_{ipp} = \varphi_{ionex\max}, \varphi_{ipp} > \varphi_{ionex\max}$$

$$\varphi_{ipp} = \varphi_{ionex\min}, \varphi_{ipp} < \varphi_{ionex\min}$$

$$\lambda_{ipp} = \lambda_{ionex\max}, \lambda_{ipp} > \lambda_{ionex\max}$$

$$\lambda_{ipp} = \lambda_{ionex\min}, \lambda_{ipp} < \lambda_{ionex\min}$$

Where:

φipp - latitude of the ionospheric pierce point, (°)

λipp - longitude of the ionospheric puncture point, (°)

The GIM boundary area itself, consisting of four adjacent values, looks like this:

$$\begin{bmatrix} \text{upper - left} & \text{upper - right} \\ \text{lower - left} & \text{lower - right} \end{bmatrix}$$

$$tecs = \begin{bmatrix} E_{0,0} E_{0,1} \\ E_{1,0} E_{1,1} \end{bmatrix}$$

Calculating auxiliary coordinate indices on the GIM map to find weight coefficients.

Longitude:

$$I_\lambda = \frac{\lambda_{ipp} - \lambda_{ionex}(0)}{\lambda_{ionex}(2)} + 1 \quad (4)$$

Latitude:

$$I_\varphi = \frac{\varphi_{ipp} - \varphi_{ionex}(0)}{\varphi_{ionex}(2)} + 1 \quad (5)$$

Let's take the initial coordinate values from the Ionex file to use them to find the reference coefficients p and q in the algorithm.

$$Lats = \{\varphi_{ionex}(0), \varphi_{ionex}(1), \varphi_{ionex}(2)\} \quad (6)$$

$$\varphi_p = Lats(I_\varphi)$$

$$Lons = \{\lambda_{ionex}(0), \lambda_{ionex}(1), \lambda_{ionex}(2)\}$$

$$\lambda_p = Lons(I_\lambda)$$

Interpolation of the tecs array used for further calculations is constructed in this way. Get the 4 TEC-values to interpolate:

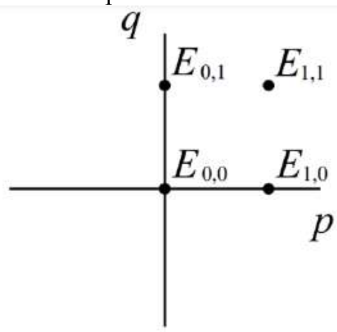

Figure 1: Bivariate interpolation using nearest 4 TEC values Eij.

weight for latitude:

$$q = (\varphi_{ipp} - \varphi_p) / abs(\varphi_{ionex}(2)) \quad (7)$$

weight for longitude:

$$p = (\lambda_{ipp} - \lambda_p) / abs(\lambda_{ionex}(2)) \quad (8)$$

The value of the estimate of the integral electron concentration in the vertical column of the ionosphere for specific coordinates is calculated from four points using the interpolation formula: (9)

$$tec = (1-p)*(1-q)*tecs(1,0) + p*(1-q)*tecs(1,1) + q*(1-p)*tecs(0,0) + p*q*tecs(0,1) \quad (9)$$

Ionospheric correction in meters:

$$iono(1) = \frac{mf * 40.3^{16}}{f_1^2} * vtec \quad (10)$$

$$iono(2) = \frac{mf * 40.3^{16}}{f_2^2} * vtec$$

3 KLOBUCHAR'S GLOBAL IONOSPHERE MODEL

Calculating the ionospheric correction using the Klobuchar model method.

Parameters transmitted in the GPS navigation message:

an are the coefficients of the cubic polynomial representing the amplitude of the vertical signal delay in the ionosphere;

bn are the coefficients of a cubic polynomial representing the period of the model;

n = 0,1,2,3. The coefficients of the polynomials an, bn are transmitted in the navigation message of the GPS system and are updated at least every 6 days.

The initial data for calculating ionospheric corrections based on the GPS ionospheric model are:

φu, λu are the approximate values of GNSS receiver coordinates;

Converting latitude and longitude from degrees to half-cycles:

$$\varphi_u = \varphi_u / 180$$

$$\lambda_u = \lambda_u / 180$$

$$Az = Az / 180$$

$$El = El / 180$$

Global model of the GPS ionosphere, developed by J. A. Klobuchar in 1975-81, on the basis of which a single-frequency GPS user can carry out ionospheric correction. The use of the GPS ionospheric model to eliminate ionospheric errors in single-frequency GNSS receiver is recommended by the GPS Interface Control Documents. The parameters of the GPS ionosphere model are transmitted in the GPS navigation message.

The GPS ionosphere model describes the global distribution of the vertical ionospheric delay in the coordinate system “local time - geomagnetic latitude” in the form of a constant throughout the day and across all latitudes of a “stand” equal to 5 ns, on which the daytime component is superimposed in the form of a cosine half-wave.

$$diono = \begin{cases} F * 5 * 10^{-9} * C_{light}, abs(x) > \pi/2 \\ F * \left(5 * 10^{-9} + amp\left(1 - \frac{x^2}{2} + \frac{x^4}{24}\right)\right) * C_{light}, abs(x) <= \pi/2 \end{cases} \quad (11)$$

Where:

Clight is the speed of light;

Ionospheric delay by first frequency, m:

$$iono(1) = diono$$

Next, the ionospheric correction is converted from L1 to L2:

$$iono(2) = iono(1) * \left(\frac{f_1^2}{f_2^2} \right) \tag{12}$$

The dependences of amplitude and period on geomagnetic latitude are specified by polynomials of the third degree, and the maximum is fixed at a local time equal to 14 hours (50400 s) for all latitudes.

Amplitude of the model:

$$amp = \begin{cases} a_0 + a_1 * \varphi_m + a_2 * \varphi_m{}^2 + a_3 * \varphi_m{}^3, amp >= 0 \\ 0, amp < 0 \end{cases} \tag{13}$$

Phase of the model (Maximum at 14.00 = 50400 sec local time):

$$x = 2 * \pi * (T - 50400) / per \tag{14}$$

Period of model:

$$per = \begin{cases} b_0 + b_1 * \varphi_m + b_2 * \varphi_m{}^2 + b_3 * \varphi_m{}^3, per >= 7200 \\ 0, amp < 0, per < 7200 \end{cases} \tag{15}$$

Slant Factor:

$$F = 1 + 16 * (0.53 - El)^3 \tag{16}$$

Subionospheric longitude:

$$\lambda_i = \lambda_u + \frac{\psi * \sin(Az * \pi)}{\cos(\varphi_i * \pi)} \tag{17}$$

Geomagnetic latitude of the ionosphere:

$$\varphi_m = \varphi_i + 0.064 * \cos((Loni - 1.617) * \pi) \tag{18}$$

Subionospheric latitude:

$$\phi_i = \begin{cases} \phi_i = \phi_u + \psi * \cos(Az * \pi) \ , |\phi_i| <= 0.416 \\ 0.416, |\phi_i| > 0.416 \\ -0.416, |\phi_i| < -0.416 \end{cases} \tag{19}$$

Where:

λi is the sub-ionospheric point longitude;

φi is the sub-ionospheric point latitude;

Earth-centered angle:

$$\psi = \frac{0.0137}{El + 0.11} - 0.022 \tag{20}$$

Seconds of day:

$$Ttr = \mathrm{mod}(Ttr, 86400) \tag{21}$$

Local time at subionosphericpoint,s:

$$T = 43200 * \lambda_i + Ttr \tag{22}$$

4 SPHERICAL HARMONICS METHOD

The construction of global ionospheric maps (GIM) is similar to the calculation of local ionospheric maps from measurements of one measuring station, but a globally distributed network of stations is used for calculations. Single-layer ionospheric models are based on the assumption that all free electrons in the ionosphere are located in an infinitely thin layer at a certain height above the Earth's surface. The slant STEC is determined by multiplying the vertical TEC by the mapping function mf(E), which depends on the elevation angle E, the height of the ionospheric layer (h = 450 km) and the Earth's radius RE.

Using the least squares method, the ionospheric delays for all satellites are simultaneously clarified, as well as the distribution of vertical VTEC in the ionosphere in the form of expansion into spherical harmonics depending on latitude and solar-fixed longitude: Calculating the electron concentration in the oblique beam STEC.

Converting from degrees to radiant:

$$el = el / 180 * \pi$$

$$az = az / 180 * \pi$$

Finding the upper and lower time index of the TEC cards, Ttr is between the card (tlow) and the card (thigh). Fraction of time difference with last TEC card in range [0,1].

Latitude of Geomagnetic Pole:

$$\varphi_{gmp} = ion\varphi_{gmp_{low}} / 180 * \pi$$

Longitude of Geomagnetic Pole:

$$\lambda_{gmp} = ion\lambda_{gmp_{low}} / 180 * \pi$$

Where:

φGMP is the latitude of geomagnetic pole, (°);

λGMP is the longitude of geomagnetic pole, (°);

ion is the structure of ionospheric parameters;

The maximum degree of coefficients in the Taylor expansion of the TEC of the ionosphere:

$$n = ionDegree(t_{low}..t_{\max})$$

$$m = ionOrder(t_{low}..t_{\max})$$

To calculate the auxiliary decomposition coefficients, we take the parameters of the local ionospheric model for our region of the area, obtained from the International GPS Service (IGS):

cosTEC is anm coefficients for cosine-term;

sinTEC is bnm coefficients for sine-term;

When determining coefficients for successive moments of time, a connection condition can be added, for example, a piecewise linear dependence:

$$X(t) = (1 - \Delta_i(t)) * X(T_i) + \Delta_i(t) * X(T_{i+1}), i = 1..25$$

Where:

X(t) is the coefficient of expansion by spherical functions at time t;

X(Ti) и X(Ti+1) is the refined expansion coefficients;

$$WeightFactor = \frac{Ttr - t_{low}}{t_{high} - t_{low}}$$ is the weight of a moment in time t between Ti and Ti+1. (23)

Calculating the auxiliary coefficients:

$$TECSIN_i = SINTEC_i + WeightFactor * (SINTEC_j - SINTEC_i) \quad (24)$$

$$TECCOS_i = COSTEC_i + WeightFactor * (COSTEC_j - COSTEC_i) \quad (25)$$

$$i = (low...\max)$$

$$j = (\max...low)$$

Calculating the ionospheric pierce point (IPP) in the solar-geomagnetic coordinate system. The ionospheric point is the point at which the satellite signal intersects with the ionospheric layer. The projection of the point of intersection of the satellite signal with the ionospheric layer on the Earth's surface is called the sub-ionospheric point. The maximum distance of a sub-ionospheric point from the GNSS receiver depends on the minimum satellite elevation angle and is determined by the expression. The central angle between the observation point and the ionospheric point.

$$yIPP = \pi / 2 - el - \arcsin\left(\frac{RE}{RE + h\_SL}\right) * \cos(el) \quad (26)$$

Geographic latitude and longitude of IPP:

$$\varphi_{ipp} = a\sin(\sin(\varphi) * \cos(yIPP) + \cos(\varphi) * \sin(yIPP) * \cos(az)) \quad (27)$$

$$\lambda_{ipp} = \lambda + \frac{\arcsin(\sin(yIPP) * \sin(az))}{\cos(\varphi_{ipp})} \quad (28)$$

Let us carry out the calculation using the formulas for geomagnetic latitude and longitude:

$$\varphi_{ippgm} = \arcsin(\sin(\varphi_{gmp}) * \sin(\varphi_{ipp}) + \cos(\varphi_{gmp}) * \cos(\varphi_{ipp}) * \cos(\lambda_{ipp} - \lambda_{gmp})) \quad (29)$$

Solar longitude in solar-fixed coordinates:

$$s = UT + \lambda - \pi$$

$$UT = \mathrm{mod}(Ttr, 86400) - leap\_\sec \quad (30)$$

$$s = UT * \frac{2 * \pi}{86400} + \lambda_{ipp} - \pi \quad (31)$$

The VTEC distribution in the local area of the station is modeled depending on the geographic latitude φi and solar-fixed longitude λi of the ionospheric pierce point:

$$VTEC = VTEC + \overline{P}_{nm} * TECCOS(i) * \cos(m(i) * s) + TECSIN(i) * \sin(m(i) * s)) \quad (32)$$

$\overline{P}_{nm} = \Lambda(n, m) P_{nm}$ is the normalized associated Legendre functions of the first kind of degree n and order m;

Λ(n,m) is the normalizing function;

$P_{nm} = legendre(n(i), \sin(\varphi_{ippgm}))$ is the Legendre functions (33)

Let's calculate the propagation delay:

$$z = \arcsin\left(\frac{\mathrm{Re}}{\mathrm{Re} + hSL}\right) * \sin\left(\frac{\pi}{2} - el\right) \quad (34)$$

Correct mapping function:

$$STEC = \frac{1}{\cos(z)} * VTECU * 10^{16} \quad (35)$$

$$iono_1 = \frac{40.3 * 10^{16}}{f_1^2} * stec \quad (36)$$

$$iono_2 = \frac{40.3 * 10^{16}}{f_2^2} * stec$$

5 METHOD USING HIGH-PRECISION PPP DATA

In this method, we use BRDC standard files from the site https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/broadcast_ephemeris_data.html, we read high-precision satellite ephemeris parameters from these files, but at the same time these files contain the current coefficients at a given time ionospheric model. Using them we will calculate the electron density, and then the ionospheric delay.

brdc is the our data stream read from file.

$$dt\_vtec_i = abs(brdcT_i - Ttr), i = 1...N \quad (37)$$

Where N is the number of measurements;

Next, we find the correction closest to our analyzed time and its index:

$$idx\_vtec_i = index(dt\_vtec_i = \min(dt\_vtec_i)), i = 1...N \quad (38)$$

Let's find the coefficients of spherical harmonics, in TECU units

$$C_{nm} = brdcC_{nm}, i = 1...MAX\_VTEC \quad (39)$$

$$S_{nm} = brdcC_{nm}, i = 1...MAX\_VTEC$$

Calculates ionospheric correction based on spherical harmonics

using coefficients that are included in the calculation formula for only one layer.

We calculate geocentric latitude from geographic latitude:

$$\varphi_u = \arctan((1 - ESqare) * \tan(\varphi_u)) \quad (39)$$

Where:

φu is a latitude of receiver;

ESquare is the eccentricity of the ellipsoid in the system WGS84;

Let's calculate the central angle of the spherical Earth between the user's location and

Projection of the pierce point onto the surface of the earth:

$$yIPP = \pi / 2 - elev - \arcsin\left(\frac{\mathrm{Re} + hU}{\mathrm{Re} + h\_SL} * \cos(elev)\right) \quad (40)$$

Where hU is the height of receiver, (km/1000);

Calculating the latitude of the ionospheric pierce point (IPP):

$$\varphi_{ipp} = a\sin(\sin(\varphi_u) * \cos(yIPP) + \cos(\varphi_u) * \sin(yIPP) * \cos(az)) \quad (41)$$

We calculate the longitude of the pierce point IPP:

$$cond1 = \varphi_u > 0, \tan(yIpp) * \cos(az) > \tan(\pi/2 - \varphi_u)$$

$$\lambda_{ipp} = \lambda_u + \pi - \arcsin\left(\frac{\sin(yIPP) * \sin(az)}{\cos(\varphi_{ipp})}\right)$$

$$cond2 = \varphi_u < 0, \tan(yIpp) * \cos(az) > \tan(\pi/2 - \varphi_u) \quad (42)$$

If both condition 1 and condition 2 are satisfied, then π is added to λipp.

Let's calculate the average longitude of IPP, fixed to the Sun and shifted in phase:

$$\lambda_s = \lambda_{ipp} + \frac{(t - 50400) * \pi}{43200} \quad (43)$$

Calculating VTEC using spherical harmonics.

$$COSINE_i = Cnm_i * \cos(mmm_i * \lambda_s), i = 1...N \quad (44)$$

$$SINE_i = Snm_i * \sin(mmm_i * \lambda_s), i = 1...N$$

$$Pleg = legendre(N, M, \varphi_{ipp}), i = 1...N$$

$$COSI = Cnm_i * \cos(m * \lambda_s), i = 1...N$$

Where:

N is the degree, M is the order of model

$n = 1...MAXN, m = 1...MAXM$

$$\begin{cases} P_{nm} = Pleg(n+1, m+1) \\ COSI(n+1, m+1) = \cos(m * \lambda_s) \\ SINU(n+1, m+1) = \cos(m * \lambda_s) \\ \mathrm{V}TEC_{nm}(n+1, m+1) = (C_{nm}(n+1, m+1) * \cos(m * \lambda_s) + S_{nm}(n+1, m+1) * \sin(m * \lambda_s)) * P_{nm} \\ \mathrm{vtec2} = \mathrm{vtec2} + \mathrm{V}TEC_{nm}(n+1, m+1) \end{cases} \quad (45)$$

Calculating stec(slope TEC) using vtec with the matching function.

$$stec = vtec / (\sin(elev + y\_IPP)) \quad (46)$$

Next we will find propagation delays using the formulas (34).

6 RESULTS

For a benchmark comparison of methods, we take the method of dual-frequency calculation of the ionospheric difference. In this method, we calculate the ionospheric free combination and apply it to the measured pseudorange and phase values. This algorithm using measurements at two frequencies is given below.

$$k_2 = \frac{f_2^2}{f_1^2 - f_2^2} \quad (47)$$

$$k_1 = \frac{f_1^2}{f_1^2 - f_2^2}$$

$$P_{ion} = k_1 * C_1 - k_2 * C_2 \quad (48)$$

$$L_{ion} = k_1 * L_1 - k_2 * L_2 \quad (49)$$

Where:

P1, L1 is the ion-free pseudorange and phase;

C1, C2 is the pseudorange values at the first and second frequencies;

L1, L2 is the phase values at the first and second frequencies;

Let's build graphs of changes in the difference in coordinates of the location of the identified object. The convergence of their values to zero is an indicator of the accuracy of location determination and its error.

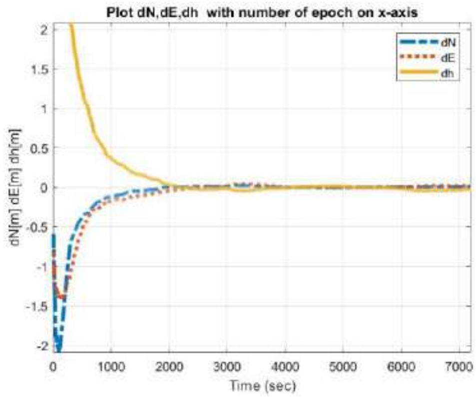

Figure 2: Plot of coordinate divergence using the method of finding the ion-free combination.

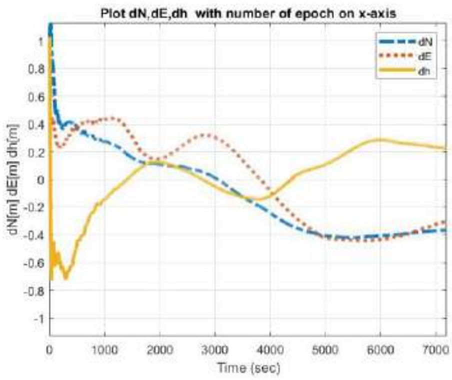

Figure 3: Plot of coordinate divergence when using calculation using Ionex files.

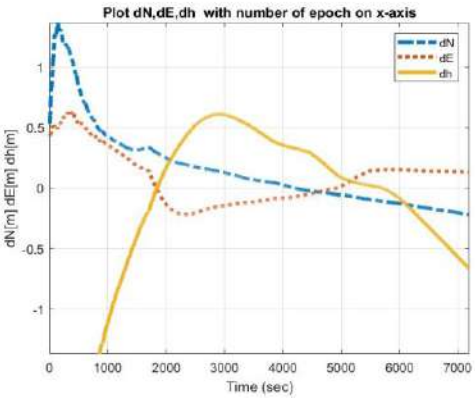

Figure 4: Plot of coordinate divergence when using calculations using the Klobuchar method.

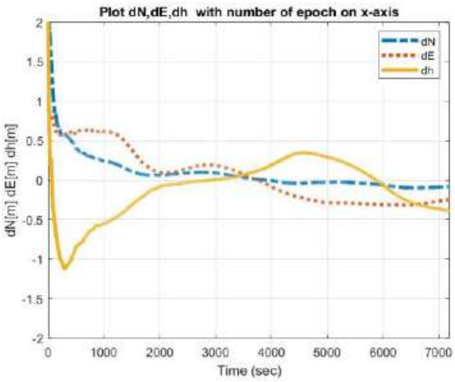

Figure 5: Plot of coordinate divergence when using the Spherical Harmonic method.

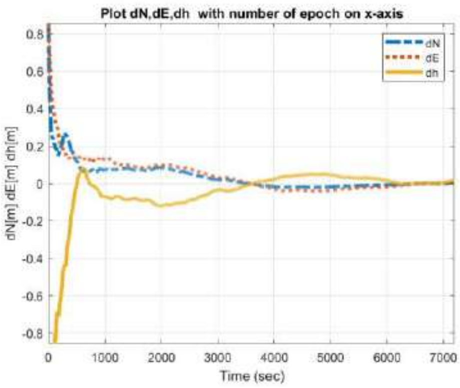

Figure 6: Plot of coordinate discrepancies using the method using high-precision PPP data.

Considering the methods for finding TEC using the Klobuchar model and using Ionex files, we can say that the disadvantages of these methods are:

• insufficiently frequent updating of model coefficients leads to a significant discrepancy between the current state of the ionosphere and the predicted one;

• the constancy of the nighttime ionospheric delay values does not correspond to the real behavior of the ionosphere, since it is known that after sunset the integral electron concentration in the ionosphere gradually decreases during the night, reaching a minimum value before sunrise;

• the maximum ionospheric error does not always occur at 14:00 local time, but can move in the range from one to two hours in the vicinity of local noon.

On the graph of the Klobuchar method and the method based on Ionex files, we see a strong divergence of coordinates over time due to the fact that the GIM map, which was taken at the start of the calculations, becomes less and less relevant as new data continues to be processed, and by the end of the two-hour recording of measurements the coordinate discrepancy reaches a maximum more than 1 m. This is the main disadvantage of using GIM maps for current measurements. The electron density distribution map changes and the error in the ionospheric correction increases.

These disadvantages do not exist in the PPP method. Here, the GIM coefficients are updated regularly by reading the latest BRDC format data from the IGS website or receiving them from support stations in the form of an NTRIP data stream containing these coefficients. This allows the calculation of ionospheric corrections in real time. Thus, the accuracy of calculating the corrections is always at the same level and we see from the graph of the coordinate deviation that over time the error decreases and by the end of the observation period it is minimal and amounts to less than 10 centimeters. In this case, the location is calculated using the PPP method using high-precision orbital corrections, which allows us to obtain such high accuracy.

In the Spherical Harmonic method, the accuracy of VTEC calculation also becomes quite high at the level of 10 centimeters by the end of the first hour of observations. But then the relevance of the model coefficients is lost and the accuracy begins to drop sharply, the difference in coordinates increases. But the accuracy is still better than in the method using Ionex files due to a more accurate calculation method using the coefficients of the spherical model in the source data, the use of interpolation, and the use of weighting coefficients for each subionospheric point.

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