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Absorption of decimetre radio waves in the Earth's high-latitude ionosphere during a geomagnetic storm in June 2015

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Abstract. We have analyzed the radio occultation (RO) results of ~100 sounding sessions of the high-latitude (>65°N) lower ionosphere of the Earth's northern hemisphere, which were carried out on 22–23 June 2015 at the GPS-frequency of 1545.42 MHz (L1 band) in the *FORMOSAT-3/COSMIC* experiment. Coronal plasma ejections that reached the Earth in this period provoked a class G4 magnetic storm (strong geomagnetic storm with planetary Kp -index equal to 8), which in turn caused significant ionospheric fluctuations of radio waves on the sounding paths: navigation (GPS) satellites – low-orbit (*FORMOSAT-3/COSMIC*) satellites. For the first time, the analysis of *FORMOSAT-3/COSMIC* radio frequency measurements revealed the absorption of L1 radio waves 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 it is possible to obtain the absorption coefficient of GPS-frequency radio waves in the Earth's ionosphere at these altitudes from experimental data of *FORMOSAT-3/COSMIC*.

1. Introduction

In the summer of 2015 (June 22–23), coronal mass ejections (CME) toward the Earth took place on the Sun (one giant and several small ejections). This event was recorded by many spacecraft and ionospheric stations [1–4]. The most powerful ejection was identified by a magnetometer as a jump of interplanetary magnetic field (IMF) from ~10 to ~40 nT, and it was also noted by SWEPAM (Solar Wind Electron, Proton, and Alpha Monitor) instrument as a sudden increase in solar wind density from ~20 to ~45 particles/cm³ with a corresponding increase in pressure to values above 50 nPa [1]. The impact of the CME with the bow shock was expected on June 22, 2015 at ~ 18.36 UT, after a smaller shock at ~05.40 UT. The geomagnetic conditions on June 22–23, 2015 during the storm (density, speed and pressure of the solar wind; components B_x , B_y , B_z of the interplanetary magnetic field and the IMF vector angle) are presented in detail in figure 1 of work [1]. The Boyle index associated with the strong southward component of the IMF vector [1, see figure 1e], sent a “yellow alert” signal at 06.04 UT and a “red alert” at 18.34 UT before the CME impacted the bow shock.

Coronal mass ejections were accompanied by powerful X-ray fluxes, which were detected by the geostationary *GOES-13* and *-15* spacecraft (figure 1, left panel). These ejections provoked a strong magnetic storm of class G4 on Earth ($G4 = Kp - 4$). The right panel of figure 1 presents estimates of the planetary Kp -index for period June 22–23, 2015, taken from the space weather data archive (URL: <ftp://ftp.swpc.noaa.gov/pub/warehouse/>).

The aim of this work is to analyze L1 radio signals (carrier frequency 1575.42 MHz), emitted by transmitters from GPS satellites and recorded by receivers onboard low orbital *FORMOSAT-*



3/*COSMIC* satellites, in order to determine the small-scale structure of the Earth's high-latitude ionosphere at altitudes from 50 to 110 km during geomagnetic storms in June 2015.

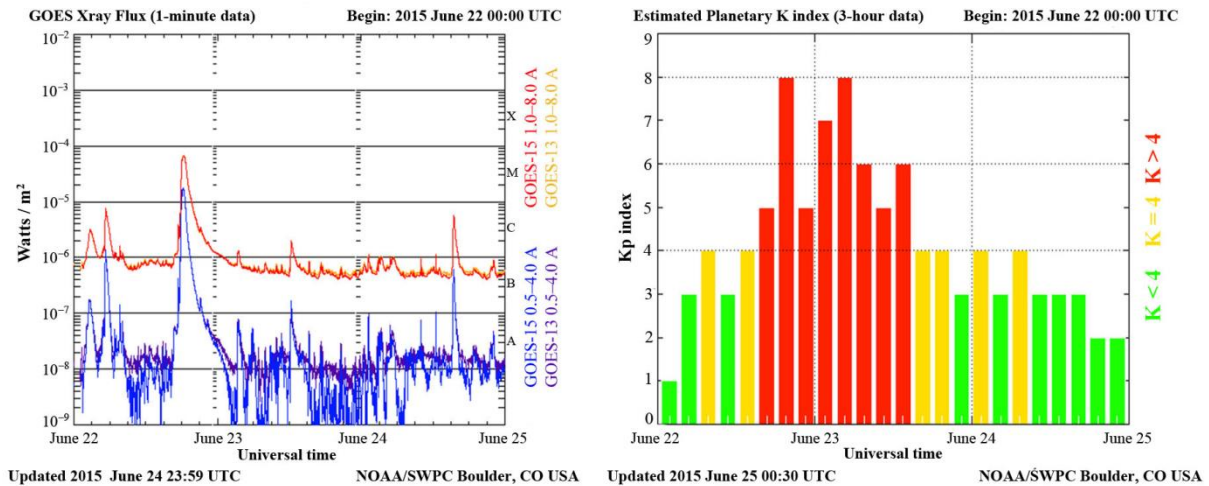


Figure 1. X-ray fluxes (left panel) recorded on June 22–23, 2015 by *GOES-13* and *-15* geostationary spacecraft, and planetary *Kp*-index estimates (right panel) (this figure was taken from the space weather data archive: <ftp://ftp.swpc.noaa.gov/pub/warehouse/>)

2. Selecting the radio occultation sessions of the *FORMOSAT-3/COSMIC* satellites

Radio soundings the Earth's atmosphere and ionosphere with aid the satellite-satellite communication links (when high-orbital (*GPS/GLONASS*) and low-orbital satellites are used) were carried out earlier in different combinations, for example: *GPS – MICROLAB*, *GPS – GRACE*, *GPS/GLONASS – METOP*, *GPS – CHAMP*, *GPS – FORMOSAT-3/COSMIC* and others. Detailed analysis of these experimental results was made in the works [5–7]. To obtain parameter estimates of the small-scale structure in the Earth's lower ionosphere during above mentioned geomagnetic storm, we selected from the large *FORMOSAT-3/COSMIC* database about 100 radio occultation measurements carried out from June 22 to 23, 2015. The selected RO sessions were performed at latitudes from 65°N to 88°N and they covered an altitude interval from 50 to 110 km.

It was shown in works [5, 8, 9] that there is a relationship between the power (P_L) of the RO signal received on a low-orbit satellite, the refractive attenuation of radio waves (X), and the acceleration (a_ψ) of the eikonal (phase-path increase ψ):

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

where p_0 is the impact parameter of radio ray, L_L and L_G are distances from the receiver (L) and transmitter (G) to the ray perigee point respectively, L_0 is the distance from transmitter to receiver along the straight line [5]. Figure 2 shows two typical altitude profiles of the normalized signal power (P) measured by the *FORMOSAT-3/COSMIC-6* satellite before geomagnetic storm on June 22, 2015 and the refractive attenuation of radio waves (X) reconstructed from eikonal data using expression (1). Curves shown in figure 2 were obtained by the fifteen points smoothing of experimental data using the moving average method. In order to find the dimensionless value P , the power P_L of signal received on the *FORMOSAT-3/COSMIC-6* satellite was normalized to the average power of radio waves (P_0) at altitudes more than 300 km, i.e. $P = P_L/P_0$. Above each part of this figure we indicated: numbers of the respective satellites from the *FORMOSAT-3/COSMIC* and *GPS* groups, the date and local time of the measurement session, as well as the coordinates (latitude and longitude) of the probed region. It can be seen that in the profiles presented in figure 2, there are quasiperiodic variations of values $P(h)$ and

$X(h)$ which are correlated in height. It was found that the cross-correlation coefficient for these variations over the indicated height interval is at least 50%.

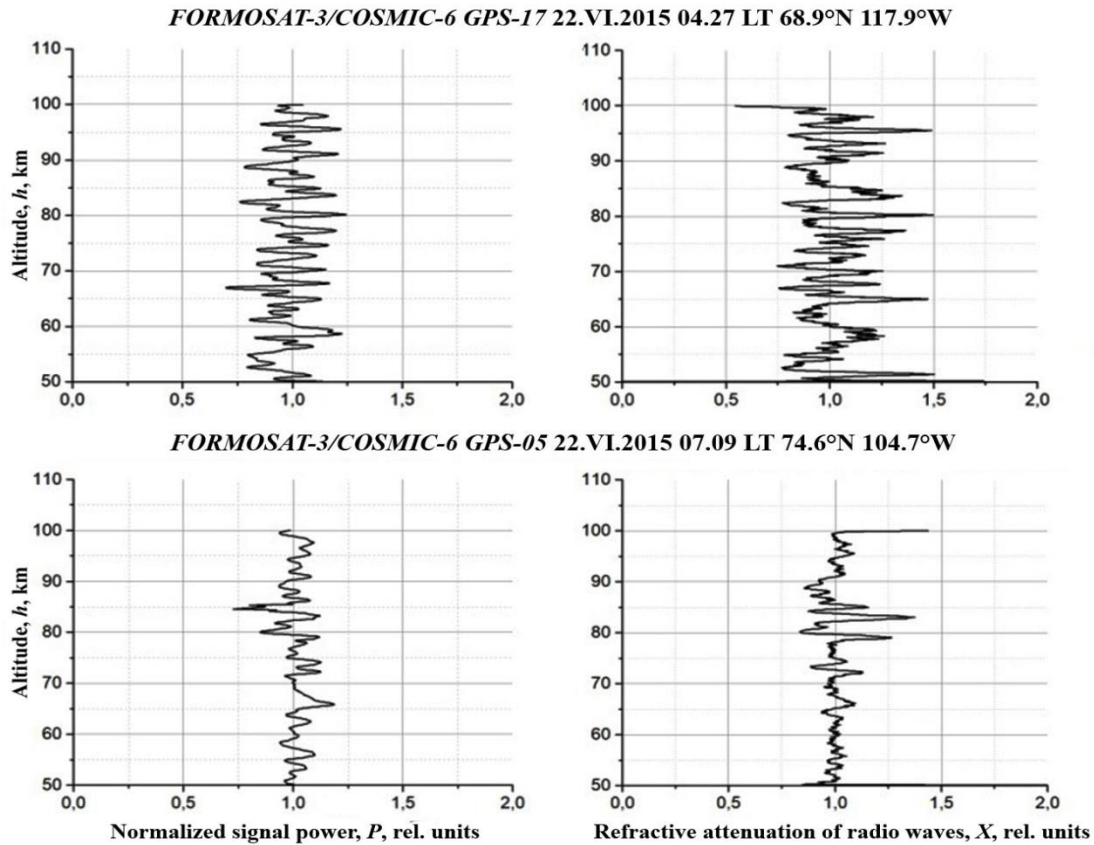


Figure 2. Altitude profiles of normalized signal power (P), measured before geomagnetic storm on June 22, 2015 by the *FORMOSAT-3/COSMIC-6* satellite, and refractive attenuation of radio waves (X) recovered from eikonal measurements

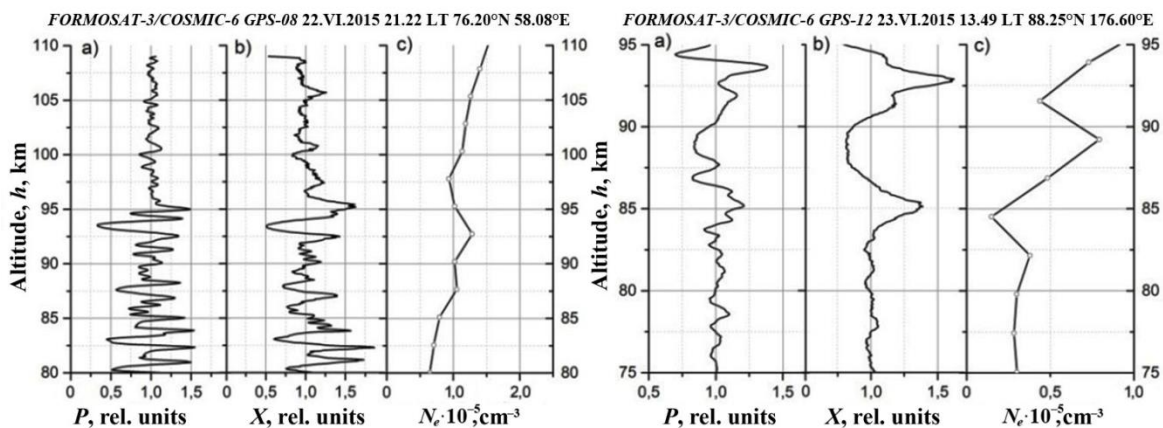


Figure 3. Altitude profiles of normalized power – $P(h)$, refractive attenuation – $X(h)$ and electron concentration – $N_e(h)$ obtained from the RO data of the *FORMOSAT-3/COSMIC-6* satellite 22.VI.2015 at 21.22 LT in the ionospheric region with coordinates 76.2°N; 58.08°E (left) and 23.VI.2015 at 13.49 LT in the region with coordinates 88.25°N; 176.6°E (right)

Although the beginning of geomagnetic storm from radio occultation data we cannot detect, however, from the moment of passage of the powerful X-ray flux (figure 1), fluctuations of the $P(h)$ and $X(h)$ values in the interval 80–100 km of the Earth's high-latitude ionosphere increase. Note that the electron concentration N_e increases at night, becoming more than 10^5 cm^{-3} (figures 3 and 4). From a comparison of the graphs in figure 3 (panels a and c), it can be seen that the altitude position of electron concentration maximum in the ionospheric layer practically coincides with the position of refractive attenuation minimum of the signal. This corresponds to results obtained in the works [8–10], where it was shown that during radio occultation sounding the sporadic E_s -structures (E_s) in the Earth's ionosphere when the propagation vector is parallel to the ionization plane of E_s -layer, then the radio wave propagation through its central part (the electron density peak) leads to strong defocusing of the rays, and when passing through the edges – to their focusing.

As can be seen from data presented in figure 4, when radio sounding 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 decreases on average to 0.1 (–10 dB), then returns to 0.5 (–3 dB) and further remains at the same level. Radio sounding of another region of the polar cap (78.1°N; 65.02°E) showed that the average signal level drops to 0.5 (–3 dB) at an altitude of 89.5 km and then remains at that level (see figure 4). An analysis of profiles $X(h)$ in figure 4 shows that the average value $\langle X \rangle = 1$ (0 dB), i.e. refractive attenuation in altitude range from 50 to 90 km is practically absent. Therefore, we believe that the aforementioned attenuation of signal power $P(h)$ observed in the analyzed altitude range can be associated with the radio wave absorption in the Earth's lower ionosphere during geomagnetic storm.

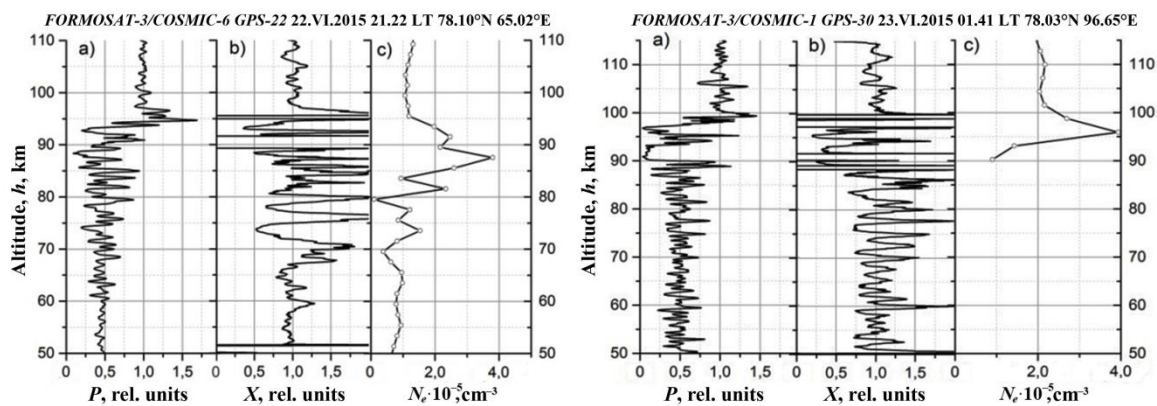


Figure 4. Altitude profiles of the normalized power – $P(h)$, refractive attenuation – $X(h)$ and electron concentration – $N_e(h)$, obtained from *FORMOSAT-3/COSMIC* radio occultation data on 22.VI.2015 at 21.22 LT in the ionospheric region with coordinates 78.1°N; 65.02°E (left) and 23.VI.2015 at 01.41 LT in the region with coordinates 78.03°N; 96.65°E (right)

3. Absorption of decimetric 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 RO data at GPS frequencies, was mentioned in the work [6]. The most characteristic features of the high-latitude ionosphere (D -region) are special absorption of radio waves in the polar cap, caused by the proton invasion with energies of tens MeV and anomalous auroral absorption associated with electron precipitations. During periods of solar flares directed toward the Earth, due to a sharp increase in solar ionizing X-ray radiation, the sudden ionospheric disturbances occur which manifest themselves as ionization increase, mainly in the D - and E - ionospheric regions. Auroral radio wave absorption, observed often in the aurora zone during periods of magnetospheric storms and substorms, is

associated with precipitations of charged particles (mainly electrons with energies of 20–100 keV) from the magnetosphere to the Earth's lower ionosphere [11].

The absorption of *LI* band signals was observed very clearly in two radio occultation sessions of *FORMOSAT-3/COSMIC* measurements in the Earth's ionosphere (see figure 4). In one of them, an attenuation of the radio wave power reached –10 dB with a return to the level of –3 dB. In other RO measurement session it was –3 dB (figure 4, panels a). Using these data and following to the work [12], one can determine the vertical profile of the radio wave absorption coefficient (Z) and estimate the effective number of electron collisions per unit time (ν) in the Earth's lower ionosphere.

The radio wave absorption in the lower ionosphere is due to collisions of electrons with ions and neutral molecules. Because of this, part of the energy transmitted by the electromagnetic field to electrons is spent on increasing the chaotic motion energy of plasma particles and leads to its heating. With each impact, an electron, on average, transfers a momentum $m \cdot dr/dt$ to an ion or molecule, where dr/dt is a mean electron speed caused by the electromagnetic field. If ν is the effective number of electron collisions per second, then its momentum changes by the value $m \cdot \nu \cdot dr/dt$ per unit time. The change in momentum due to collisions is equivalent to the action of a certain friction force. Assuming that the frequency of the radio waves $\omega = 2\pi f$ satisfies the inequality $\omega^2 \gg \nu^2$, authors of the work [12] obtained the following estimate of absorption coefficient Z of radio waves:

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

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

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

Here, integration is performed along the trajectory of the probing radio ray. As can be seen from formula (2), in order to estimate the parameter ν it is necessary to know the vertical profile of absorption coefficient and the distribution of electron concentration with height. For this, we have at our disposal profiles $N_e(h)$ (figure 4, panels c). Using expression (3), one can solve the inverse problem and determine the vertical profile of radio wave absorption coefficient $Z(h)$, as well as estimate the value ν in the lower Earth's ionosphere.

4. Conclusion

The results of about 100 radio occultation sessions of probing the high-latitude ($>65^\circ\text{N}$) ionosphere of the Earth's northern hemisphere have been analyzed in the work. These *FORMOSAT-3/COSMIC* measurements were carried out on June 22–24, 2015 at the carrier GPS-frequency 1545.42 MHz (band *LI*). It was found that the altitude location of electron concentration maximum in the ionospheric layer practically coincides with the altitude position of refractive attenuation minimum of the signal, which corresponds to early RO sounding results of sporadic *E*-layers in the Earth's ionosphere.

Based on the analysis of *FORMOSAT-3/COSMIC* RO measurements carried out during strong geomagnetic storm June 22–23, 2015 (class *G4*), the absorption of decimeter radio waves (*LI* band) in the Earth's high-latitude lower ionosphere was detected. The absolute value of absorption is ~3 dB in the interval of 60–90 km, and in some cases it reaches ~10 dB at altitudes from 90 to 95 km. It is shown that, based on the data obtained, one can find altitude profiles of the absorption coefficient Z of radio waves and estimate the effective number of collisions per second ν in the Earth's lower ionosphere.

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