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Variations in the Parameters of Radio Waves in the Earth's High-Latitude Ionosphere on the Satellite–Satellite Paths during the Geomagnetic Storm of June 22–23, 2015

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Abstract—This paper analyzes the results of about 100 radio occultation sessions of sounding of the high-latitude (>65 °N) lower ionosphere of the Earth's Northern Hemisphere, which were carried out on June 22–23, 2015, on the carrier *GPS* frequency of 1545.42 MHz (*L1* range) in the *FORMOSAT-3/COSMIC* experiment. Coronal plasma ejections that reached Earth during this period provoked a magnetic storm of class *G4* (a strong geomagnetic storm with a planetary *Kp* index is 8), which, in turn, caused significant ionospheric fluctuations of radio waves on "navigation (*GPS*) satellites–low-orbit (*FORMOSAT-3/COSMIC*) satellites" sounding paths.

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1. INTRODUCTION

In the summer of 2015 (June 22–23), coronal mass ejections (CMEs) towards the Earth (one giant and several small ejections) took place on the Sun. This event was recorded by many spacecraft and ionospheric stations [1–4]. The most powerful ejection was identified by the magnetometer as a jump in the interplanetary magnetic field (IMF) from ~10 to ~40 nT, as well as also being noted by the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) instrument as a sudden increase in the solar wind density from ~20 to ~45 particles/cm^3 with a corresponding increase in pressure to values over 50 nPa [1]. A collision of the CME with the bow shock was expected on June 22, 2015, at ~18.36 UT, after a weaker shock at ~05.40 UT. Geomagnetic conditions during the storm on June 22–23, 2015 (density, velocity, and pressure of the solar wind; components *Bx*, *By*, and *Bz* of the interplanetary magnetic field and the angle of the IMF vector), are shown in detail in Fig. 1 of work [1]. The Boyle's index associated with the strong southern component of the IMF vector [1, see Fig. 1d] sent a "yellow signal" of alarm at 06.04 UT and a "red signal" at 18.34 UT on the eve of the collision of the CME with the bow shock.

Coronal mass ejections were accompanied by powerful fluxes of X-ray radiation, which was recorded by the *GOES-13* and *-15* spacecraft in geostationary orbit (Fig. 1, left panel). These ejections provoked a strong magnetic storm of class G4 (G4 = *Kp* – 4). The right panel in Fig. 1 shows the estimates of the planetary *Kp* index for the period of June 22–23, 2015, taken from the Space Weather Data Archive (URL: ftp://ftp.swpc.noaa.gov/pub/warehouse/).

The purpose of the work is to analyze radio signals of the *L1* range (with a frequency of 1575.42 MHz), emitted by transmitters of satellites of the *GPS* navigation system and recorded by receivers onboard the *FORMOSAT-3/COSMIC* satellites, to determine the parameters of the small-scale structure of the Earth's high-latitude ionosphere at heights from 50 before 110 km during a geomagnetic storm in June 2015.

2. SELECTION OF *FORMOSAT-3/COSMIC* RADIO OCCULTATION SESSIONS

Radio sounding of the Earth's atmosphere and ionosphere was carried out according to the satellite–satellite scheme involving high- (*GPS*/*GLONASS*) and low-orbit (*LEO*) satellites in different combinations, for example, geostationary satellite–*MIR* orbital station, *GPS*–*MICROLAB*, *GPS*–*GRACE*, *GPS*/*GLONASS*–*METOP*, *GPS*–*CHAMP*, *GPS*–*FORMOSAT-3*/*COSMIC*, and others. There is an extensive literature on the results of the analysis of these experiments [5–7]. To obtain estimates of the parameters of the small-scale structure of the lower ionosphere during the previously mentioned geomagnetic storm, we use the large *FORMOSAT-3/COSMIC* database. We selected about 100 radio occultation sessions of measurements carried out in the period from 22 to 23 June 2015. The selected sessions were performed at latitudes from 65° to 88° N and covered an altitude interval of 50–110 km.

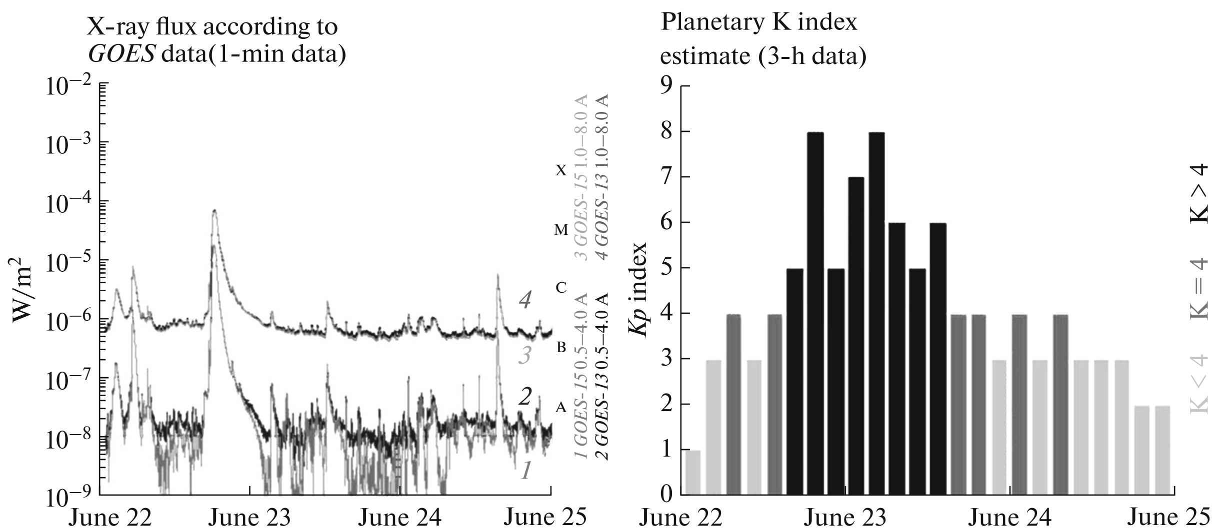

Fig. 1. X-ray fluxes (left panel) recorded on June 22–23, 2015, by the spacecraft *GOES-13* and *-15* in geostationary orbit and estimates of the planetary *Kp* index (right panel).

It was shown in [5, 8, 9] that there is a relationship between power P_L of the signal received on the *LEO* satellite, refractive attenuation of radio wave power X, and acceleration a_ψ of the eikonal (phase path ψ):

$$1 - X(t) = ma_\psi = m \cdot d^2\psi/dt^2, \quad m = r_\psi/(dp_0/dt)^2, \quad r_\psi = L_L \cdot L_G/L_0, \tag{1}$$

where p_0 is the impact parameter of the radio ray; L_L and L_G are, respectively, the distances from receiver L and transmitter G to the ray perigee point; and L_0 is the distance from transmitter to receiver in a straight line [5]. Figure 2 shows two typical height profiles of normalized power P of the signal measured before the geomagnetic storm on June 22, 2015, by the *FORMOSAT-3/COSMIC-6* satellite and refractive attenuation of radio waves X recovered from the data on the eikonal using expression (1). The curves in Fig. 2 were obtained by smoothing the experimental data using the moving average method over 15 points. To find dimensionless quantity P, power received by the *FORMOSAT-3/COSMIC-6* satellite signal P_L was normalized to the value of average power of radio waves P_0 at altitudes over 300 km; i.e., $P = P_L/P_0$. The date and local time of the measurement session, as well as coordinates (latitude and longitude) of the sounded area are indicated above each part of the figure. It can be seen that profiles shown in Fig. 2 exhibit height-correlated quasi-periodic variations in the values of $P(h)$ and $X(h)$. It was found that the cross-correlation coefficient for these variations at the indicated height interval is at least 50%.

The beginning of a geomagnetic storm cannot be detected from radio occultation data. Nevertheless, since the passage of a powerful X-ray flux (Fig. 1), fluctuations in the values of $P(h)$ and $X(h)$ increase in the interval of 80–100 km of the Earth's high-latitude ionosphere. Note that electron concentration N_e increases at night, becoming more than 10^5 cm^{-3} (Figs. 3, 4).

Comparing the graphs in Fig. 3 (panels a, c), it can be seen that the altitude position of the maximum of the electron concentration in the ionospheric layer practically coincides with the position of the minimum of the refractive attenuation of the signal. This corresponds to the results obtained in [8–10], where it was shown that during radio occultation sounding of sporadic E structures (E_s) in the Earth's ionosphere, when the propagation vector is parallel to the ionization plane E_s layer, the passage of radio waves to its central part (peak of electron density) leads to strong defocusing of the rays and, when passing through the edges, to their focusing.

As can be seen from the data presented in Fig. 4, for radio sounding in the region of the Earth's polar cap (78.03° N, 96.65° E) at altitudes from 101.5 to 90.3 km (the ray descends from top to bottom), the power of decimeter radio waves on average falls to a level of 0.1 (–10 dB), then returns to the value 0.5 (–3 dB), and then remains at the same level. Radio sounding of another region of the polar cap (78.1° N, 65.02° E) showed that, at an altitude of 89.5 km, the average signal level drops to 0.5 (–3 dB) and then remains at this level (see Fig. 4). Dependency analysis of $X(h)$ in Fig. 4 shows that the average $\langle X \rangle$ equals $\langle X \rangle = 1$ (0 dB); i.e., there is practically no refractive attenuation in the altitude range from 50 to 90 km. Therefore, we believe that the above signal power attenuation $P(h)$ observed in the analyzed height interval may be associated with the absorption of radio waves in the lower ionosphere of the Earth during a geomagnetic storm.

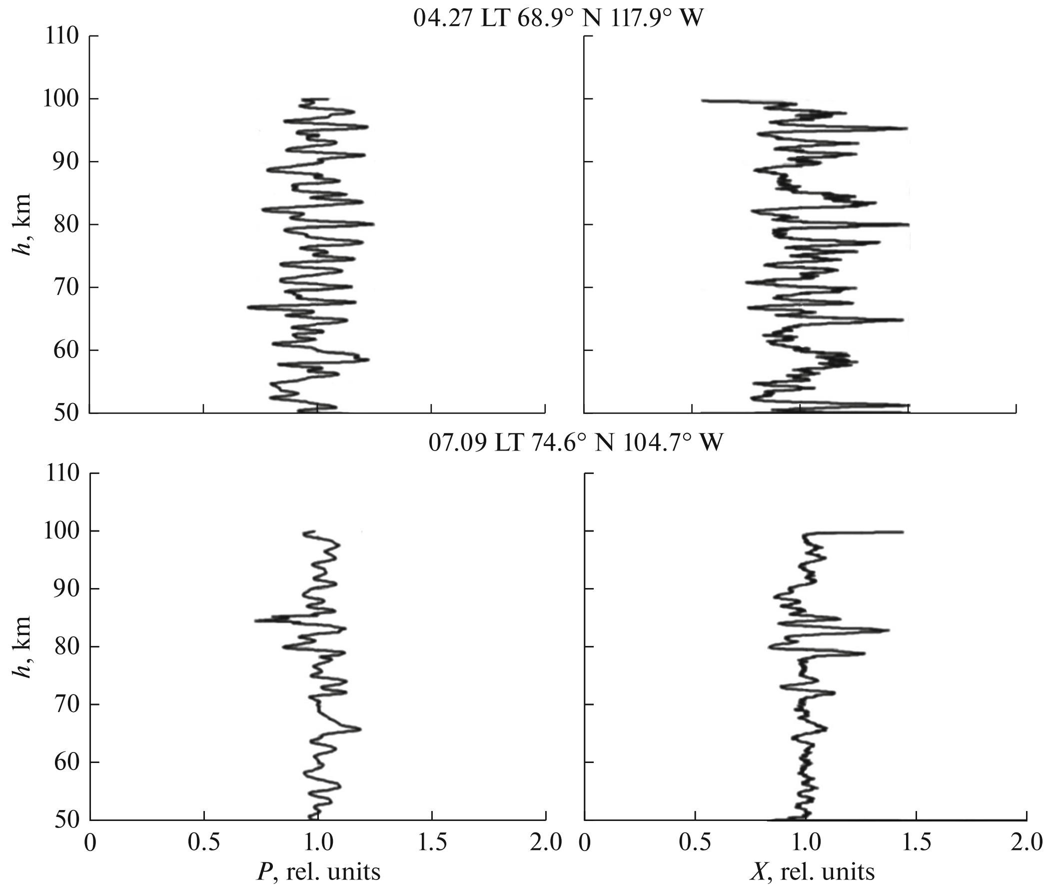

Fig. 2. Altitude profiles of normalized signal power *P*, measured before the geomagnetic storm on June 22, 2015 by the *FORMOSAT-3/COSMIC-6* satellite, and refractive attenuation of radio waves *X* retrieved from eikonal measurements.

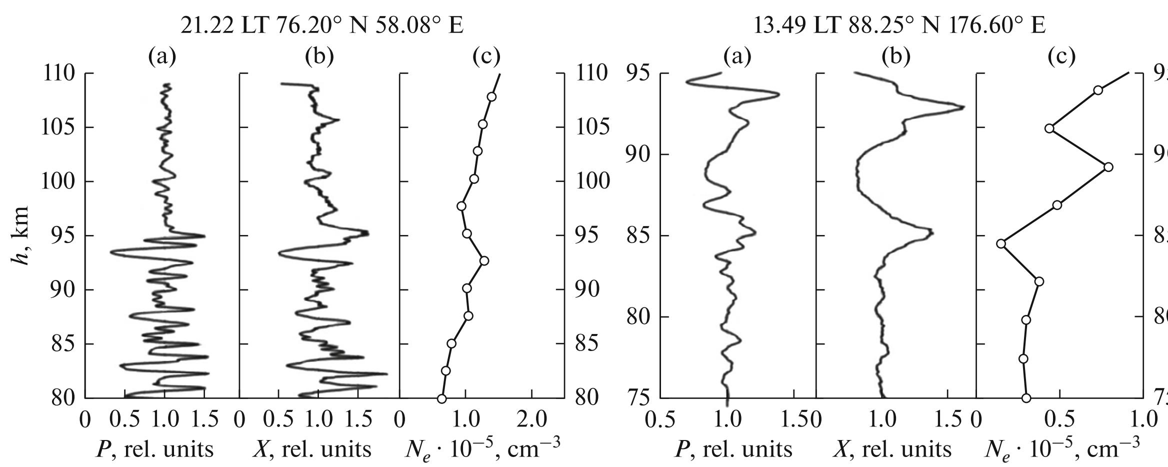

Fig. 3. Altitude dependences of normalized power *P*(h), refractive attenuation *X*(h), and electron concentration $N_e(h)$ obtained from *FORMOSAT-3/COSMIC-6* satellite radio occultation data on June 22, 2015, at 21.22 LT in the ionospheric region.

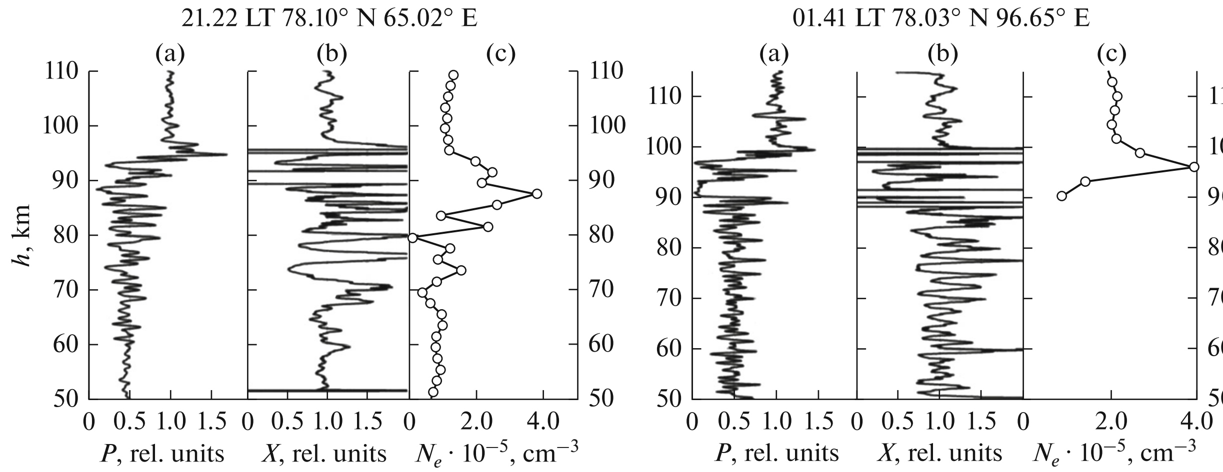

Fig. 4. Altitude dependences of normalized power $P(h)$, refractive attenuation $X(h)$, and electron concentration $N_e(h)$ obtained from *FORMOSAT-3/COSMIC* radio occultation data on June 22, 2015, at 21.22 LT in the ionospheric region.

3. ABSORPTION OF DECIMETER RADIO WAVES AND ESTIMATING THE EFFECTIVE NUMBER OF COLLISIONS IN THE EARTH'S LOWER IONOSPHERE

A small absorption (up to –1 dB) of radio waves, which can be seen in the data on *GPS* frequencies, was noted in [6]. The most characteristic features of the high-latitude ionosphere (the *D* region) is a specific absorption of radio waves in the polar cap (PCA) caused by the invasion of protons with energies of tens of megaelectronvolts and anomalous auroral absorption associated with precipitation of electrons. During periods of solar flares directed towards the Earth, due to a sharp increase in solar ionizing radiation, mainly in the X-ray range, sudden ionospheric disturbances (SIDs) occur that are manifested in an increase in ionization, mainly in *D* and *E* areas of the ionosphere. Auroral absorption of radio waves, which is often observed in the auroral zone during magnetospheric storms and substorms, is associated with the precipitation of charged particles (mainly electrons with energies of 20–100 keV) from the magnetosphere into the Earth's lower ionosphere [11].

Absorption of *L1* range signals (frequency 1575.42 MHz) was observed very disctictly in two radio occultation sessions of measurements by *FORMOSAT-3/COSMIC* in the Earth's ionosphere (see Fig. 4). In one of them, the attenuation of radio wave power reached –10 dB with a return to –3 dB, and in the other measurement session it was –3 dB (Fig. 4, panels a). Using this data and following work [12], it is possible to determine the vertical profile of absorption coefficient of radio waves *Z* and to evaluate effective number of electron collisions per unit time ν in the Earth's lower ionosphere.

The absorption of radio waves in the lower ionosphere is due to collisions of electrons with ions and neutral molecules. Because of this, some of the energy transferred by the electromagnetic field to the electrons is spent on increasing the energy of the chaotic motion of plasma particles and leads to plasma heating. At each impact, an electron on average transfers momentum $m \times d\mathbf{r}/dt$ to an ion or molecule, where $d\mathbf{r}/dt$ is the mean velocity of electrons under the field influence. If ν is the effective number of collisions of an electron per second, then per unit time its momentum changes by the value $m\nu d\mathbf{r}/dt$. The change in momentum due to collisions is equivalent to the action of a certain frictional force.

Assuming that the frequency of radio waves is $\omega = 2\pi f$ satisfies the inequality $\omega^2 \gg \nu^2$, the authors of [12] obtained the following estimate of absorption coefficient Z of radio waves:

$$Z = \frac{e^2 N_e \nu}{\pi m c f^2} = 2.70 \times 10^{-3} \frac{N_e \nu}{f^2}, \quad [Z] = \text{cm}^{-1}, \qquad (2)$$

where m is electron mass, e is electron charge, c is the speed of light, N_e is expressed in cm^{-3}, ν in s^{-1}, and f in Hz. When propagating through the ionosphere, the radio wave flux is absorbed, and normalized signal power P is equal to [12]

$$P = \exp\left[-\int_{h_{\min}}^{h_{\max}} Z\, ds\right] = \exp\left[\frac{-2.70 \times 10^{-3}}{f^2} \int_{h_{\min}}^{h_{\max}} N_e \nu ds\right]. \qquad (3)$$

Here, integration is performed along the trajectory of the probing radio ray. As can be seen from formula (2), to estimate parameter ν it is necessary to know the vertical profile of the absorption coefficient and the height distribution of the electron concentration. For this purpose, we have profiles of $N_e(h)$ (Fig. 4, panels c) at our disposal, which allow using (3) to solve the inverse problem and determine the vertical profile of absorption coefficient of radio waves $Z(h)$, and also to estimate the value of ν in the lower ionosphere of the Earth.

CONCLUSIONS

The paper analyzes the results of about 100 radio occultation sessions of sounding the high-latitude (>65° N) atmosphere of the Earth's Northern Hemisphere, which were conducted on June 22–23, 2015, at a carrier *GPS* frequency of 1545.42 MHz (*L1* range) in the experiment *FORMOSAT-3/COSMIC*. It was found that the altitude position of the maximum of the electron concentration in the ionospheric layer practically coincides with the position of the minimum of the refractive attenuation of the signal, which corresponds to the results obtained earlier during radio occultation sounding the sporadic *E*-layers in the Earth's ionosphere.

Based on the analysis of *FORMOSAT-3/COSMIC* radio occultation measurements conducted during a strong geomagnetic storm on 22–23 June 2015 (class *G4*), absorption of radio waves in the *L1* range in the lower high-latitude ionosphere of the Earth. The absorption value is ~3 dB in the range of 60–90 km, and in some cases reaches ~10 dB at altitudes from 90 to 95 km. It is shown that the obtained data can be used to determine the altitude profile of the absorption coefficient *Z* radio waves and to estimate the effective number of collisions per second ν in the Earth's lower ionosphere.

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