Probing ionospheric TEC near South Geomagnetic Pole by use of GNSS observations

K V Zheltova¹, D A Trofimov¹, S D Petrov¹, S S Smirnov¹, I V Chekunov², Yu A Serov³ and O A Troshichev³
¹Saint Petersburg State University, Saint Petersburg Russia
²Bauman Moscow State Technical University, Moscow, Russia
³Arctic and Antarctic Research Institute, Saint Petersburg Russia
E-mail: kseniyazhel@mail.ru

Abstract. Total electron content (TEC) is one of the most important parameters of the Earth’s ionosphere. This parameter determines the degree of ionization and the dispersion properties of the ionosphere. Now the most affordable way to determine ionospheric parameters is the use of radio signals from the global navigation satellite systems GLONASS, GPS, GALILEO and BDS. TEC is now being routinely monitored by global GNSS networks almost everywhere on Earth except geomagnetic poles. The observations of TEC at the Vostok antarctic station were carried out jointly by Saint Petersburg State University and Arctic and Antarctic Research Institute. Observations were started in 2016 and continued to this day with small interruptions. In this work we have processed the GNSS observations with RTKLIB and GeNeSiS software packages. As a result of this processing we have estimated the TEC from code and phase observables. The resulting TEC time series were analysed and compared to the global TEC map. A reasonable accordance with previous results has been reached. However, our results are specific to the South Geomagnetic Pole and reflect ionospheric behaviour near it. It can be seen that TEC changes more abruptly near the Geomagnetic Pole than elsewhere. These results may potentially augment our knowledge about ionosphere structure and evolution near the geomagnetic poles.

1. Introduction
The ionosphere is a layer of the Earth’s atmosphere that is highly ionized by radiation. The Earth’s ionosphere consists of a mixture of neutral gases and a quasi-neutral plasma. The ionosphere starts at about 60 km. One of the main parameters of the state of the ionosphere is total electron content. It is the number of free electrons located in a cylinder with a cross section of 1 square meter and oriented along the line of sight. This value is measured in TECU (Total Electron Content Unit), 1 TECU = $10^{16}$ electron/m². TEC is determined by the delay of the radio signal passing through the ionosphere. Signal transmission at two frequencies allows to take into account this effect, which is used in Very Long Baseline Interferometry (VLBI) and Global Navigation Satellite System (GNSS). At present, GNSS is the most convenient technology for determining the TEC, since the receiving equipment is the cheapest among analogues, and the constellations of the existing GNSS systems (GPS, GLONASS, Galileo and Baidou) provide a fairly dense coverage of the celestial sphere for the observer. In the case of code measurements, the TEC is determined from the ratio:
\[ P_2 - P_1 = \frac{40.4(f_1^2 - f_2^2)}{f_1^2 f_2^2}T EC + B^s + B_r + \epsilon_P, \]

where \( P_2, P_1 \) are pseudoranges at frequencies \( f_2 \) and \( f_1 \), \( B^s \) and \( B_r \) are delays in the satellite and receiver equipment.

In case of phase measurements:

\[ L_1 - L_2 = \frac{40.4(f_1^2 - f_2^2)}{f_1^2 f_2^2}T EC + [\lambda_1 N_1 - \lambda_2 N_2] + b^s + b_r + \epsilon_L, \]

where \( \lambda_1, \lambda_2 \) are wavelengths, \( N_1, N_2 \) are integer ambiguities, \( b^s \) and \( b_r \) are delays in the satellite and receiver equipment.

Thus, GNSS is a good and inexpensive method for determining the state of the ionosphere. Radio communication depends on the state of the ionosphere, thus determining the parameters of the ionosphere is an important task. Of interest is the determination of ionosphere parameters at high latitudes of the northern and southern hemispheres.

2. Observations

The observations were carried out jointly by Saint-Petersburg State University and Arctic and Antarctic Research Institute. To carry out observations, the Department of Astronomy of St.Petersburg State University provided the JAVAD TRIUMPH-1 geodetic GNSS receiver. During the first expedition of 2016–2017, a GNSS station was established at Vostok Antarctic base. Station coordinates are 78°28′ south latitude and 106°50′ east longitude. The height of the station is 3488 metres. A beam was frozen in the firm, and a platform with a heating cable and a screw mark was installed on top of the beam, where the receiver was fixed. Before the receiver was delivered to the Vostok station, a 24-day series of observations was made at Progress station on the coast of Antarctica.

The observations at Vostok station were carried out from February 7, 2016 and ended on January 31, 2017. A year later, a new expedition was organized, where observations were made at the same receiver and observation post from February 4, 2018 to February 10, 2019. In all series, observations were carried out at two frequencies with the possibility of phase and code measurements. The interval between measurements is 30 seconds.

3. Data processing and results

The TEC shown in the figures below was calculated on the basis of code and phase measurements, from a linear combination of the pseudoranges and pseudophases obtained at two frequencies (used frequencies \( L_1 \) and \( L_2 \)) for each satellite. The slant electron content in the ionosphere (along the line of sight) was calculated, after which the vertical electron content was determined based on the mapping function \( F(z) \) for each satellite:

\[ STEC = F(z) \ast VTEC, \]

\[ F(z) = \frac{1}{\sqrt{1 - \sin^2 z'}}, \]

\[ \sin z' = \frac{R}{R + H} \sin z, \]
Figure 1. Receiver installation at Vostok station.

where $R$ is range from the receiver to the center of the earth, $H$ is the height of the single layer, $z$ is the zenith angle on the ground station and $z'$ is the zenith angle on the point, where signal transmitted from satellite to receiver crosses ionospheric pierce point (IPP), STEC is the slant TEC and VTEC is the vertical TEC. The height of the conductive layer was taken equal to 450 km. The final result were obtained by simple averaging over the all satellites at the time of observations.

The result of the series of 2018 based on code and phase measurements from GPS and GLONASS observations were compared with the global ionospheric maps of the Center for Orbit Determination in Europe (CODE). Comparison of data shows the high reliability of our TEC values. Due to the fact that the observations were carried out at very high latitudes, it was interesting to compare the results of GPS and GLONASS observations. As it is evident from the graphs, TEC received from the GLONASS satellites is in good agreement with the TEC obtained by GPS. The figures show the series for 9 days from 2018.
Figure 2. TEC from GPS observations at the Vostok station based on code and phase measurements.

Figure 3. TEC from GPS and GLONASS observations at the Vostok station based on code measurements in comparison with CODE.

4. Conclusions
As a result of the work, a three-year series of observations was processed and a series of the total electron content of the ionosphere above the Vostok Antarctic station was obtained by code and phase measurements. For the first time a long and detailed TEC time series near the South Geomagnetic Pole has been estimated. This time series is in good accordance with global ionospheric map but gives more details of ionospheric structure and behaviour near the South Geomagnetic Pole. It can be seen that TEC changes in this region are more abrupt than elsewhere. This is most probably due to abundant ionospheric scintillations in this region of the ionosphere. In order to study the ionospheric scintillations further we need to decrease an observation interval up to one second and less, this will be the subject of future research. Our analysis also shows that GLONASS observations are more adequate than GPS ones for this region which is well expected since inclinations of GLONASS orbits are higher than those of GPS ones. As a result the GLONASS observations produce more accurate estimates of TEC then the GPS ones near the South Geomagnetic Pole.

References
[1] Alizadeh M, Wijaya D, Hobiger T, Weber R and Schuh H 2013 Ionospheric Effects on Microwave Signals *Springer Berlin Heidelberg* (Berlin, Heidelberg) pp 35–71
[2] Sulaiman S, Ali M and Yatim B 2007 Ionospheric GPS-TEC observations at Scott Base Antarctica during 2004 Asia-Pacific Conference on Applied Electromagnetics p 1
[3] Purohit P, Bhawre P, Mansoori A, Khan P and Gwal A 2011 GPS derived Total Electron Content variations over Indian Antarctica station, Maitri *World Academy of Science, Engineering and Technology* 59 597
[4] Correia E, Junqueira Paz A and Gende M 2013 Characterization of GPS total electron content (GPS-TEC) in Antarctica from 2004 to 2011 *Annals of Geophysics* 56 305
[5] Trofimov D, Serov Y, Petrov S, Chekunov I and Shombina L 2017 GNSS-observations at the Vostok station *Geodesy, cartography, geoinformatics and cadastre. From idea to application* p 74