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The Absorption Coefficient of Decimeter Radio Waves (~19 cm) in the Earth's Ionosphere Based on the Inverse Problem Solution in Radio Occultation Satellite Studies during the June 2015 Magnetic Storm

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Abstract—The absorption of decimeter (DM) radio waves (wavelength ~19 cm) in the high-latitude lower ionosphere of the Earth is found based on analysis of *FORMOSAT-3/COSMIC* radio occultation data. A method is proposed to reconstruct the vertical profiles of the absorption coefficient by solving the inverse problem of radio sounding in the Earth's lower ionosphere. This method is general and can be used for different radio wave bands and other global navigation satellite system (GNSS) signals. During radio occultation sessions the absorption layers, which are caused by powerful X-ray bursts and strong changes in geomagnetic conditions during storms, are reliably identified. It is also found that at altitudes of ~90 to ~100 km, the absorption coefficient of DM radio waves reached values of $(5.7 \pm 1.4) \times 10^{-3}$ dB/km. The practical significance of studying the effects of radio wave absorption in the *D*- and *E*-regions of the ionosphere is associated with ensuring smooth operation of space radio communication and navigation systems.

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1. INTRODUCTION

Previously, we processed and analyzed ~100 satellite radio occultation sessions from the *FORMOSAT-3/COSMIC* spacecraft that took place during the geomagnetic storm of June 22–23, 2015 in the Earth's high-latitude ionosphere [1, 2]. It was shown that ionospheric disturbances of radio wave characteristics are caused by both geomagnetic conditions and the activity of powerful X-ray flares during the measurements. The radio occultation sessions taken after the onset (16:30 UT June 22, 2015) of the powerful X-ray bursts and during the main phase (18:36 UT June 22–02:00 UT June 23) of the magnetic storm were characterized by elevated electron density in the *D*- and *E*-regions of the Earth's ionosphere. We also searched for the absorption of decimeter (DM) radio waves (~19-cm signal wavelength) on GPS carrier frequency f_1 = 1545.42 MHz. By means of the analysis of eikonal and DM signal intensity measurements from *FORMOSAT-3/COSMIC* spacecraft, the absorption of DM radio waves in the *D*- and *E*-regions of the Earth's high-latitude ionosphere was first detected [1, 2]. It was found that the absolute value of the integral absorption in radio occultation traces is ~3 dB in the altitude range of ~50–90 km; and in some cases, it reaches ~10 dB at levels from ~90 to ~95 km.

In [3, 4], expressions for determining refractive attenuation *X* of the radio wave power were presented:

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

where a_{ψ} is the eikonal (phase path ψ) acceleration, p_0 is the impact parameter of the radio beam, and L_L and L_G are the distances from the receiver (LEO) and transmitter (GPS) to the planet's limb, correspondingly. There is a relation between refractive attenuation *X* and normalized signal power *P* measured on the *FORMOSAT-3/COSMIC* low-orbit spacecraft. In order to find dimensionless value *P,* power P_L of the signal received at the low-orbit satellite was normalized to mean power value P_0 of radio waves at altitudes over 300 km; i.e., $P = P_L/P_0$.

Integral absorption Γ of the radio occultation DM signal can be determined using the following relation:

$$\begin{gathered} \Gamma(\text{rel. un.}) = P(\text{rel. un.})/X(\text{rel. un.}), \\ \Gamma(\text{dB}) = P(\text{dB}) - X(\text{dB}). \end{gathered} \tag{2}$$

The practical significance of studying the effects of radio wave absorption in the *D*- and *E*-regions of the

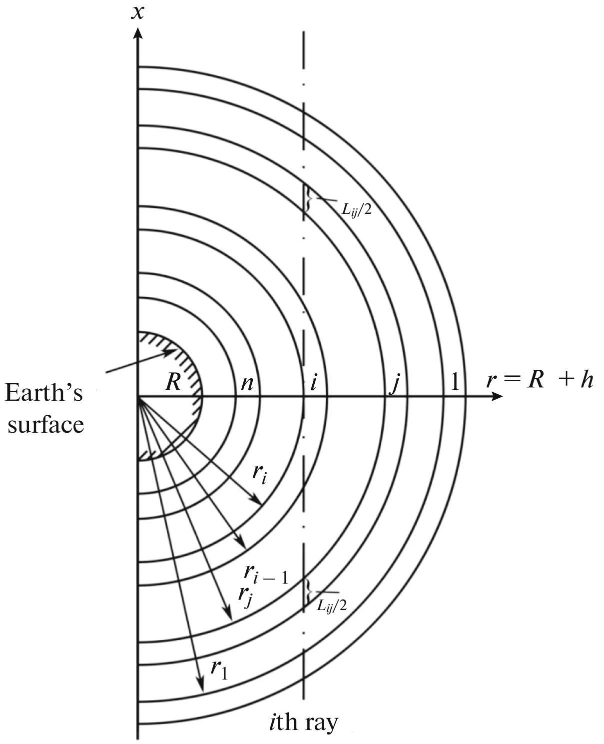

Fig. 1. Cross-section of the Earth's ionosphere consisting of n spherical layers.

Earth's ionosphere is associated with ensuring smooth operation of space radio communication and navigation systems. The possibility of determining absorption in the Earth's atmosphere and ionosphere was previously discussed in [5–9]. Absorption is a function of meteorological parameters and frequency, and it can be used to formulate the inverse problem of the reconstruction of meteorological parameters. Absorption measurements in three frequency ranges (for a sufficiently high accuracy of the signal amplitude measurement) make it possible to reconstruct pressure, temperature, and humidity profiles without a priori information [10].

The goal of this work is to reconstruct the altitude profiles of the $Z(h)$ absorption coefficient of the decimeter signal at altitudes below ~100 km during a magnetic storm in 2015 by solving the inverse problem of radio wave absorption.

2. METHOD FOR SOLVING THE INVERSE PROBLEM OF RADIO WAVE ABSORPTION

Initial experimental data on normalized power $P(h)$ of radio waves were first filtered by the moving average method over 50 points. Thus, the averaged vertical profiles of normalized power $\Theta(h)$ of the decimeter signal were obtained. Here, $h = r - R$ is the height of the analyzed layer above the Earth's surface, where $R = 6371$ km is the mean radius of the planet and r is the distance from the center of the Earth to the ionospheric layer. For the vertical velocity of ray descent in the Earth's ionosphere of ~2 km/s, this corresponds to averaging data over a vertical interval of ~2 km. In the case of such averaging, the information about the fine-scale structure of the ionosphere is obtained almost without loss, because the vertical resolution in the geometric optics (GO) analysis is $2(\lambda L_L)^{1/2} = 1.5$ km, where λ is the signal wavelength (~19 cm) and L_L is the distance from the low-orbiting LEO satellite to the atmospheric limb of the Earth (~3000 km). In geometric optics, two physical rays (rays together with their Fresnel volumes) are considered to be distinguishable if they do not intersect each other. Analysis of refractive attenuation profiles $X(h)$ showed that there is almost no regular (averaged) refractive attenuation $\langle X\rangle$ of the radio wave power in measurement sessions at altitudes >50 km. Therefore, we believe that the observed attenuation of mean signal power $\langle P(h)\rangle$ may be due to the absorption of radio waves in the Earth's lower ionosphere during a magnetic storm [1, 2, 11].

Let us consider in more detail how Eq. (3) can be inversely transformed to obtain the vertical profile of absorption coefficient $Z(h)$:

$$\Theta(h) = \exp\left[-\int_s Z dL\right]. \tag{3}$$

The integration in expression (3) is carried out over trajectory s of the radio ray used to sound the ionosphere. The procedure described here is based on the assumption that the Earth's ionosphere is spherically symmetrical. The geometry of the problem is shown in Fig. 1, where n rays pass through the Earth's ionosphere, which consists of n spherical layers. Figure 1 illustrates and explains a way of solving the inverse problem of radio wave absorption which does not use the Abel transform. Each layer of the ionosphere has constant absorption coefficient Z and constant thickness $\Delta r = \Delta h = 2$ km. For example, if an altitude interval of 110–50 km is analyzed, the number of ionospheric layers is $n = 30$. Here, it is convenient to replace Eq. (3) by a system of the following n linear equations:

$$\Theta(h_i) = \exp\left[-\int_s Z dL\right] = \exp\left[-\sum_{j=1}^{i} L_{ij} Z_j\right], \quad \text{where } i = 1\ldots n, \tag{4}$$

where $\Theta(h_i)$ is the Θ value for ith ray and Z_j is the radio wave power absorption coefficient in the jth layer. Matrix element L_{ij} denotes the length of the part of the

ith ray that is enclosed within the jth layer as shown in Fig. 1.

Let us express $\Theta(h_i)$ in decibels and expand the above expressions (4) as a matrix equation:

$$\Theta_{dB}(h_i) = 10\log\left(\Theta(h_i)\right) = \begin{bmatrix} \Theta_{dB}(h_1) \\ \Theta_{dB}(h_2) \\ \vdots \\ \Theta_{dB}(h_i) \\ \vdots \\ \Theta_{dB}(h_n) \end{bmatrix} = -10\log(e) \times \begin{bmatrix} L_{11} & & & & & \\ L_{21} & L_{22} & & & & \\ \dots & \dots & \dots & & & \\ L_{i1} & L_{i2} & \dots & L_{ii} & & \\ \dots & \dots & \dots & \dots & \dots & \\ L_{n1} & L_{n2} & \dots & L_{ni} & \dots & L_{nn} \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_i \\ \vdots \\ Z_n \end{bmatrix}, \tag{5}$$

where $e = 2.718...$ is the base of natural logarithms, and $10\log(e) = 4.343...$; $j = 1...i$; $i = 1...n$; Z_i is the absorption coefficient of radio waves in the ith layer.

2D matrix L_{ij} is related with the radius of layers of the Earth's ionosphere as

$$\begin{aligned} L_{ij} &= 2\left[\sqrt{r_{j-1}^2 - r_i^2} - \sqrt{r_j^2 - r_i^2}\right] \\ &= 2\left[\sqrt{(R + h_{j-1})^2 - (R + h_i)^2} - \sqrt{(R + h_j)^2 - (R + h_i)^2}\right] \end{aligned} \tag{6}$$

for $i > j$ and as

$$L_{ii} = 2\sqrt{r_{i-1}^2 - r_i^2} = 2\sqrt{(R + h_{i-1})^2 - (R + h_i)^2} \tag{7}$$

for $i = j$.

Solving matrix equation (5) with respect to Z, we obtain

$$\begin{aligned} Z_1 &= -\frac{\Theta_{dB}(h_1)}{4.343 L_{11}}, \\ Z_2 &= \left(-\frac{\Theta_{dB}(h_2)}{4.343} - L_{21}Z_1\right)\Big/ L_{22}, \\ &\dots\dots\dots\dots\dots\dots \\ Z_i &= \left(-\frac{\Theta_{dB}(h_i)}{4.343} - \sum_{j=1}^{i-1} L_{ij}Z_j\right)\Big/ L_{ii}, \\ &\dots\dots\dots\dots\dots\dots \end{aligned} \tag{8}$$

Solving the inverse problem gives us a recurrence relations that explicitly relate the values $Z(h_i)$ with $\Theta_{dB}(h_i)$.

Thus, we determined vertical profiles $Z(h)$ of the radio wave absorption coefficient with an altitude scale of ~2 km and estimated errors of their reconstruction δZ for each analyzed radio occultation session. The estimate of error δZ for analyzed profile $Z(h)$ was the absolute value of its maximal residual when solving the inverse problem of radio wave absorption. The correspondence of the reconstructed absorption coefficient profiles to the initial experimental data was verified using the solution of the direct radio sounding problem for the layers with a width of ~2 km. In this case, calculated radio wave flux power $P_{DP}(h_i)$ was determined by the following formula:

$$P_{DP}(h_i) = -\left[\sum_{j=1}^{i-1} L_{ij}Z_j + L_{ii}Z_i\right] \times 4.343. \tag{9}$$

3. ANALYSIS OF RESULTS AND CONCLUSIONS

Using the solution of the inverse problem of radio sounding, the vertical profiles of the DM radio wave absorption coefficient were found, and the errors of their reconstruction in the Earth's lower ionosphere were determined. The analysis of the results shows that the geomagnetic conditions of the main storm phase and powerful bursts of X-ray fluxes during measurements strongly influenced the propagation of radio waves in the E- and D-layers of the Earth's ionosphere. The verification of the results obtained by solving the direct radio sounding problem showed good agreement between the calculated and initial experimental data:

$$P_{DP}(h_i) \approx \Theta_{dB}(h_i). \tag{10}$$

Figure 2 shows the vertical profiles of normalized power $P(h)$ (solid thin line with breaks), normalized power after filtering $\Theta_{dB}(h)$ (solid thick line), normalized power from the direct radio sounding problem solution $P_{DP}(h)$ (solid thin line), and DM radio wave absorption coefficient $Z(h)$ obtained in radio occultation sessions of 17:22 UT (Figs. 2a, 2b) and 19:01 UT (Figs. 2c, 2d) of June 22, 2015 in the Earth's ionosphere. For each analyzed session, the latitude and longitude of the sounding area, the date and time of the experiment, and the numbers of spacecraft are indicated. Errors δZ of the reconstruction of absorption coefficient profiles $Z(h)$ are given on the right. The measurements related to the profiles in Figs. 2a and 2b were performed after the onset of powerful X-ray bursts (~16:30 UT June 22, 2015) and before the arrival (18:36 UT June 22, 2015) of the main coronal mass ejection (CME) into the Earth's magnetosphere. A feature of sounding of this region with coordinates 77.6° N and 66.1° E is that the mean signal power drops to the level of ~0.5 (–3 dB) at an altitude of

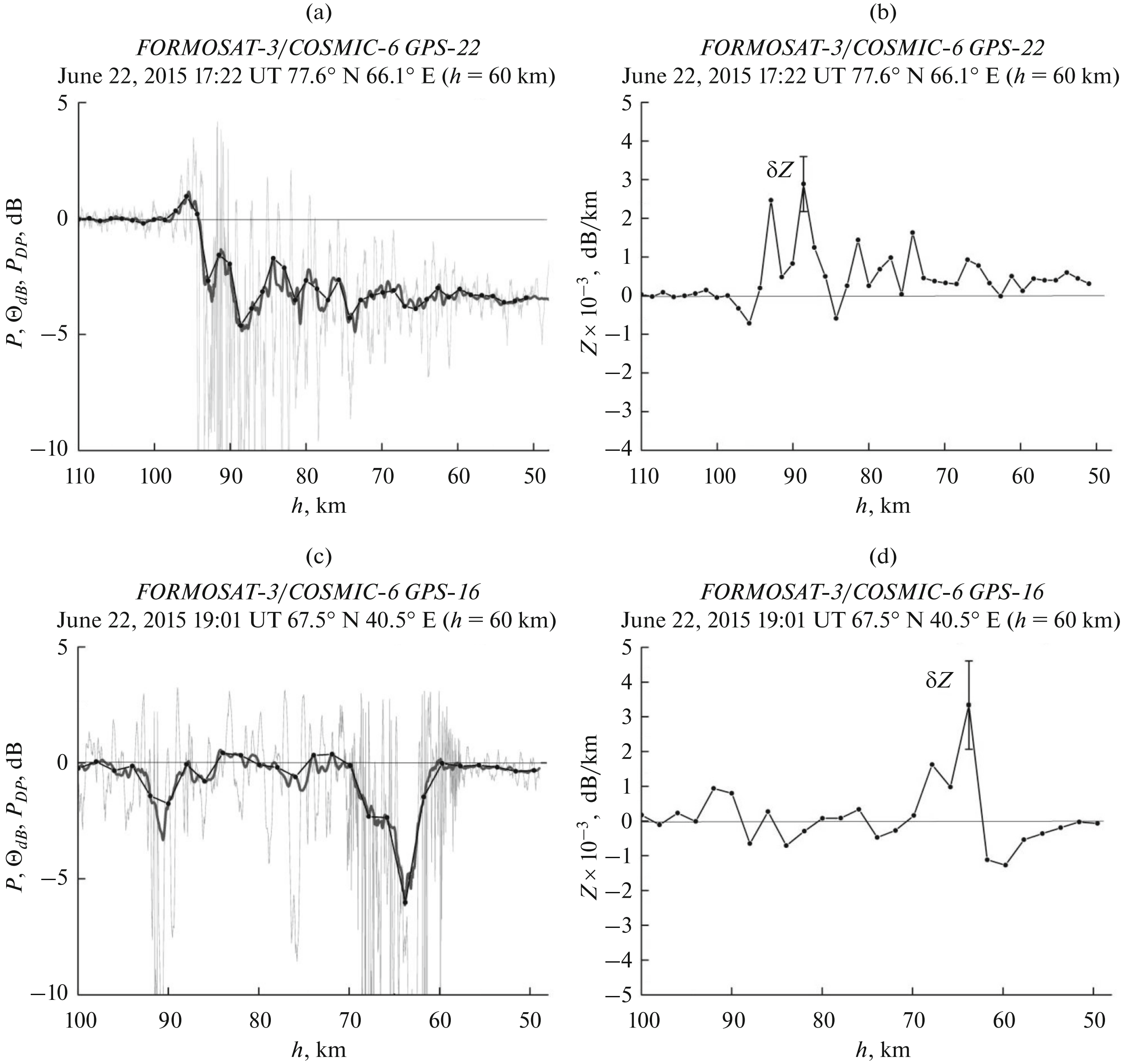

Fig. 2. Vertical profiles of the normalized power $P(h)$ (solid thin line with breaks), normalized power after filtering $\Theta_{dB}(h)$ (solid thick line), normalized power from the direct radio sounding problem solution $P_{DP}(h)$ (solid thin line), and DM radio wave absorption coefficient $Z(h)$ obtained in radio occultation sessions of 17:22 UT (Figs. 2a, 2b) and 19:01 UT (Figs. 2c, 2d) of June 22, 2015, in the Earth's ionosphere. Errors δZ of the reconstruction of absorption coefficient profiles $Z(h)$ are given on the right.

~90 km and remains at the same level with decreasing altitude (Fig. 2a). The local maxima of the absorption coefficient of 2.5 ± 0.7 and 2.9 ± 0.7 dB/km are observed at the heights of 92.9 and 88.6 km, respectively (Fig. 2b). These measurements can be influenced by X-ray bursts, and they are not affected by the geomagnetic conditions of the main storm phase. The measurements related to the radio occultation profiles in Fig. 2c and 2d made at 19:01 UT on June 22, 2015, show strong ionospheric disturbances due to the influence of both the main phase of the magnetic storm and powerful fluxes of X-rays. Here, the local maximum of the absorption coefficient (3.3 ± 1.3 dB/km) is at the height of 63.8 km (Fig. 2d). Table 1 shows altitude intervals of the DM radio wave absorption in the Earth's ionosphere, heights $h_{\max}$ of absorption coefficient maxima and values of maxima $Z_{\max}$ for the measurement sessions analyzed in this work.

The most reliable absorption of DM band signals was detected in the radio occultation session presented

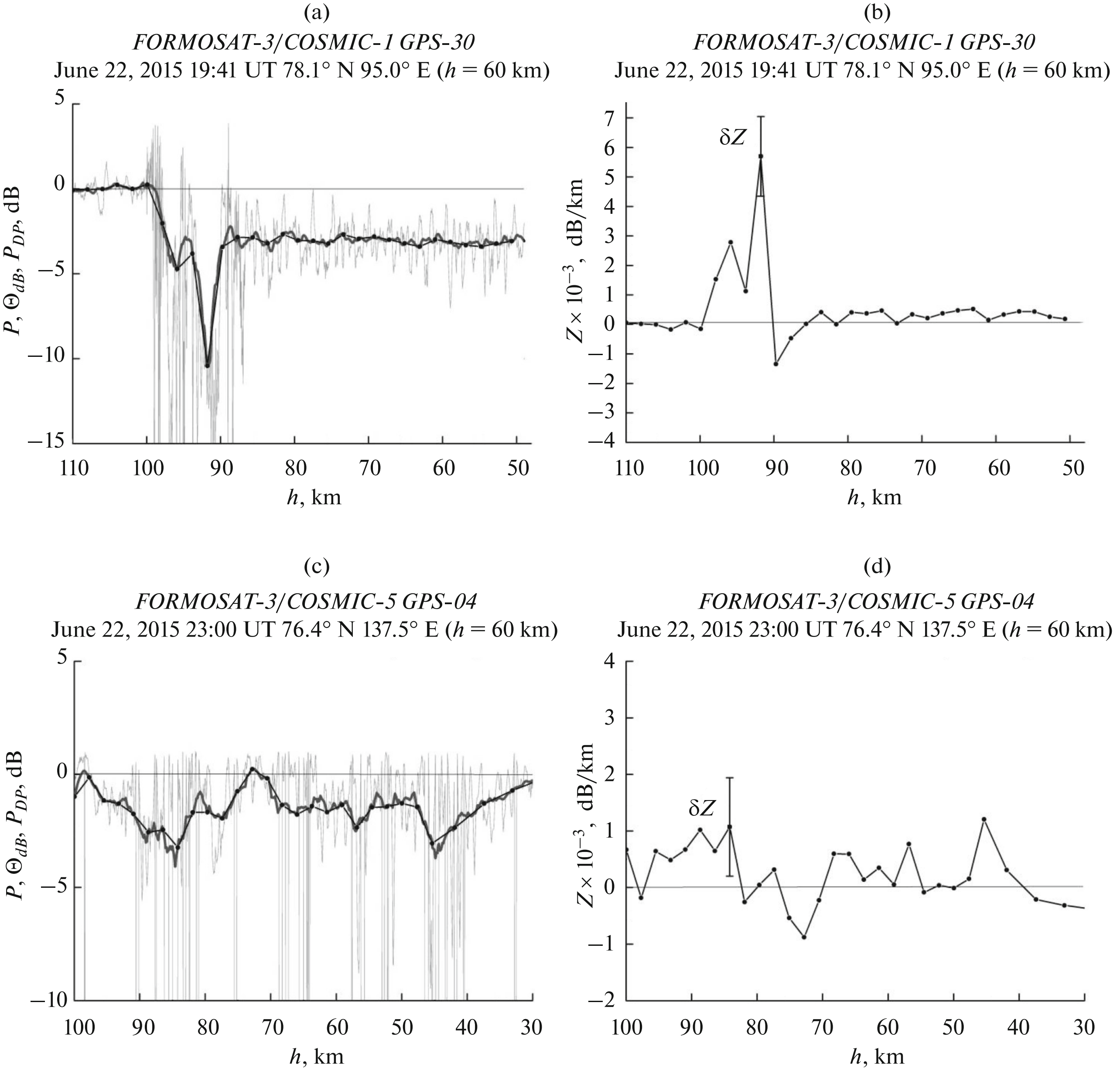

Fig. 3. Normalized power profiles $P(h)$, normalized power after filtering $\Theta_{dB}(h)$, normalized power from the direct radio sounding problem solution $P_{DP}(h)$, and DM radio absorption coefficient $Z(h)$ obtained in radio occultation sessions at 19:41 UT (Figs. 3a, 3b) and 23:00 UT (Figs. 3c, 3d) on June 22, 2015 in the Earth's ionosphere. The notations here are the same as in Fig. 2.

in Figs. 3a and 3b. These measurements were taken at 19:41 UT on June 22, 2015, and they show the strongest disturbances due to both powerful bursts of X-rays and changes in the geomagnetic conditions during the main storm phase. As can be seen from the presented data, during the radio sounding of this region (78.1° N; 95.0° E) of the Earth's polar cap (ray descends from top to bottom), the decimeter radio wave power first decreases to ~0.1 (−10 dB) at heights from 101.5 to 90.3 km, then increases to ~0.5 (−3 dB), and then continues at the same level with decreasing height (Fig. 3a). The local maximum of the absorption coefficient in this session reaches the highest value (for all analyzed sessions) 5.7 ± 1.4 dB/km and is located at the height of 91.8 km (Fig. 3b). The absorption in the radio occultation session presented in Figs. 3c and 3d is less pronounced compared to that in the sessions discussed above.

Figure 4 shows the data on radio wave absorption in the Earth's ionosphere obtained in the radio

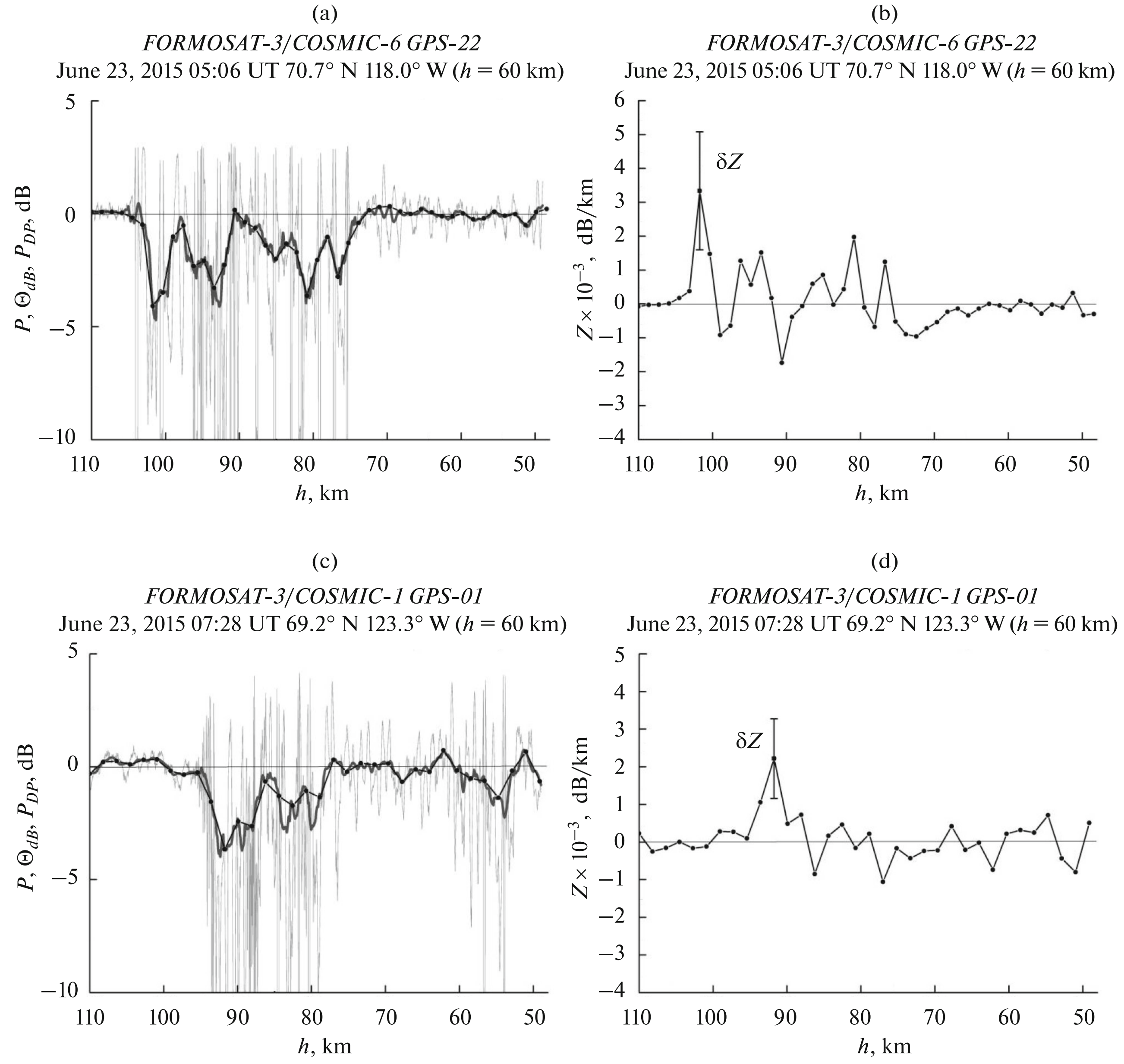

Fig. 4. Normalized power profiles $P(h)$, normalized power after filtering $\Theta_{dB}(h)$, normalized power from the direct radio sounding problem solution $P_{DP}(h)$, and DM radio absorption coefficient $Z(h)$ obtained in radio occultation sessions at 05:06 UT (Figs. 4a, 4b) and 07:28 UT (Figs. 4c, 4d) on June 23, 2015 in Earth's ionosphere. Notations are the same as in Figs. 2 and 3.

occultation sessions at 05:06 UT (Figs. 4a and 4b) and 07:28 UT (Figs. 4c, 4d) on June 23, 2015 in the Earth's ionosphere. The indicated measurement times correspond to the end of the main phase of the storm (~03:00–05:00 UT June 23, 2015) [1]. As can be seen from the data presented in Fig. 4, the absorption of radio waves is observed quite clearly in these sessions. The local absorption coefficient maxima of 3.3 ± 1.7 (Fig. 4b) and 2.2 ± 1.1 dB/km (Fig. 4d) are observed at heights of 101.7 and 91.8 km, respectively.

Thus, we propose a method for reconstructing the vertical absorption coefficient profiles by solving the inverse problem of radio sounding in the Earth's lower ionosphere. This method is general and can be used for different radio bands and other GNSS signals. The absorption layers in the radio occultation sessions during the magnetic storm of June 22–23, 2015 were reliably identified. It was found that at altitudes from ~90 to ~100 km the absorption coefficient of DM radio waves reached values of (5.7 ± 1.4) ×

Table 1. Altitude intervals of DM radio wave absorption in the Earth's ionosphere, heights $h_{\max}$ of absorption coefficient maxima, and values of maxima $Z_{\max}$

Measurement date	Measurement time	LEO satellite number	GPS satellite number	Latitude and longitude of measurement area (h ~ 60 km)	Absorption height interval, km	Absorption maximum height $h_{\max}$, km	Absorption coefficient maximum value $(Z_{\max} \pm \delta z) \times 10^{-3}$, db/km
June 22, 2015	17:22 UT	6	22	77.6° N	96–72	92.9	2.5 ± 0.7
				66.1° E		88.6	2.9 ± 0.7
						81.4	1.4 ± 0.7
						74.2	1.6 ± 0.7
June 22, 2015	19:01 UT	6	16	67.5° N	70–62	67.8	1.6 ± 1.3
				40.5° E		63.8	3.3 ± 1.3
June 22, 2015	19:41 UT	1	30	78.1° N	100–91	95.8	2.8 ± 1.4
				95.0° E		91.8	5.7 ± 1.4
June 22, 2015	23:00 UT	5	4	76.4° N	99–43	88.7	1.0 ± 0.9
				137.5° E		84.2	1.0 ± 0.9
						45.4	1.2 ± 0.9
June 23, 2015	05:06 UT	6	22	70.7° N	104–74	101.7	3.3 ±1.7
				118.0° W		80.8	2.0 ± 1.7
June 23, 2015	07:28 UT	1	1	69.2° N	95–79	91.8	2.2 ± 1.1
				123.3° W			

10^{-3} dB/km. The practical significance of studying the effects of radio wave absorption in the D- and E-regions of the ionosphere is associated with ensuring smooth operation of space radio 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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