Using Android smartphones with dual-frequency multi-GNSS receiver to measure the total electron content of the ionosphere

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Abstract. The results of raw GNSS data recorded using a Xiaomi Mi 8 android smartphone equipped with a dual-frequency GNSS module BCM47755 capable of receiving and processing signals from the GPS, Galileo, QZSS systems in the L1 and L5 frequency sub-bands are presented in the paper. The indices of ionospheric activity that as variations in the relative slant total electron content, the rate of total electron content, the rate of total electron content index, root-mean-square deviation of relative slant total electron content on the base of raw GNSS data are calculated. A comparison study of the data obtained with the data from the KZN2 station of the International GNSS Service network, equipped with a professional GNSS receiver of a geodetic class is carried out. It is shown that the median value of signal strength at frequencies L1 and L5 for the data obtained from the satellites G08, G10, G27, G32, E09 on the Xiaomi Mi 8 smartphone is ≈ 5-25% lower than data from the KZN2 station. The indices of ionospheric activity registered by the Xiaomi Mi 8 smartphone have a higher signal-to-noise ratio in comparison with the data of the KZN2 station. Median levels of variations of the relative slant TEC, ROT, ROTI, and RMSTEC obtained by the Trimble Alloy receiver at KZN2 station were 45÷70% lower than that for the Xiaomi Mi 8 smartphone. Nonetheless, the possibility of registering the indices of ionospheric activity such as relative slant total electron content and others based on dual-frequency raw GNSS measurements (primarily carrier-phase and pseudorange) of GNSS signals received by smartphones opens up prospects for attracting as wide a community as possible for collecting GNSS data and monitoring the ionosphere.

1. Introduction
Over last 30 years, the method of radiosonding the upper atmosphere by navigation satellite signals to the main global navigation satellite systems (GNSS like as GPS, GLONASS, Galileo, Beidou) followed by the estimation of the total electron content (TEC) in the Earth’s ionosphere from the dual carrier-phase and pseudorange (code) measurements combinations at frequencies L1 and L2 or L1 and L5 has found wide application for the study of various phenomena occurring in the ionosphere. For example, in studies of the ionospheric effects of extreme heliogeophysical events such as magnetic storms [1], solar flares [2], as well as regular events, such as the solar terminator passage (ST) [3]. This method is also used to study the response of the ionosphere to earthquakes and the search for their precursors [4]. Since the mid-2000s various scientific groups started to intensely use GNSS signals to determine the TEC in the Earth’s ionosphere in experiments on ionosphere modification by high-power HF radio waves at HAARP, EISCAT,
Sura facilities [5, 6]. They devote part of the research to the study of the influence of ionospheric and magnetospheric disturbances on the stability of GNSS functioning during periods of various heliogeophysical events [7].

Since the release of the Android 7 smartphone operating system (2016), users have been able to receive raw GNSS measurements recorded using the GNSS receiver installed in the smartphone. However, the capabilities of these modules at that time allowed receiving navigation signals from the main GNSS only in the L1 sub-band \(^1\). The relative slant TEC data got because of single-frequency measurements (by using a combination of carrier-phase and pseudorange (code) measurement at a single frequency (primarily L1 band)) have a significantly lower signal-to-noise ratio compared to the TEC data got by a combination of two-frequency carrier-phase measurements at frequencies L1 and L2 or L1 and L5. However, with the development of the BCM47755 dual-frequency GNSS receiver which provides reception in the L1 and L5 frequency sub-bands for GPS, Galileo, and QZSS systems, it became possible to calculate the TEC based on two-frequency carrier-phase measurements at the L1 and L5 frequencies recorded on a smartphone. For example, figure 1 shows results of calculated relative slant TEC for the GPS PRN 27 by using single and dual frequencies carrier-phase and pseudorange (code) measurements. As you can see from the fig. 1 slant TEC colored blue (Xiaomi Mi8) and the red (Trimble Alloy GNSS receiver at the International GNSS Service (IGS) KZN2 station) got by dual carrier-phase combination at frequencies L1 and L5 they have a significantly higher signal-to-noise ratio compared to single-frequency L1 and L5 measurements by using a single-frequency combination of carrier-phase and pseudorange measurement and dual pseudorange combination.

\[ sTEC, \text{ TECU} \]

\[ \text{L1C/L5Q M8} - \text{L1C/L5X KZN2} - \text{C1C/C5Q M8} - \text{C1C/C5X KZN2} - \text{C1C/L1C M8} - \text{C1C/L1C KZN2} - \text{C5Q/L5Q M8} - \text{C5X/L5X KZN2} \]

**Figure 1.** Relative slant TEC was calculated for the GPS PRN 27 by using single and dual frequencies carrier-phase and pseudorange (code) measurements. Dual carrier-phase combination at frequencies L1 and L5 colored blue (Xiaomi Mi8) and red (Trimble Alloy). Dual pseudorange combination at frequencies L1 and L5 colored orange (Xiaomi Mi8) and brown line (Trimble Alloy). Single-frequency combination of carrier-phase and pseudorange at L1 colored green (Xiaomi Mi8) and gray line (Trimble Alloy). Single-frequency combination of carrier-phase and pseudorange at L5 colored black (Xiaomi Mi8) and pink line (Trimble Alloy).

\(^1\) The L band is the IEEE designation for the range of frequencies in the radio spectrum from 1÷2 GHz. For example, the center frequencies in the L band of the GPS system are L1 – 1575.42 MHz; L2 – 1227.60 MHz; L3 – 1381.05 MHz; L5 – 1176.45 MHz.
Given the above, it can be assumed that the use of a smartphone as an independent budget and mobile GNSS receiver, sometimes, can serve as an additional channel for information about the state of the upper atmosphere, and given the growing number of smartphones equipped with dual-frequency GNSS receiver, it will also be useful for continuous monitoring of the state of near-Earth space. The capabilities of smartphones equipped with a dual-frequency GNSS receiver, both from the point of view of ionospheric studies and from the point of view of accurate positioning, are considered in several recent articles [8–11]. The dual-frequency GNSS receiver is confirmed in the following smartphone models: Xiaomi Mi8, Mi9, Mix 3; Huawei Mate Pro 20, P30, P30 Pro; Oppo Reno; Google Pixel 4; OnePlus 7 Pro.

2. Description of the measuring equipment and the organization of the experiment

To record the raw GNSS measurements, the Xiaomi Mi 8 smartphone is used, which is the first commercial device equipped with the BCM47755 GNSS module. BCM47755 allows you to receive and process the following GNSS signals: GPS L1C/A, L5, GLONASS L1, Beidou (BDS) B1, QZSS L1, L5, Galileo E1, E5a.

For the quality of technical characteristics of the GNSS receiver installed in the smartphone, a comparative analysis of the raw GNSS data recorded on the Xiaomi Mi 8 smartphone was carried out with the data recorded synchronously at the KZN2 station, which is part of the IGS. Given the prime requirements applied to the stations included the IGS network and the long series of continuous measurements, the data got at the KZN2 station will be a reference and verified. The smartphone during recording was in a static position and was in an urban environment (geodetic coordinates: $55.7915^\circ$ N, $49.1174^\circ$ E), at distance $\approx 144$ meters from the IGS – KZN2 network station, which is equipped with a professional Trimble Alloy GNSS receiver with a Trimble TRM 59800 antenna ($55.7908^\circ$ N, $49.1192^\circ$ E). The scheme of devices location in the experiment is shown in fig. 2.

![Figure 2. Scheme of the mutual arrangement of the Xiaomi Mi 8 smartphone and KZN2 station of the IGS network in experiment on 30.04.2020.](image)

In the Google Play (app store for Android smartphones), various application options are available that allow you to convert raw GNSS measurements recorded on smartphones to Radio Technical Commission for Maritime Services (RTCM) and/or Receiver Independent Exchange Format (RINEX). In this article, data were recorded hourly files with a parameter registration frequency of 1 Hz in the RINEX 3.03 format using the app Geo++ RINEX Logger. A similar
format to RINEX, the frequency of data recording and the period of their recording was used on the station KZN2.

3. The Results
Figure 3 shows the results recorded of carrier-phase measurements at frequencies L1 and L5 for four GPS satellites (G08, G10, G27, G32) and one satellite of Galileo (E09) in the interval 16:20–19:00 UTC. The data for each satellite presented in different colors is shown in the legend in figure 3. Data from other satellites in this time interval contained losses of phase lock at the L5 frequency for the Xiaomi Mi 8 smartphone and were therefore excluded from further analysis. In fig. 3a and fig. 3c solid lines show data for carrier-phase measurements at frequencies L1 and L5 recorded by the Trimble Alloy GNSS receiver (IGS – KZN2 network station) and dotted lines show signal strength (carrier to noise ratio) at these frequencies. Data for carrier-phase measurements at frequencies L1 and L5 by the Xiaomi Mi 8 smartphone presented by solid lines and dotted lines for signal strength at these frequencies is shown in fig. 3b and fig. 3d. The difference in the carrier-phase measurements at frequencies L1 and L5, between the smartphone and Trimble Alloy GNSS receiver, is about ± 1500 full cycles in all cases. For pseudo-range measurements, we have ≈ 200 m on L1 and L5.

Figure 3. Carrier-phase measurements (solid line) and signal strength (carrier to noise ratio) (dotted line) at frequencies L1 (upper panels) and L5 (bottom panels) for the satellites G08, G10, G27, G32, E09 (G–GPS; E–Galileo). L1, L5 data recorded by the Trimble Alloy GNSS receiver IGS KZN2 station (a, c); L1, L5 data recorded by the Xiaomi Mi 8 smartphone (b, d).

Figure 4 shows the median level of signal strength at frequencies L1 and L5 for the satellites G08, G10, G27, G32, E09 (a, c – KZN2 Trimble Alloy; b, d – Xiaomi Mi 8). The median level of signal strength for all five satellites at the L1 frequency for Trimble Alloy was 47.6 dBHz and Xiaomi Mi 8 – 40.64 dBHz. The median level of signal strength at L5 frequency for Trimble Alloy was 49.6 dBHz and Xiaomi Mi 8 – 42.08 dBHz. The median level of signal strength at Xiaomi Mi 8 is lower than at the Trimble Alloy at ≈ 17% (for L1: G08 ≈ 10%; G10 ≈ 13.5%; G27
≈ 5%; G32 ≈ 11%; E09 ≈ 21% and for L5: G08 ≈ 18%; G10 ≈ 12.5%; G27 ≈ 20%; G32 ≈ 24%; E09 ≈ 24%).

Figure 4. Median level of signal strength at frequencies L1 and L5 for the satellites G08, G10, G27, G32, E09. L1 (a); L5 data (b).

The next step was to evaluate the capabilities of the smartphone with a dual-frequency GNSS receiver for the study of the ionosphere using TEC measurements. For this purpose, using carrier-phase measurements at frequencies L1 and L5 for the satellites G08, G10, G27, G32, E09 slant TEC along the line of sight (LOS) between Trimble Alloy and Xiaomi Mi 8 sites and satellites were calculated. We calculated slant TEC using the following equations [12]:

\[
sTEC_{L1L5} = \frac{1}{K} \frac{f_1^2}{f_5^2} (L_1\lambda_1 - L_5\lambda_5) + \text{const},
\]

where \(K = 40.308 \cdot 10^{16} \text{ m}^{-2} \text{ TECU}^{-1} \); \(f_1, f_5\) – GNSS frequencies (GPS – L1/L2/L5; GLONASS – L1/L2; BeiDou – B1/B2/B3; Galileo – E1/E5/E6); \(L_1, L_5\) – carrier-phase measurements at GNSS frequencies \(f_1, f_5\); \(\lambda_1, \lambda_5\) – wavelength at GNSS frequencies \(f_1, f_5\) (\(\lambda_i = c/f_i, (i = 1, 5, c\) – the speed of light in a vacuum 299 792 458 m/s)); \(L_1\lambda_1, L_5\lambda_5\) – measurements of the carrier-phase path of radio signals at GNSS frequencies \(f_1, f_5\); \(\text{const}\) – uncertainty constant; total electron unit (TECU). 1 TECU = \(10^{16}\) el./m\(^2\).

For the comparison analysis we selected four parameters calculated based on GNSS TEC: 1) variations in the relative slant TEC (fig. 5a); 2) the rate of TEC (ROT) (fig. 5b); 3) the rate of TEC Index (ROTI) (fig. 5c); 4) Root-mean-square deviation (RMSD) of relative slant TEC in a window of 100 s (RMSTEC) (fig. 5d)). The figure 5 shows data from Trimble Alloy (left panels), Xiaomi Mi 8 smartphone (right panels). The data for different LOS between Trimble Alloy and Xiaomi Mi 8 sites colors shown in legend.

The selection of the TEC variations from the slant TEC, the trend dedicated by the 6th-degree polynomial, was first removed, and then the got values were filtered using a moving average (with a window of 601 s). To the calculation of the parameters ROT and ROTI [13] were used the following equations:
\[ ROT = \frac{sTEC(t + \Delta t) - sTEC(t)}{\Delta t}, \]  

(2)

where \( sTEC \) — slant TEC at \( \Delta t = 1 \) m.

\[ ROTI(t) = \sqrt{\frac{1}{N-1} \sum_{t=1}^{N} \left| ROT(t) - \overline{ROT} \right|^2}, \]  

(3)

where \( \overline{ROT} \) — mean \( ROT \) at 5-min time interval, \( N \) — total number of epochs.

The results of the analysis of four parameters shown in fig. 5 used in this work for the initial assessment of the TEC registration characteristics show that the median level of variations in the relative slant TEC (fig. 5a) according to the data of all five satellites for the Trimble Alloy GNSS receiver of KZN2 station is 62% lower than for the Xiaomi Mi 8 smartphone. For the parameters of the ROTI (fig. 5c) and the RMSTEC (fig. 5d), the overall qualitative picture remains similar when compared.

**Figure 5.** Parameters for the comparison analysis obtained from five GNSS satellites:  

- **a)** — variations in the relative slant TEC;  
- **b)** — the rate of TEC (ROT);  
- **c)** — the rate of TEC Index (ROTI);  
- **d)** — RMS deviation of relative slant TEC in a window of 100 s. (RMSTEC). The figure shows data from Trimble Alloy (left panels), Xiaomi Mi 8 smartphone (right panels). The data for each satellite presented in different colors is shown in the legend.
4. Conclusion

Thus, based on the data of carrier-phase and pseudorange (code) measurements at the frequencies L1, L5 were variations calculated in the relative slant TEC, ROT, ROTI, and RMSTEC parameters, and comparison study was carried out with similar simultaneously recorded data obtained at the KZN2 station, which was included into the IGS network.

According to the results of measurements of the signal strength of the navigation signal using data from five GNSS satellites at frequencies L1 and L5, it is shown that the median signal strength level for the Xiaomi Mi 8 smartphone is ≈ 17% lower than that for the Trimble Alloy GNSS receiver of KZN2 station. Signal strength for a smartphone is always ≈ 3÷10 dBHz lower than for geodetic receivers and weakly depends on the elevation angle of the satellite, which is consistent with the results of a comparative analysis conducted in [14]. The TEC variations, ROT and ROTI parameters obtained using a smartphone have a lower signal-to-noise ratio compared to the data of the KZN2 station equipped with a Trimble Alloy GNSS receiver with a precision GNSS antenna with a stable phase center. From the comparison data analysis of the relative slant TEC and the parameters calculated on its basis (ROT, ROTI, and RMSTEC) presented in fig. 5 the median levels for the data obtained on the Trimble Alloy receiver at the KZN2 station are at 45÷70% lower than for the Xiaomi Mi 8 smartphone. However, the use of even the simplest methods of digital filtering makes it possible to use the data of ionospheric perturbation estimation calculated on the TEC basis obtained on smartphones with a dual-frequency GNSS module as a compact device for recording ionospheric perturbations.

Further measurements using data from various smartphone models and the accumulation of a larger sample of data are required to better assess the capabilities of smartphones with dual-frequency GNSS modules in ionospheric studies. The increase of the number of smartphones equipped with dual-frequency modules opens up great prospects for ionospheric monitoring as the smartphone at the moment is one of the most popular devices in the world and the chance of using it as an affordable tool for rapid registration of TEC and will attract the widest possible community of professionals and amateurs to collect GNSS data. Moreover, using that kind of smartphones will make possible familiarize the public with current state of research of the Earth’s atmosphere using GNSS signals in popular science and scientific and methodological purposes.

Unfortunately, as shown by our research, using a dual-frequency smartphone does not allow to get long series of TEC measurements, yet. That phenomena associated with the problem of frequent tearing of the navigation signal phase and clock drift is caused by a clock generator in the GNSS module with lower stability then in geodetic class GNSS receivers. Frequent phase corruption in mobile devices is primarily associated with the Duty cycle slips mode when the power to the GNSS receiver is not supplied constantly, but only during a short period when the device receives the necessary GNSS data.

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