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Determination of the Effective Collision Frequency of Electrons in the *E* and *D* Regions of the High-Latitude Ionosphere from Analysis of Radio-Occultation Measurements

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Abstract—Collisions between electrons and neutral molecules are of special interest for the physics of the Earth's ionosphere, in particular, for determining the ionospheric conductivity and current systems in the lower ionosphere of the planet, as well as elucidating the role they play in attenuating radio waves propagating inside the *D* and *E* regions of the ionosphere. The effective collision frequency of electrons can be estimated from laboratory studies of electron mobility in atmospheric gases in combination with rocket measurements of temperature and particle density in the Earth's upper atmosphere, or it can be determined independently from analysis of radio-occultation data. We have developed a method for reconstructing the vertical profiles of the absorption coefficient of decimeter (wavelength ~19 cm) radio waves by solving the inverse problem of signal absorption in the *D* and *E* regions of the Earth's ionosphere. Based on the analysis of radio-occultation data from the *FORMOSAT-3/COSMIC* satellites, the altitude profiles of the absorption coefficient of decimeter (DM) radio waves in the planet's ionosphere during the geomagnetic storm on June 22–23, 2015, were determined. It is known that the absorption coefficient at a given fixed frequency is directly proportional to both the electron density and the collision frequency of electrons with ions and neutrals. Using the data on the vertical profiles of the absorption coefficient of DM radio waves and the electron density reconstructed from the analysis of *FORMOSAT-3/COSMIC* radio occultation, we estimated the effective collision frequency of electrons in the *D* and *E* regions of the Earth's high-latitude ionosphere. The practical significance of studying the frequency of electron collisions and the effects of radio-wave absorption in the *D* and *E* regions of the planet's ionosphere is associated with maintaining the uninterrupted operation of space radio communication and navigation systems.

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INTRODUCTION

Radio probing of the Earth's ionosphere can be carried out using both artificial and natural sources of radio emissions located beyond the ionosphere. Decimeter radio waves of sufficiently high frequency transmitted from a navigation satellite traverse the ionosphere and can be received on the Earth's surface or on board another (low Earth orbit) satellite. The integral electron content along the path of the radio beam can be determined through measurements of the phase path (eikonal) of the received signal. Observations of variations in the intensity of satellite signals or space radio noise that have passed through the ionosphere indicate variations in radio wave absorption and, consequently, variations in electron content and collision frequency in the lower ionosphere of the planet [1–4]. During ionospheric radio probing, operational GPS (Global Positioning System) frequencies are used, which significantly exceed the natural frequencies of the ionosphere, making the radio-occultation method independent of the state of the ionosphere. This advantage sets it apart from traditional methods of studying the ionosphere using reflected radio waves. These methods involve waves with frequencies close to the plasma frequency, which are strongly influenced by the ionosphere. The influx of energetic particles during geomagnetic disturbances leads to an increase in electron density in the lower layers of the ionosphere and an increase in radio-wave absorption, making the use of these traditional methods impossible during intense disturbances [5]. The probing method that we propose will be effective exactly when the need for ionospheric studies is particularly acute, such as during strong magnetic storms. The study of collisions between free electrons and neutrals and ions is important for the analysis of various macroscopic phenomena. In the *E*-region altitude range, these collisions determine the thermal and electrical conductivity of the plasma and current systems that generate geomagnetic disturbances [6, 7].

Until now, radio-occultation measurements have not been used to study radio wave absorption at GPS frequencies and determine the collision frequency of electrons in the lower ionosphere of the Earth. This was due to the fact that, in quiet geomagnetic conditions, according to the analysis of radio-occultation measurements, only weak disturbances in the *E* and *D* regions of the ionosphere occurred without any signs of radio-wave absorption [1]. At the same time, the analysis revealed reliably identified layers of increased absorption in radio-occultation measurement sessions, which were caused by powerful X-ray bursts and significant variations in geomagnetic conditions during a June 2015 storm [3]. Since the operational GPS frequencies significantly exceed the critical frequency of the ionosphere, nondeviating absorption is recorded in radio-occultation measurements [5]. Substantial exceeding of the critical frequency is also important for ensuring reliable measurements in conditions of increased radio-wave absorption during strong magnetic storms.

The aim of this study is to reconstruct and analyze the vertical profiles of the effective collision frequency of electrons in the *D* and *E* regions of the high-latitude ionosphere of the Earth based on the processing of radio-occultation measurements from the *FORMOSAT-3/COSMIC* satellites during the magnetic storm on June 22–23, 2015.

METHODOLOGY FOR DETERMINING THE EFFECTIVE COLLISION FREQUENCY OF ELECTRONS

Our previous studies [1–3] were dedicated to the analysis of radio-occultation measurements conducted using navigation GPS and low-orbit *FORMOSAT-3/COSMIC* satellites in the Earth's ionosphere during the magnetic storm on June 22–23, 2015. The measurement sessions (~100) were performed at latitudes ranging from ~65° to 88° N and covered an altitude range from ~50 to ~110 km. Each of these sessions contained dependences of the eikonal (phase path) and signal power (L_1 band, wavelength ~19 cm) on the perigee height of the beam, as well as a vertical profile of electron density. The error in reconstructing electron density N_e from eikonal data is $\delta N_e \approx 10^4$ cm^{-3}, and its values are given with a vertical step of 2.5 km [1]. It was found that powerful X-ray bursts and geomagnetic conditions during the main phase of the storm caused disturbances and elevated levels of electron density in the *D* and *E* regions of the ionosphere. The search for absorption of decimeter radio waves (signal wavelength ~19 cm) on GPS carrier frequency f_1 = 1545.42 MHz showed that the magnitude of the integral absorption on the radio-occultation paths (navigation GPS to low-orbit *FORMOSAT-3/COSMIC* satellites) was ~3 dB in the altitude range of ~50–90 km and, in some cases, reached ~10 dB at altitudes from ~90 to ~95 km [1, 2]. In [3, 4], a general method for reconstructing vertical profiles of absorption coefficient *Z* was proposed based on solving the inverse problem of radio-wave absorption in the lower ionosphere of the Earth. Here, we also present the results of determining the altitude profiles of absorption coefficient $Z(h)$ of the DM signal in the planetary ionosphere and uncertainties δZ in their reconstruction at altitudes below ~100 km during the magnetic storm on June 22–23, 2015. The estimate of uncertainty δZ for analyzed profile $Z(h)$ is the absolute value of the maximum discrepancy for the solution of the inverse problem of radio-wave absorption (see Table 1 in [3]).

If frequency $\omega = 2\pi f$ of the radio wave satisfies the inequality $\omega^2 \gg \nu^2$, absorption coefficient *Z* is directly proportional to the product of νN_e and inversely proportional to the square of the frequency (f^2) of the wave [5]. The effective collision frequency of electrons can be determined from the following expression:

$$Z(h) \simeq 1.15\times10^3\,\frac{N_e(h)\nu(h)}{f^2}, \tag{1}$$

where N_e is electron density, cm^{-3}; *f* is frequency, Hz; and *Z* is the absorption coefficient, dB/km. Thus, according to Eq. (1), the formula for reconstructing profile $\nu(h)$ from the data on absorption coefficient $Z(h)$ at GPS carrier frequency $f_1 = 1.54542\times10^9$ Hz and electron-density profile $N_e(h)$ has the form

$$\nu(h) \simeq \frac{Z(h)f_1^2}{1.15\times10^3 N_e(h)}. \tag{2}$$

Taking into account the errors $\delta Z/Z$ and $\delta N_e/N_e$ in determining absorption coefficient *Z* and electron density N_e, we can find relative error $\delta\nu/\nu$ in reconstructing effective collision frequency ν of electrons:

$$\delta\nu/\nu = \sqrt{(\delta Z/Z)^2 + (\delta N_e/N_e)^2}. \tag{3}$$

The selection criteria for the $Z(h)$ profile for calculating the effective collision frequency of electrons with neutrals and ions are as follows:

(a) $Z(h)$ profiles were selected where local maxima of the absorption coefficient were reconstructed with a relative error of no more than $\delta Z/Z \approx 50\%$ (see Table 1 in [3]); and

(b) data on electron density in the analyzed altitude range should be available for the considered radio-occultation measurement session.

Regarding the applicability of the radio-occultation method for determining ν, the answer largely depends on how well and with what uncertainties the values of local maxima Z_{max} are reconstructed in alti-

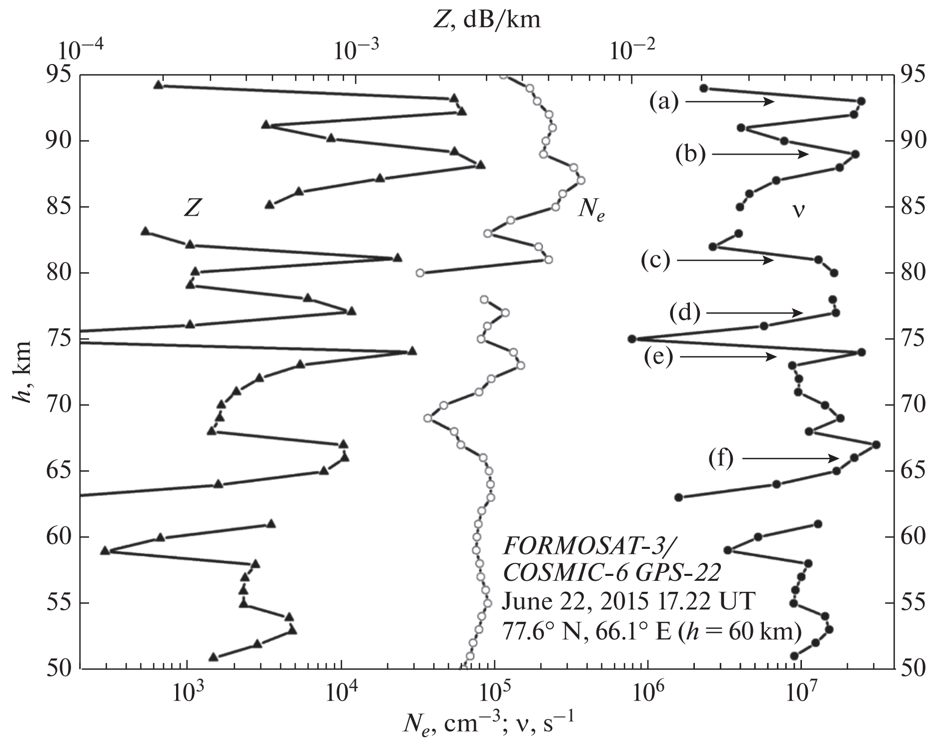

Fig. 1. Vertical profiles of absorption coefficient $Z(h)$ of radio waves, electron density $N_e(h)$, and effective frequency of electron collisions $\nu(h)$ in the Earth's ionosphere obtained from the analysis of the *FORMOSAT-3/COSMIC-6 GPS*-22 session of radio-occultation measurements (June 22, 2015). Values of relative error dn/n for the selected experimental points: (a) ~28, (b) ~25, (c) ~50, (d) ~71, (e) ~45, and (f) ~75%.

tude profiles of absorption coefficient $Z(h)$. These uncertainties mainly affect the errors in determining ν, since the influence of errors in reconstructing electron density (~10%) can be neglected in this case.

EXPERIMENTAL DATA AND ANALYSIS OF RESULTS

The collision frequency between electrons and neutral molecules in the lower ionosphere of the planet determines the resistance of the medium experienced by an electron in its motion. The effective collision frequency is the sum of the frequencies of electron–ion collisions and collisions with neutral particles [8]. It is also important to understand the role that collisions play in the attenuation of radio waves propagating inside the *D* and *E* regions of the ionosphere. The effective collision frequency of electrons can be estimated through laboratory studies of electron mobility in atmospheric gases, combined with rocket measurements of temperature and particle density in Earth's upper atmosphere. Despite the recognition of the importance of collision frequency, research on this characteristic is relatively scarce and fragmentary due to experimental difficulties [9, 10]. Let us consider examples of reconstructing vertical profiles of the effective collision frequency (using the analysis of radio-occultation data from the *FORMOSAT-3/COSMIC* satellites).

Figure 1 shows an example of such reconstruction (*FORMOSAT-3/COSMIC-6 GPS-22* data from June 22, 2015). The experimental N_e values were reconstructed with an error $\delta N_e \approx 10^4$ cm^{-3}, and they are shown as white circles in Fig. 1. Triangles represent the values of the absorption coefficient *Z*, which were determined with error $\delta Z \approx 0.7 \times 10^{-3}$ dB/km [3]. Using Eq. (2) and the experimental data mentioned above, the effective collision frequency ν of electrons was calculated (black circles). Relative error $\delta\nu/\nu$ in the reconstruction of these values was found using Eq. (3). The most reliable results obtained in reconstructing the $\nu(h)$ profile with a relative error of less than ~100% are indicated by letters in Fig. 1. The error values for the selected experimental points are provided in the figure caption. It should be noted that the radio-occultation measurements were conducted immediately after the onset of powerful X-ray bursts (~16:30 UT on June 22, 2015) and before the arrival (18:36 UT on June 22, 2015) of the main coronal-mass ejection (CME) into the planet's magnetosphere. Therefore, they are only influenced by X-ray-burst events, and there is no influence of geomagnetic conditions during the main phase of the storm [1, 3].

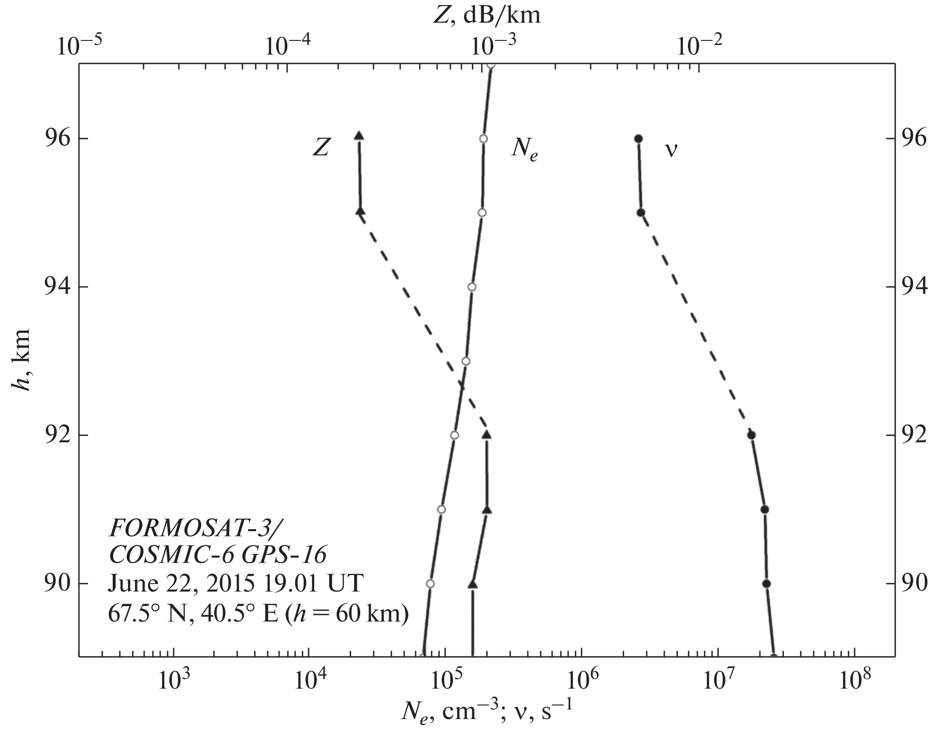

Fig. 2. Same as Fig. 1, but for the *FORMOSAT-3/COSMIC-6 GPS-16* measurement session (June 22, 2015).

Figure 2 shows profiles of absorption coefficient $Z(h)$, electron density $N_e(h)$, and effective collision frequency $\nu(h)$ in the planet's ionosphere (*FORMOSAT-3/COSMIC-6 GPS-16* data from June 22, 2015). In this profile, the error in reconstructing Z is $\pm 1.3 \times 10^{-3}$ dB/km [3]. Two clear maxima of the absorption coefficient $(1.6 \pm 1.3) \times 10^{-3}$ and $(3.3 \pm 1.3) \times 10^{-3}$ dB/km were recorded at altitudes of 67.8 and 63.8 km, respectively (see Table 1 in [3]). Unfortunately, there is no electron-density data for these altitudes, which prevents the determination of ν values. It can be seen from Fig. 2 that the values of the absorption coefficient at altitudes above 90 km, where electron density data are available, do not exceed 10^{-3} dB/km. The relative error in reconstructing the absorption coefficient values at these altitudes is obviously greater than 100%. Therefore, the accuracy of reconstructing vertical profile $\nu(h)$ in this measurement session is not sufficiently high ($\delta\nu/\nu > 100\%$).

Figure 3 presents the higher-quality results of reconstructing the vertical profile $\nu(h)$ in the radio-occultation measurement session *FORMOSAT-3/COSMIC-1 GPS-30*, where the signal absorption in the DM range was reliably registered. Measurements were conducted at 19:41 UT on June 22, 2015, and show the most significant disturbances caused by both powerful X-ray bursts and changes in geomagnetic conditions during the main phase of the storm. The values of absorption coefficient Z in this measurement session were determined with an error of $\delta Z \approx 1.4 \times 10^{-3}$ dB/km. The local maximum of the absorption coefficient is located at an altitude of 91.8 km and reaches the maximum value of $(5.7 \pm 1.4) \times 10^{-3}$ dB/km for all sessions in the analysis [3, 4]. The most reliable results in reconstructing vertical profile $\nu(h)$ are indicated by letters, and the error values for the selected experimental points are provided in the figure caption. The results of reconstructing the $\nu(h)$ profile demonstrate elevated values of effective collision frequency $\nu \approx 10^8$ s^{-1} for electrons at altitudes ~91–92 km, which were obtained from the analysis of data in this measurement session with sufficient accuracy (~26–27%).

Figures 4 and 5 present data on the effective collision frequency ν of electrons obtained on June 23, 2015, during measurements in the Earth's ionosphere at 05:06 UT (Fig. 4) and 07:28 UT (Fig. 5). The measurement times correspond to the end of the main phase of a magnetic storm (~03:00–05:00 UT) [1, 3]. As is seen from the data, radio-wave absorption in these two sessions is quite clear. The uncertainty in determining radio-wave-absorption coefficient Z was $\delta Z \approx 1.7 \times 10^{-3}$ and ~1.1×10^{-3} dB/km, respectively. The most reliable results in reconstructing the vertical $\nu(h)$ profiles are indicated by letters, and error values for the selected experimental points are provided in the figure captions.

We compared our results with collision frequency ν_m of monoenergetic electrons presented in [9] (Fig. 1). The authors of that study claim that the results they present generalize the most reliable data obtained by

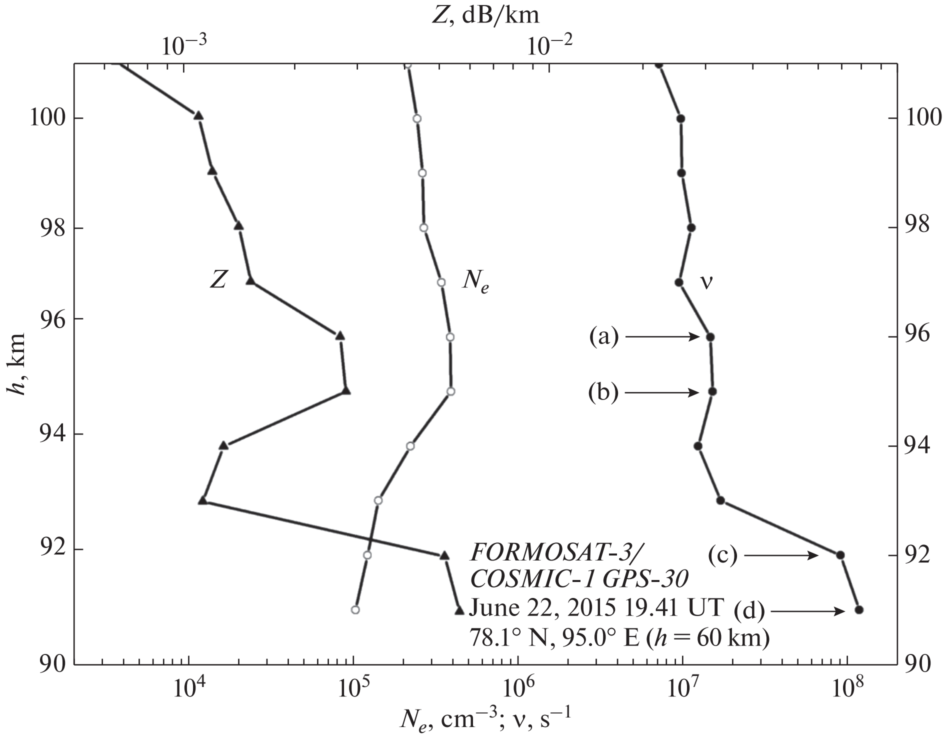

Fig. 3. Same as Fig. 1, but for the *FORMOSAT-3/COSMIC-1 GPS-30* measurement session (June 22, 2015). Values of relative error δν/ν for the selected experimental points: (*a*) ~50, (*b*) ~50, (*c*) ~27, and (*d*) ~26%.

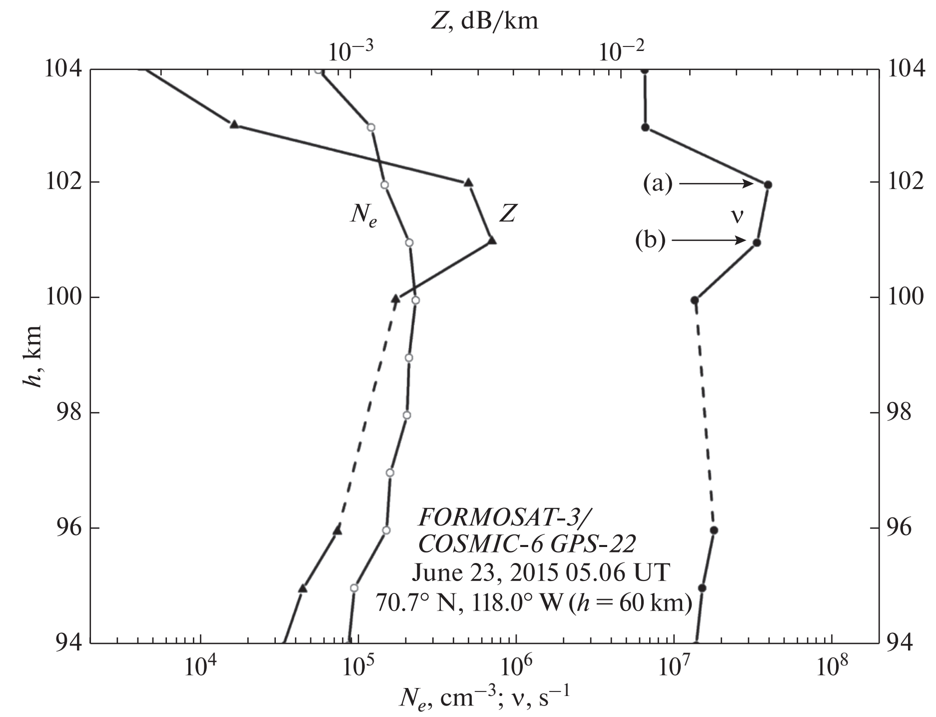

Fig. 4. Same as Fig. 1, but for the *FORMOSAT-3/COSMIC-6 GPS-22* measurement session (June 23, 2015). Values of relative error δν/ν for the selected experimental points: (*a*) ~53 and (*b*) ~52%.

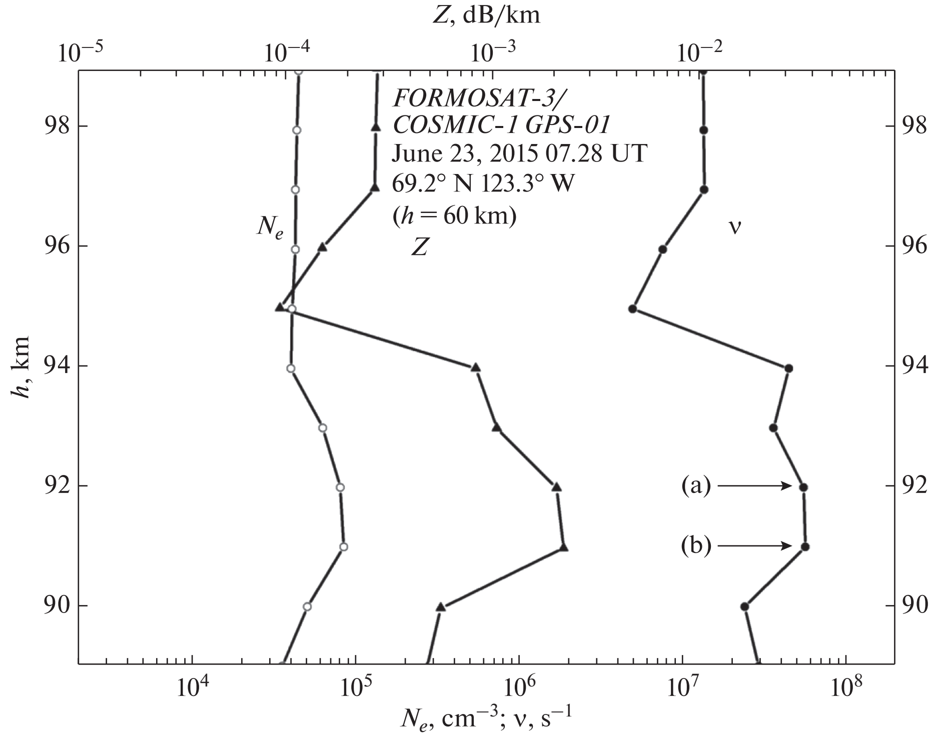

Fig. 5. Same as Fig. 1, but for the *FORMOSAT-3/COSMIC-1 GPS-01* measurement session (June 23, 2015). Values of relative error $\delta\nu/\nu$ for the selected experimental points: (*a*) ~52 and (*b*) ~52%.

various researchers. Unfortunately, these results do not contain information for the altitude range of ~88–106 km, which makes it challenging to compare our data with the results of [9]. In the region of overlapping data, at an altitude of ~70 km, collision frequency ν_m of monoenergetic electrons is ~7×10^6 s^{-1} and matches the Larmor frequency of electrons in absolute value [9, 11]. According to our data (Fig. 1), the values of the effective collision frequency of electrons at altitudes of ~74 and ~66 km are (~$2.5 \pm 1.1) \times 10^7$ and (~$2.0 \pm 1.5) \times 10^7$ s^{-1}, respectively. Thus, we see that our data differ from the results of study [9] by approximately a factor of 3. These differences may be associated with the fact that our measurements were conducted during a strong magnetic storm, while the data presented in [9] pertain to a quiet geomagnetic period in Earth's ionosphere.

Model representations of the altitude–time variations of the collision frequency of electrons with molecules in the undisturbed mid-latitude *D* region of the ionosphere were presented and analyzed in [12]. The models involved method of partial reflections (PR) and rocket methods. The experimental results showed that variations in $\nu(h)$ in the mid-latitude *D* region during daylight hours do not exceed the measurement errors of the PR method (≤30%), indicating no dependence of collision frequencies on the solar zenith angle. Based on numerous experiments, a seasonal dependence of $\nu(h)$ was established. For example, at an altitude of 66 km, the average collision-frequency values for summer and winter conditions are 1.74×10^7 and 1.64×10^7 s^{-1}, respectively, which align well with our data at the same altitude (Fig. 1).

In [13] (Fig. 7), the profile of the effective collision frequency of electrons in the *D* region was determined based on radar measurements of incoherent scatter and accompanying riometric measurements. The value of effective collision frequency ν at an altitude of ~65 km is ~10^7 s^{-1}, which also corresponds to our data, considering the ν reconstruction errors.

CONCLUSIONS

As a result of the analysis of radio-occultation data, a method has been developed for reconstructing vertical profiles of the effective collision frequency of electrons in the *D* and *E* regions of the Earth's ionosphere. The effective collision frequency of electrons in the *D* and *E* regions of the high-latitude ionosphere during the magnetic storm on June 22–23, 2015, has been estimated using data on vertical profiles of the absorption coefficient of DM radio waves and electron density reconstructed from the *FORMOSAT-3/COSMIC* radio-occultation measurements. The practical significance of studying the collision frequency of electrons and radio wave absorption effects in the *D* and *E* regions of the Earth's ionosphere is associated with maintaining the uninterrupted operation of space communication and navigation systems.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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