GPS L1 signals absorption in high-latitude lower ionosphere during severe geomagnetic storm in June 2015

To cite this article: V E Andreev *et al* 2021 *J. Phys.: Conf. Ser.* **1991** 012006

GPS L1 signals absorption in high-latitude lower ionosphere during severe geomagnetic storm in June 2015

V E Andreev[1], V N Gubenko[1], I A Kirillovich[1]

[1] Kotel'nikov Institute of Radio Engineering and Electronics RAS (Fryazino branch) Vvedensky square 1, Fryazino 141190, Moscow region, Russia

E-mail: v.e.andreev@gmail.com, vngubenko@gmail.com

Abstract. Based on the results of an analysis of *FORMOSAT-3/COSMIC* radio occultation measurements, the absorption of DM-radio waves (wavelength ~19 cm) in the lower high-latitude ionosphere of the Earth was detected. The maximum absorption value is ~3 dB in the range from ~60 to ~90 km and, in some cases, it reaches ~10 dB at altitudes from ~90 to ~95 km. A method for determining the vertical profiles of the absorption coefficient by solving the inverse problem of radiosonding in the Earth's lower ionosphere is proposed. The absorption layers, caused by powerful bursts of X-ray radiation and strong changes in geomagnetic conditions during the storm, were reliably identified in individual sessions. It was found that, at altitudes from ~90 to ~100 km, the value of the absorption coefficient of DM-radio waves reached values $(5.69 \pm 1.35)\cdot 10^{-3}$ dB/km.

Keywords: radio occultation measurements, signal intensity fluctuations, absorption coefficient of DM-radio waves, high latitude ionosphere

1. Introduction

Radio sounding of the Earth's atmosphere and ionosphere according to the satellite–satellite scheme, when high-orbital (GPS/GLONASS) and low-orbital (LEO) satellites are used, was previously carried out in different combinations, for example: geostationary satellite – orbital station MIR, GPS – MICROLAB, GPS – GRACE, GPS/GLONASS – METEOR, GPS – FORMOSAT-3/COSMIC and others. Based on the results of an analysis of radio wave parameters in these experiments conducted in different regions of the Earth's ionosphere and atmosphere, the dynamics and altitude characteristics of the Earth's ionosphere and atmosphere were studied [1–4]. It is known that disturbances in the ionosphere of the Polar Regions strongly depend on the solar activity. Therefore, these disturbances should leave their mark on the parameters of radio waves that have passed through the polar ionosphere. It is generally assumed that radio sounding of the polar ionosphere is carried out if the geographical latitude of the point of the greatest approach of the radio path to the Earth's surface was of ~70° and higher [1].

Coronal mass ejections (CMEs) towards the Earth (one giant and several small ejections) occurred in the summer of 2015 (June 22). These events were recorded by many spacecrafts, such as SOHO (https://cdaw.gsfc.nasa.gov/CME_list/index.html), ACE [5], and ionospheric stations [6, 7]. Coronal mass ejections were accompanied by powerful X-ray fluxes, which were recorded by GOES -13, -15 spacecrafts at geostationary orbits [8]. These CMEs triggered a strong G4-class magnetic storm on Earth (G4 = Kp – 4). The G-index is a five-point scale for the strength of magnetic storms, which was introduced by the US National Oceanic and Atmospheric Administration (NOAA) in November 1999.

The G-index characterizes the intensity of a geomagnetic storm. On this scale, magnetic storms are classified into levels from G1 (weak storms) to G5 (extreme storms). G-index corresponds to the maximum value of Kp-index (Kp^{max}) minus 4; that is, G4 corresponds to Kp^{max}=8. On the night of June 22–23, the residents of Russia observed the aurora borealis even at the middle latitudes of Moscow (~55ºN) and Volgograd (~49ºN) (https://www.kp.ru/daily/26396/3273894/).

The authors had at their disposal the results of measurements of the parameters of DM radio waves (frequency 1575.42 MHz) emitted by the transmitters of the GPS navigation system satellites and recorded by the receivers on board the low-orbital FORMOSAT-3/COSMIC satellites in June 2015 [9, 12]. Sounding data at high sighting altitudes (> 130 km) were carried out with a low sampling frequency (1 Hz), and when the sighting height of the radio path reached ~130 km and below, measurements were started with a high sampling frequency of 50 Hz. An analysis has shown that in the period from June 22 to 23, at high target altitudes (more than ~130 km), no noticeable fluctuations in the intensity of radio waves, possible due to the influence of CME, were detected in the sounding data. At altitudes below 110 km, strong fluctuations were observed in an analysis of altitude profiles of radio wave intensity. It was noted in [9] that these intensity fluctuations could occur due to the absorption of radio waves at altitudes below 100 km during a geomagnetic storm.

The aim of this work is to obtain altitude profiles of the absorption coefficient of DM-radio waves at altitudes from 50 to 110 km during a geomagnetic storm by solving the inverse sounding problem.

2. Absorption of decimeter radio waves in the Earth's lower ionosphere

A small absorption (up to –1 dB) of radio waves, which could be seen in the data at GPS frequencies (wavelength ~19 cm), is mentioned in [2]. The most characteristic features of the high-latitude ionosphere (**D**-region) are the specific absorption of radio waves in the polar cap, associated with the intrusion of protons with energies in the tens of MeV, and the anomalous auroral absorption associated with the 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 occur, manifested in an increase in ionization, mainly in the D-and E-regions of the ionosphere. Auroral absorption of radio waves observed in the auroral zone during periods of magnetospheric storms and sub-storms is associated with the precipitation of charged particles (mainly electrons with energies of 20-100 keV) from the magnetosphere into the lower ionosphere of the Earth [11].

The absorption of radio waves in the lower ionosphere is caused by collisions of electrons with ions and neutral molecules [10, 11]. Because of this, part of the energy transmitted by the electromagnetic field of the electron is spent on increasing the energy of the chaotic motion of the plasma particles and leads to heating of the plasma. At each impact, the electron on average transmits to the ion or molecule an impulse $\mathbf{m \cdot dr/dt}$, where $\mathbf{dr/dt}$ is the ordered velocity of the electron under the action of the field. If $\boldsymbol{\nu}$ is the effective number of electron collisions per second, then the electron momentum changes by the value $\mathbf{m \cdot \boldsymbol{\nu} \cdot dr/dt}$ per unit of time. The change in momentum due to collisions is equivalent to the action of a certain friction force.

3. Method for solving the inverse problem of radio sounding the lower ionosphere

The experimental data of the normalized radio wave power $\mathbf{P(h)} = \frac{\mathbf{I(h_i)}}{\mathbf{I_0}}$ at altitudes of ~130 km and below are first filtered by the moving average method over fifty points and the curves $\mathbf{\Theta(h)}$ are obtained. The sampling rate of data on the amplitude (power) of radio occultation signals at the analyzed altitude intervals (<130 km) was equal to 50 Hz. The 50-points smoothing of the data was applied only for the sampling rate 50 Hz at altitudes of ~130 km and below. Taking into account the vertical speed of the ray descending ~2 km/s, we find that the data smoothing interval is equal to ~2 km. The vertical resolution in the method of geometric optics (GO) corresponds to the size (diameter $d_f = 2r_f$) of the first Fresnel zone $d_f = 2r_f = 2(\lambda D)^{1/2}$ ~1.5 km, where λ ~20 cm is the wavelength of the sounding signal, D ~3090 km is the distance from the FORMOSAT-3/COSMIC satellite to the planet's atmospheric limb. In geometric optics, two physical beams (together with their Fresnel volumes) are considered distinguishable if they do not intersect with each other. Since the size of the data smoothing interval is comparable to the vertical resolution of the GO-method, the data after smoothing retain all information about the vertical small-scale structure in the Earth's ionosphere.

The curves $\boldsymbol{\Theta}(\mathbf{h})$ in decibels ($\boldsymbol{\Theta}_{\mathbf{dB}}(\mathbf{h})$) are shown in the left panels of Figures 1, 2 as thick solid lines in red. There are quite strong drops in the power of DM-radio waves (from –3dB to –10 dB). The signal power dips may have been caused by the absorption of DM-radio waves in these regions of the Earth's ionosphere. Analysis of the eikonal data and calculation of the refractive attenuation profiles for the selected sessions showed that regular refractive attenuation was not observed in them. This confirms the hypothesis about the absorption of DM radio waves.

Analyzing the data on the vertical profiles of electron density in the sessions made on 17.22 UT and 19.41 UT June 22, 2015 [9], the estimates of the maximal horizontal gradients of electron density in the Earth's lower ionosphere were obtained by us. So, at an altitude of ~95 km in these measurement sessions, the electron densities differed by $\sim 2.9\cdot 10^5$ cm^{-3} and the horizontal separation between measurement points was about 640 km. In this case, the possible horizontal gradient of electron density is equal to $\sim 4.6\cdot 10^2\, cm^{-3}\, km^{-1}$. It should be noted that this estimate of the horizontal gradient of electron density can be greatly overestimated, since the time of the considered measurement sessions differed by almost 2.5 hours. During the interval between these measurement sessions, dramatic events took place, namely: I) interaction (~18.34 UT) of CMEs with a bow shock in the magnetosphere [5]; II) powerful bursts (~18.00 UT) of X-ray fluxes exceeding their background values by 2-3 orders of magnitude [Figure 1, left panel, 9]. Therefore, these phenomena could significantly distort the real horizontal gradient estimate of electron density in the Earth's lower ionosphere.

Imagine the ionosphere at target altitudes **h** from ~110 km to ~50 km from the Earth's surface, consisting of **n** nested spherically symmetric layers centered at the center of the Earth. When propagating through the layered ionosphere, the radio wave stream is attenuated:

$$\boldsymbol{\Theta}(\mathbf{h}) = \exp\left(-\int_s \mathbf{Z}\cdot d\mathbf{L}\right) = \exp\left(-\sum_{j=1}^{i} \mathbf{L}_{ij}\cdot \mathbf{Z}_i\right), \text{ где } \mathbf{i} = \mathbf{1}\ldots\mathbf{n}.$$

Let us express $\boldsymbol{\Theta}(\mathbf{h})$ in decibels and expand the specified formula:

$$\boldsymbol{\Theta}_{\mathbf{dB}}(\mathbf{h}_i) = \mathbf{10}\cdot \lg(\boldsymbol{\Theta}(\mathbf{h}_i)) = -\mathbf{10}\cdot \lg(\mathbf{e})\cdot \begin{bmatrix} L_{11} & & & & & & \\ L_{21} & L_{22} & & & & & \\ \cdots & \cdots & \cdots & & & & \\ L_{i1} & L_{i2} & \cdots & L_{ij} & \cdots & L_{ii} & \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \\ L_{n1} & L_{n2} & \cdots & L_{nj} & \cdots & \cdots & L_{nn} \end{bmatrix} \cdot \begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_i \\ \vdots \\ Z_n \end{bmatrix},$$

where **e** = 2.71828; **i** = **1**…**n, j** = **1**…**i**; $\mathbf{Z}_i$ – absorption coefficient in layer **i**.
$\mathbf{L}_{ij}$ at $\mathbf{i} \neq \mathbf{j}$ is the length of the segment of the path of the probing beam between the layers **j–1** and **j**:

$$\mathbf{L}_{ij} = \mathbf{2}\cdot\left[\sqrt{(\mathbf{R}+\mathbf{h}_{j-1})^2 - (\mathbf{R}+\mathbf{h}_i)^2} - \sqrt{(\mathbf{R}+\mathbf{h}_j)^2 - (\mathbf{R}+\mathbf{h}_i)^2}\right];$$

and $\mathbf{L}_{ij}$ at **i** = **j** is the length of the segment of the path of the probing beam in layer **i**:

$$\mathbf{L}_{ii} = \mathbf{2}\cdot\sqrt{(\mathbf{R}+\mathbf{h}_{i-1})^2 - (\mathbf{R}+\mathbf{h}_i)^2};$$

R – mean Earth's radius (**R** = 6371 км).
In this case, the absorption coefficient **Zi** in each layer is defined as:

$$\mathbf{Z}_i = \frac{-\frac{\Theta_{dB}(h_i)}{4.343} - \sum_{j=1}^{i-1} L_{ij}\cdot Z_j}{L_{ii}},$$

Thus, the vertical profile **Z(h)** is determined - the absorption profile of radio waves with an altitude scale of ~2 km. The error of reconstruction of the high – altitude profile of the absorption coefficient- **δZ** for each radio sounding session is estimated. The **Z(h)** profiles are shown in Figures 1 and 2 on the right panels. The values of **δZ** in the figures are shown as vertical segments. The experimental **P(h)** curves with pronounced features, obtained on June 22 and 23, 2015, are shown on the left panels of Figures 1, 2 in the form of gray thin solid lines. The figures for each session indicate the latitudes and longitudes of the probed areas, the time of the experiment, and the pair of spacecrafts from which the ionosphere was radio sounded.

Verification of the correspondence of the obtained radio wave absorption profiles to the experimental data was carried out by solving the direct radio sounding problem for layers with a width of ~2 km. The calculated power of the $\mathbf{P_{DP}(h)}$ radio wave stream is:

$$\mathbf{P_{DP}(h) = -\left(\sum_{j=1}^{i-1} L_{ij} \cdot Z_j + L_{ii} \cdot Z_i\right) \cdot 4.343.}$$

The resulting $\mathbf{P_{DP}(h)}$ curves are shown in the left panels of Figures 1, 2 as solid blue lines with dots.

4. Results

By solving the inverse problem of radio sounding, vertical profiles of the absorption coefficient of DM-radio waves in the lower ionosphere of the Earth were found. Errors in reconstructing the profiles of the radio wave absorption coefficient in the ionosphere are determined. A method used by us for determination of the absorption coefficient profiles is general and can be applied for other GNSS signals and other signals in DM band. The analysis of the obtained results shows that geomagnetic conditions and powerful bursts of X-ray radiation fluxes had a strong influence on the propagation of radio waves in the **E** and **D** layers of the ionosphere during the storm.

Verification of the obtained results by solving the direct radio sounding problem showed a good correspondence between the calculated and experimentally obtained data:

$$\mathbf{P_{DP}(h) \approx \Theta_{dB}(h).}$$

From the data shown in Figures 1 and 2, it can be seen that at altitudes from ~100 km to ~70 km in the ionosphere, strong disturbances of the power of the DM-radio wave are observed. The absorption layers in individual sessions were reliably identified (Figure 1, panels a, b, and c) due to powerful bursts of X-ray radiation and strong changes in geomagnetic conditions during the storm. The maximum values of the radio wave absorption coefficient and the height in the layers on which these coefficients are found are shown in Table 1.

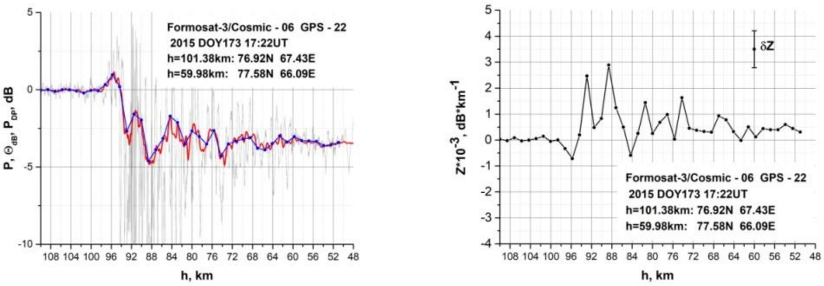
The highest value of the absorption coefficient was recorded in the session by a pair of FORMOSAT-3/COSMIC-1 – GPS-30 satellites on June 22, 2015 at 19.41: Z_{max}= 5.69×10^{-3} dB/km at an altitude of 91.77 km. It should be noted that during this time period, the geostationary satellites GEOS-13 and -15 recorded a powerful flow of X-ray radiation towards the Earth [8]. Indeed, it follows from Figure 1 of the work [9] that at 19.41 UT the X-ray flux in the range 0.5–4.0 Å is equal to ~10^{-6} W/m^2 and it is higher the background level by two orders of magnitude. At the same time, the X-ray flux in the 1.0–8.0 Å range is equal to ~10^{-5} W/m^2, which is an order of magnitude higher than the background values. We believe that the measurements performed on June 22 at 19.41 UT demonstrate strong ionospheric disturbances caused by the influence of both the main phase of the geomagnetic storm and powerful fluxes of X-ray radiation.

It should also be noted that the absorption of radio waves in a pair of satellites FORMOSAT-3/COSMIC-5-GPS-4 on June 22, 2015 at 23.00 was observed even at altitudes of about ~45 km: Z_{max}= 1.21×10^{-3} dB/km at an altitude of 45.36 km.

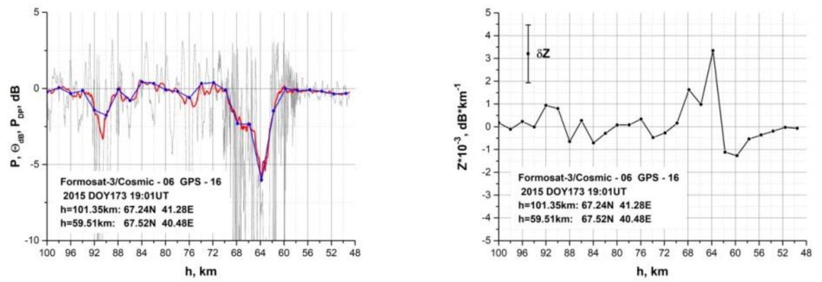
The presence of a layer with an absorption coefficient of ~3 × 10^{-3} dB/km (Figure 1 a) or ~5 × 10^{-3} dB/km (Figure 1 c) in a layer with a width of ~10 km (at target altitudes of about 96–86 km) leads to a drop in the radio wave power from ~5 dB to ~10 dB. Then, as the track descends lower, the power level of the radio wave does not return to its original level, but remains at ~3 dB to an altitude of ~48 km. The presence on the track of a narrower layer ~7 km (at target altitudes of about 69–62 km) with an absorption coefficient of ~3×10^{-3} dB/km (Figure 1 b) leads to a drop in the radio wave power to ~6 dB with a return to the original level, which is possible after the radio wave path passes the specified layer.

We believe that the local character of powerful X-ray fluxes during measurements is one of the possible reasons for negative values of the absorption coefficient (see Figures 1 and 2) when solving the inverse problem. This will lead to the appearance of horizontal gradients in the Earth's ionosphere and the violation of the local spherical symmetry of the medium during its sounding. Negative values of the absorption coefficient in the solution of the inverse problem can appear in the presence of the above factors, and their absolute values may serve as a practical estimate of the error in recovering the absorption coefficient.

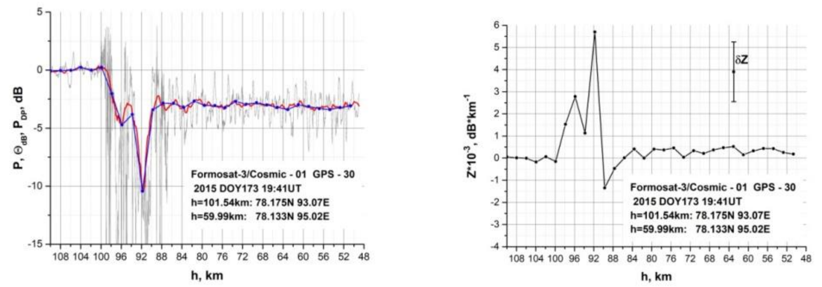
a)



b)



c)



d)

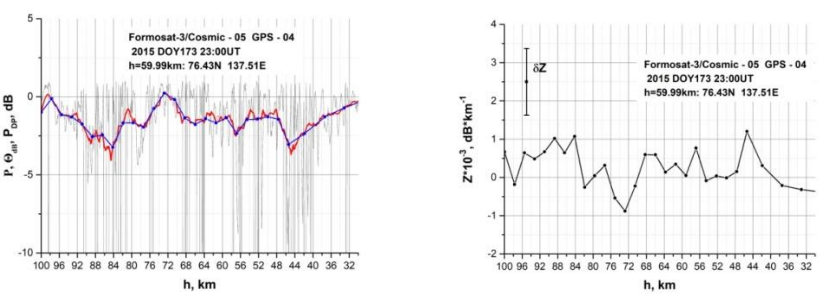
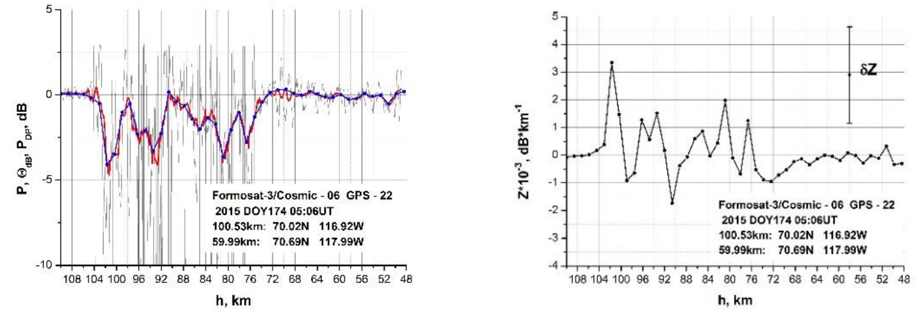


Figure 1. Profiles of the normalized power – **P(h),** normalized power after filtration – $\mathbf{\Theta_{dB}(h)}$, normalized power from the solution of the direct radio sounding problem – $\mathbf{P_{DP}(h)}$, and the absorption coefficient of DM-radio waves – **Z(h)** for June 22, 2015.

a)



b)

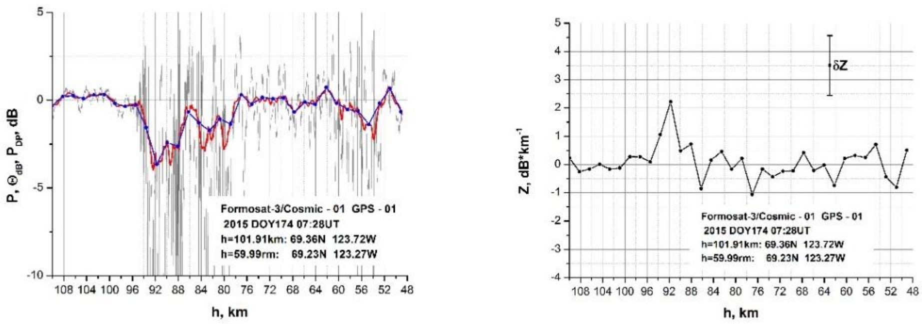


Figure 2. Profiles of the normalized power – **P(h),** normalized power after filtration – $\mathbf{\Theta_{dB}(h)}$, normalized power from the solution of the direct radio sounding problem – $\mathbf{P_{DP}(h)}$, and the absorption coefficient of DM-radio waves – **Z(h)** for June 23, 2015.

Table 1. The range of heights at which the absorption of DM-radio waves was observed, the height values – h_{max} and the corresponding maximum values of the absorption coefficient –$Z_{max}(h)$

DOY	LEO No.	GPS No.	UT	Lat and Long (h~60 km)	interval of absorption, km	h_{max}, km	$(Z_{max}(h) \pm \delta Z)\cdot 10^{-3}$, dB/km
173	6	22	17.22	77.58°N 67.42°E	96 – 72	92.90 88.61 81.42 74.22	2.47 ± 0.71 2.89 ± 0.71 1.44 ± 0.71 1.63 ± 0.71
173	6	16	19.01	67.52°N 40.48°E	70 – 62	67.84 63.78	1.62 ± 1.27 3.34 ± 1.27
173	1	30	19.41	78.13°N 95.02°E	100 – 91	95.84 91.77	2.78 ± 1.35 5.69 ± 1.35
173	5	4	23.00	76.43°N 137.51°E	99 – 43	88.69 84.17 45.36	1.02 ± 0.87 1.07 ± 0.87 1.21 ± 0.87
174	6	22	05.06	70.69°N 117.99°W	104 – 74	101.70 80.81	3.34 ±1.74 1.97 ± 1.74
174	1	1	07.28	69.23°N 123.27°W	95 – 79	91.75	2.23 ± 1.06

5. Conclusion

According to the results of the analysis of the FORMOSAT-3/COSMIC radio-frequency measurements, the absorption of DM radio waves (wavelength ~19 cm) in the lower high-latitude ionosphere of the Earth was detected. The absorption layers in individual sessions caused by powerful bursts of X-ray radiation and strong changes in geomagnetic conditions during the storm were reliably identified. The maximum absorption value is ~3 dB in the altitude interval of 60–90 km, and in some cases it reaches ~10 dB at altitudes from ~90 to ~95 km.

A method for determining the vertical profiles of the absorption coefficient by solving the inverse problem of radio sounding in the lower ionosphere of the Earth is proposed. This method is general and can be applied for other GNSS signals and other signals in DM band. It was found that at altitudes from 90 to 100 km, the value of the absorption coefficient of DM-radio waves reached the values $(5.69 \pm 1.35)\times10^{-3}$dB/km.

6. Acknowledgments

This study was made in the framework of state task and it was partially supported by the Russian Foundation for Basic Research (RFBR project no. 19-02-00083 A).

References

[1] Yakovlev O I, Pavelyev A G and Matugov S S 2014 *Satellite monitoring of the Earth: Radio occultation monitoring of the atmpsphere and ionosphere* (Moscow: Publishing House "LIBROKOM") p 208 [in Russian].
[2] Gorbunov M E 2017 *Radio occultation sounding the atmosphere* (Dynamics of wave and exchange processes in the atmosphere) 2017 (Moscow: Publishing House "GEOS") chapter 4 pp 407–457 [in Russian].
[3] Gubenko V N, Pavelyev A G, Kirillovich I A and Liou Y-A 2018 *Adv. Space Res.* **61** 1702, doi: 10.1016/ j.asr.2017.10.001.
[4] Gubenko V N and Kirillovich I A 2019 *Solar-Terrestrial Physics* **5** 98, doi: 10.12737/stp-53201912.
[5] Reiff P H et al. 2016 *Geophys. Res. Lett.* **43** 7311, doi: 10.1002/2016GL069154.
[6] Astafyeva E, Zakharenkova I, Huba J D, Doornbos E and van den Ijssel J 2017 *J. Geophys. Res.* **122** 1, doi: 10.1002/2017JA024174.
[7] Mansilla G A 2018 *Pure and Applied Geophys* **175** 1139, doi:10.1007/s00024-017-1741-5.
[8] Archive of space weather data URL: ftp://ftp.swpc.noaa.gov/pub/warehouse/
[9] Andreev V E, Gubenko V N, Pavelyev A A, Kirillovich I A, Gubenko T V 2020 *J. Phys.: Conf. Ser.,* doi:10.1088/1742-6596/1632/1/012008
[10] Kolosov M A, Armand N A and Yakovlev O I 1969 *Propagation of radio waves in space communications* (Moscow: Publishing House "SVYAZ") p 155 [in Russian].
[11] Brunelli B E and Namgaladze A A 1988 *Physics of ionosphere* (Moscow: Publishing House "NAUKA") p 528 [in Russian].
[12] Yakovlev O I, Matugov S S and Pavelyev A A 2019 *Radiophysics and Quantum Electronics* **62** 174, doi:10.1007/s11141-019-09965-y.