Modeling of the Lower Ionosphere During Solar X-Ray Flares of Different Classes

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Abstract This study presents the results obtained from modeling the lower ionosphere response to C-, M- and X-class solar X-ray flares. This model is based on a 5-component scheme for the ionization-recombination cycle of the ionospheric D-region. Input parameters for the plasma-chemical model under different heliogeophysical conditions corresponding to selected X-ray flares were determined by using data received from the AURA, SDO, and GOES satellites. Verification of the obtained results was carried out with use of ground-based radiophysical measurements taken at the geophysical observatory Mikhnevo. The results obtained from a comparison of the calculated and experimental radio wave amplitude variations along six European very low frequency (VLF) paths show that the average normalized root mean square error is ~7%, 14%, and 18% for C-, M-, and X-class flares, respectively. Qualitative and quantitative analysis of the verification results for the VLF signal amplitude show good predictive capability of the model built for describing weak and moderate ionospheric disturbances.

1. Introduction

At present, researchers are intensively develop modeling for all layers of the ionosphere for solving research problems of various profiles, as well as for applied tasks; particularly, improvement of the estimated accuracy of the propagation of radio waves in a wide range of frequencies.

Despite the fact that currently there exists a significant number of theoretical estimates and experimental data for processes occurring in ionospheric plasma and about the spatial and temporal distribution of the concentrations of its components (Bilitza et al., 2017; Marsh et al., 2013; Nava et al., 2008; Wait & Spies, 1964), the prediction accuracy for ionospheric parameters, especially under conditions of various disturbances, is low.

The lower part of the ionosphere (h ∼ 60–90 km) remains the least studied to date. Difficulties in studying the D-region are due to a large number of photochemical processes and incapability of continuous measurements of the ionosphere parameters, such as, first of all, concentration of electrons Ne, at these amplitudes (Egorova et al., 2011; Friedrich et al., 2018; Krivolutsky et al., 2015; Turunen et al., 1992, 1996; Verronen et al., 2005, 2016).

The state of the lower ionosphere parameters is determined by the latitude, longitude (Brunelli & Namgaladze, 1988) and space weather factors, such as solar cosmic rays, magnetospheric storms, precipitation of charged particles, ionizing electromagnetic radiation (Kumar & Kumar, 2018; Kumar et al., 2015, 2017; Maurya et al., 2012, 2018; Peter et al., 2006; Thomson et al., 2004, 2005). Solar flares are accompanied by considerably increased intensity of X-radiation, which leads to a significant change in the electron concentration in the illuminated area of the lower ionosphere (Grubor et al., 2005, 2008; Mitra, 1974; Nina et al., 2011; Poppoff & Whitten, 1962; Ryakhovskiy et al., 2018). Such Ne variations significantly distort the amplitude and phase characteristics of the very low frequency (VLF) signals within a frequency range of 3–30 kHz propagating in the Earth-Ionosphere waveguide with the D-region as its upper boundary (Brunelli & Namgaladze, 1988; Gavrilov, Ermak, et al., 2019; Han et al., 2011; Hargreaves, 1995; Schunk & Nagy, 2009; Wait & Spies, 1964). This allows use of measurements of the amplitude and phase of VLF signals for studying the state of the lower ionosphere, and application of these measurements as a tool for verification of the medium models (Bekker et al., 2018; Lyakhov et al., 2018; Palit et al., 2013). Verification on the basis of data obtained from ground-based radiophysical measurements allows direct assessment of a model's predictive
capability at solving problems for VLF signal propagation. Moreover, the quantity of radiophysical data is many orders of magnitude greater than the electron concentration measurements taken for the D-region, which makes it possible to carry out verification under almost any heliophysical conditions including solar flares.

This work is devoted to modeling the lower ionosphere during solar X-ray flares of different classes and analysis of the results obtained by verification with ground-based radiophysical measurements taken at the Mikhnevo geophysical observatory of the Sadovsky Institute of Geospheres Dynamics (Gavrilov et al., 2017, 2019a).

2. Experimental Data Obtained at the Mikhnevo Geophysical Observatory

Since 2014, Mikhnevo has been continuously monitoring the amplitude and phase characteristics of electromagnetic signals from VLF transmitters located throughout the world (Gavrilov, Zetser, et al., 2019).

To verify the results of modeling, we used measurements of the amplitude of the signals received at the Moscow region observatory Mikhnevo (55°N 38°E) from six transmitters located at the European midlatitudes (Figure 1). The main characteristics of the transmitters are listed in Table 1.

The amplitude of the signal passing through the simulated medium was calculated by using the LWPC program (Ferguson, 1998). The configured nominal power of the transmitters was 1 kW. Amplitude values were taken in (dB) for the purpose of quantitative comparison of theoretical and experimental daily variations. The amplitude shift due to the difference between the unknown actual transmitter power and the power used for the calculations was determined from the difference between the theoretical amplitude value and the experimental data obtained at a quiet heliophysical day that preceded each considered flare (Palit et al., 2013).

3. Plasma-Chemical Model of the Lower Ionosphere

As stated in the introduction, at present there are a significant number of empirical and theoretical models of the lower ionosphere, describing its state with some accuracy. For solving applied problems of radio wave propagation, the two-parameter Wait-Ferguson model (Ferguson, 1995; Wait & Spies, 1964) is most often used. On the one hand, this model makes it possible to simulate the radioequivalent ionosphere to successfully calculate radio wave propagation. On the other hand, the modeled vertical electron concentration profiles do not correspond to the real profiles, since the model is based on an exponential \(Ne\) profile.

When choosing the number of plasma-chemical processes on which the model under development is based, it is necessary to take into account not only the expected accuracy of the results but also the possibility

| Station | Location | Coordinates | Frequency (kHz) | Path length [km] |
|---------|----------|-------------|----------------|-----------------|
| GBZ     | England  | 55°N 3°W    | 19.6           | 2,585           |
| ICV     | Italy    | 41°N 10°E   | 20.3           | 2,580           |
| FTA     | France   | 49°N 3°E    | 20.9           | 2,500           |
| GQD     | England  | 55°N 3°W    | 22.1           | 2,565           |
| DHO     | Germany  | 33°N 8°E    | 23.4           | 1,960           |
| TBB     | Turkey   | 37°N 27°E   | 26.7           | 2,100           |

Figure 1. The locations of the Mikhnevo geophysical observatory and the VLF transmitters. VLF, very low frequency.
of rapid calculation of the environmental parameter variations at natural disturbances. Today, there exist global three-dimensional numerical models of the lower ionosphere, taking into account hundreds of components and photochemical reactions. These models describe the behavior of ionospheric components under calm conditions and under the influence of various disturbances (Krivolutsky et al., 2015; Turunen et al., 1992, 1996; Verronen et al., 2016). However, such models require extremely high computational power and time resources, and, therefore, the applied tasks of forecasting radio wave propagation cannot be promptly solved using these models. Moreover, the number of unknown reaction rate constants increases with the number of considered plasma-chemical processes, which can lead to higher errors.

The system of differential equations for the ionization-recombination cycle describes the behavior of charged and neutral components, the dynamics of which are most important at D-region heights. Analysis of the results obtained from calculation of the electron concentration in four-component (Glukhov et al., 1992), five-component (Egoshin et al., 2012), and eight-component (Kudryavtsev & Romanyukha, 1995) plasma-chemical models of the lower ionosphere shows no significant difference between the results for the latter two models. However, not accounting for the variations of concentration of the negative cluster ions that are absent in the four-component model leads to a noticeable decrease in the Ne concentration at altitudes less than 70 km, which fundamentally affects the results of the calculation of the VLF radio wave propagation both under calm conditions and at X-ray flares.

Therefore, the five-component ionization-recombination cycle of the ionospheric D-region (1) was selected as the best model for this work. This system describes the behavior of the concentration of electrons Ne and four ion types: NO\(^+\), O\(^2\)_\(-\), positive and negative cluster ions XY\(^+\), XY\(^-\). It takes into account almost all major photochemical processes occurring in the lower ionosphere.

$$
\begin{align}
\frac{d[NO^+]}{dt} &= q - 4 \cdot 10^{-7} \left(\frac{300}{T}\right)^{1/5} \left[NO^+ \right] N_e - B \left[NO^+ \right] - 10^{-7} \left([O_2] + [XY^-]\right); \\
\frac{d[XY^+]}{dt} &= B \left[NO^+ \right] - 2.55 \cdot 10^{-5} \left[XY^+ \right] N_e - 10^{-7} \left([O_2] + [XY^-]\right); \\
\frac{d[O_2^-]}{dt} &= 1.4 \cdot 10^{-26} \left(\frac{300}{T}\right) \exp \left(\frac{-600}{T}\right) \left[O_2\right] N_e - 0.33 \left[O_2\right] - 4 \cdot 10^{-10} \left[O_3\right] \left[O_2\right] - 10^{-7} \left([O_2] + [XY^-]\right) - 4 \cdot 10^{-31} \left[O_2\right] \left[O_2\right]; \\
\frac{d[XY^-]}{dt} &= 4 \cdot 10^{-10} \left[O_3\right] \left[O_2\right] + 4 \cdot 10^{-31} \left[O_3\right] \left[O_2\right] - 10^{-7} \left[XY^-\right] \left([NO^+] + [XY^+]\right) - [XY^-]; \\
\frac{dN_e}{dt} &= \frac{d[NO^+]}{dt} + \frac{d[XY^+]}{dt} - \frac{d[O_2^-]}{dt} - \frac{d[XY^-]}{dt}; \\
\end{align}
$$

3.1. Input Data

The system input parameters are the ionization rate \(q\), concentration of neutrals \(M\), temperature \(T\), and concentration of small neutral components \([H_2O], [CO_2], [O_3]\).

It is known that ionization rate is the key parameter responsible for changes in the Ne concentration during solar flares, which is why its calculation must be carried out particularly carefully. At the same time, for a correct modeling of the lower ionosphere during disturbances of various natures, we need to know
the state of the medium before and after the perturbation. In other words, we must correctly calculate the background Ne values. There are at least two reasons for this. First, the accuracy for calculating the background concentration of Ne significantly affects the quality of the modeling of small solar flares (Palit et al., 2013). Second, vertical profiles for Ne during a calm Sun are used to normalize the radio wave amplitude during verification of the results (see paragraph 2). At the same time, the accuracy of the calculation of the background electron concentration values in addition to the ionization rate significantly depends on the temperature and concentration of neutrals (Bekker, 2018). Therefore, great attention was paid to the accuracy of determining not only \( q \) but also other parameters of the system.  

To obtain the most reliable values for \( T, [N_2], [O_2], [H_2O] \) and \([O_3]\), a statistical analysis of the experimental atmospheric data obtained by the AURA satellite from 2004 to 2018 (Livesey et al., 2013) was performed. This period includes a maximum and two minimums for the solar activity.

It is obvious that when solving the system of ionization-recombination cycle under some specific heliogeophysical conditions, use of averaged values rather than separate measurements from a satellite as input parameters is more correct. In addition, it is necessary to approach such averaging carefully, because the results of the calculation of the electron concentration significantly depend on the selected ranges for the heliogeophysical conditions - latitude, longitude, zenith angle, season, index \( F_{10.7} \). On the one hand, the selected ranges for the heliogeophysical conditions should be wide enough to include a representative sample of measurements, and, on the other hand, a considered parameter should not change significantly within the given limits. To solve this problem, the daily, seasonal, latitudinal, and longitudinal dependence of satellite data \( T, [N_2], [O_2], [H_2O], \) and \([O_3]\), as well as the dependence on solar activity (index \( F_{10.7} \)), was considered. For each of the parameters, the probability density functions were built and their dynamics were analyzed when each heliogeophysical condition was changed in turn with the other conditions fixed.

Figure 2 shows the neutrals temperature \( T \) dependence on latitude for different months and levels of solar activity at an altitude of \( h = 60 \) km. The colors in the figure correspond to the values of the probability den-
sity function of temperature $P(T)$ normalized to its maximum. As shown, the temperature has a latitudinal dependence. Therefore, the latitude step $\Delta \varphi$ must be selected in such a way that the temperature does not change significantly. For example, during the summer months, when choosing $\Delta \varphi = 10^\circ$, the difference between the nearby latitudinal $T$ values does not exceed 3.5%. The final value of $\Delta \varphi$ was chosen so that the temperature change did not exceed 5%.

In addition, one should pay attention to how the function $P(T)$ varies with season. Not only does the average value profile differ but also its dispersion changes: the spread of values for the winter period is much larger than that for the summer. This point was also taken into account for the simulation, and temperature values were considered for each month separately. For solar activity, as a rule, the dispersion of the values increases with its growth, but the median remains practically unchanged, especially within the latitudinal range we are modeling (30–60$^\circ$). That is why separation of data according to levels of solar activity was not carried out.

The next parameter essentially influencing $N_e$ at the $D$-region altitudes is the concentration of neutrals $M$. It is found that the average concentration does not depend on latitude. However, an increased spread in values is clearly observed on approach to the poles. A change in seasonal value is seen only at $h \leq 80$ km and not for the entire range of latitudes. Figure 3 shows the seasonal variation of the neutrals concentration $M$ for different latitude ranges at an altitude of 75 km. The colors in the figure correspond to the values of the probability density function $P(M)$ normalized to its maximum. As follows from Figure 3, the seasonal $M$ profile is observed at latitudes of $\varphi > 40^\circ$, and, within the equatorial part, its value remains almost constant. Since the concentration at low latitudes does not depend on the season, it is natural that the dispersion of concentrations here is lower.

The daily variation of temperature and concentration of neutrals was not detected at any of the altitudes.

The behavior of small neutral components is nearly the same as that of the concentration of neutrals $M$, since experimental satellite measurements of [$H_2O$], [$O_3$], and [$CO_2$], as well as measurements of the [NO] concentration required for the calculation of $q$ are given in (ppmv) (Anderson et al., 1986; Bekker, 2018; Brunelli & Namgaladze, 1988). Other regularities registered make an insignificant contribution to the already discovered dependences, so they are not discussed here.

The performed statistical analysis of $T$, [$N_2$], [$O_2$], [$H_2O$], and [$O_3$] allows one to carry out careful and individual selection of acceptable ranges of heliogeophysical conditions for each parameter, thus providing for the most correct approach to calculate the profiles of the input parameters of the ionization-recombination cycle system within the available data received from the satellite.

**Figure 3.** The seasonal dependence of the normalized probability density function $P(M)$ for (left panel) $0^\circ < \varphi < 40^\circ$ and (right panel) $\varphi > 40^\circ$ ($h = 75$ km).
3.2. Calculation of the Ionization Rate

As noted above, one of the key parameters of the system of Equation 1 is the ionization rate $q$. The main source of the Earth’s atmosphere ionization is the electromagnetic radiation of the Sun with wavelengths of $\lambda \leq 134$ nm.

Under calm conditions, the main contribution to the ionization of the medium by photons with $\lambda \leq 102.57$ nm arises from the ionization of the main atmospheric components. Most of this radiation is absorbed above 90 km (Solomon & Qian, 2005). Softer radiation ionizes small components, mainly the NO molecule, with an ionization threshold of 134 nm. The loss of the photon flux with $\lambda > 101$ nm occurs due to interaction with O$_2$ molecules. Particle ionization in this range occurs by the photoelectric effect mechanism, which leads to the production of only one electron with an energy that is not sufficient to knock out additional electrons by electron impact.

As shown by satellite measurements, solar radiation with $\lambda > 101$ nm has weak temporal variations. Measurements of the EUVE channel (115–127 nm) from the GOES-13, -14, -15 satellites (Machol & Viereck, 2016; Machol et al., 2016) show that the maximum of the radiation flux $W_{EUVE}$ (W/m$^2$) is approximately two times higher than its minimum. Moreover, a sharp change in $W_{EUVE}$ values is observed during some solar flares.

Taking into account the above, an algorithm for calculating the ionizing effect of UV radiation on the D-layer of the ionosphere was developed based on the LASP Reference Spectrum (No. 1 March 25–29, 2008) (https://lasp.colorado.edu/lisird/data/whi_ref_spectra/).

The following functions are determined for $\alpha$ particles based on the LASP spectrum:

$$ c_\alpha(S_{O_2}) = \int_{\lambda_{\text{min},\alpha}}^{\lambda_{\text{max},\alpha}} F_{\text{LASP}}(\lambda) \cdot \sigma_{\text{ion},\alpha}(\lambda) \cdot \exp(-\sigma_{\text{abs},O_2}(\lambda) \cdot S_{O_2}) d\lambda $$ \hspace{1cm} (2)

$$ S_{O_2} = \int [O_2] dl $$ \hspace{1cm} (3)

where $c_\alpha(S_{O_2})$ is the ionization rate coefficient of $\alpha$ particles, $S_{O_2}$ is the integral of the number of O$_2$ molecules along the ray $l$, $\lambda_{\text{min},\alpha}$ and $\lambda_{\text{max},\alpha}$ are the lower and upper wavelengths of the photons, respectively, $F_{\text{LASP}}(\lambda)$ is the spectral density of the number of particles, $\sigma_{\text{abs},O_2}$ is the absorption cross section of O$_2$ molecules, and $\sigma_{\text{ion},\alpha}$ is the ionization cross section of the $\alpha$ particles. The cross sections were taken from previous papers (Fennelly & Torr, 1992; Keller-Rudek et al., 2013) and an electronic resource (http://satellite.mpic.de/spectral_atlas/cross_sections/).

The electron production rate at a point with a particle concentration of $N_\alpha$ can be calculated by using the following formula:

$$ Q_\alpha(S_{O_2}) = \frac{W_{EUVE}}{W_{\text{LASP}}} \cdot c_\alpha(S_{O_2}) \cdot N_\alpha $$ \hspace{1cm} (4)

where $W_{\text{LASP}} = 6.79 \times 10^{-3}$ W/m$^2$ is the radiation flux of the reference spectrum in the 115–127 nm range, and $W_{EUVE}$ is the measured flux in the channel.

This work takes into account the ionization of NO molecules in the 102.57–134 nm range and O$_3$ in the 101–102.57 nm range.

Ionization by galactic cosmic rays $Q_{\text{CR}}$ plays an important role below $\sim 70$ km under calm conditions. This source of ionization for mid-latitudes is based on previous papers by Thomas & Bowman (1985) and Ermakov et al. (1997) and does not change over time.

The X-ray ionization $Q_{\text{XR}}$ (100 eV–100 keV) plays a decisive role in the ionization of the lower ionosphere during an X-ray flare. Ionization occurs via two different ways: photoelectric effect and Compton scattering, and photoelectrons lead to additional ionization by electron impact in the general case. In the framework of this work, the electron production rate inducted by X-ray radiation was determined as:
where \( \varepsilon = 33 \, \text{eV/electron} \) is the electron energy price, \( h \nu \) is the photon energy, \( E(h \nu) \) is the average energy transferred from a photon to the medium in one interaction, \( E_{\text{c}}(h \nu) \) is the average energy of a Compton electron, \( N_{\beta} \) is the concentration of particles \( \beta \), \( F(h \nu) \) is the spectral density of photons arriving at the considered point in space, \( F_{\text{XR}}(h \nu) \) is the spectral density of photons in the Earth’s orbit, \( \tau(h \nu) \) is the optical depth, \( S_{\beta} \) are quantities similar to 3 for particles \( \beta \), \( \sigma_{\text{ion, } \beta} \), \( \sigma_{\text{com, } \beta} \), and \( \sigma_{\text{abs, } \beta} \) are cross sections for photoionization, Compton scattering, and total absorption of photons by particles, respectively. In Equation 6, the particles \( N_{2}, O_{2} \), and \( O \) were taken into account, and, in Equation 8, \( Ar \) was added to them. Cross sections were determined according to the EPDL97 model (Cullen et al., 1997). Molecular cross sections were calculated as double cross sections of the corresponding atoms.

The spectral density of the photons was calculated from measurements in the XL (0.1–0.8 nm) and XS (0.05–0.4 nm) channels of the GOES-13 and -15 satellites (with correction) and the QD channel (0.1–7 nm) of the SDO satellite (Woods et al., 2012) according to the HMSXS model (Korsunskaja, 2019). Satellite data averaged with a step of 1 min were used.

Thus, the total ionization rate was calculated by using the following formula:

\[
q = Q_{NO} + Q_{O2} + Q_{XR} + Q_{CR}.
\]

The solar gamma-ray is not taken into account in this approximation.

### 3.3. Calculation of Electron Concentration

Altitude profiles for the electron concentration were calculated for separate VLF paths, for which further verification of the results was carried out. We calculated the profiles along the paths with steps of \( \sim 300 \) km that could vary slightly so that the profiles were distributed evenly.

For the simulation, we selected several X-ray flares of different classes (\( C, M \)- and \( X \)-class), meeting the following conditions:

1. Available X-ray solar flux measurements from the GOES and SDO satellites to be used for the ionization rate calculation
2. Full illumination of the European VLF paths during the flares
3. Operable condition of VLF signal transmitters and a receiver located at the Mikhnevo geophysical observatory, allowing for verification of the results

According to these criteria, we selected several X-ray flares of different classes that occurred in October 2013 and June 2014. Table 2 features the data for the flares under consideration. Data for the quiet days on October 22, 2013 and June 8, 2014 preceding the events listed in Table 2 were used for normalization of the amplitude values.

We selected these two series of consecutive flares of different classes because we also wanted to check if the temporal dynamics of small neutral atmospheric components during the X-radiation growth should be

| Date             | Start time (UT) | Maximum time (UT) | Maximum flux |
|------------------|-----------------|-------------------|--------------|
| October 24, 2013 | 09:59           | 10:09             | M2.5         |
| October 24, 2013 | 10:30           | 10:33             | M3.5         |
| October 25, 2013 | 07:53           | 08:01             | X1.7         |
| October 25, 2013 | 09:43           | 10:12             | M1.0         |
| June 9, 2014    | 12:24           | 12:29             | C9.0         |
| June 10, 2014   | 08:17           | 08:25             | C3.9         |
| June 10, 2014   | 09:17           | 09:31             | C5.1         |
| June 10, 2014   | 10:04           | 10:17             | C5.0         |
| June 10, 2014   | 11:36           | 11:42             | X2.2         |
| June 10, 2014   | 12:36           | 12:52             | X1.5         |
included in the ionospheric models. In our model, the concentrations of small neutrals are considered external input parameters and are not modified during the calculation process. If the hard radiation noticeably modifies the small neutrals during a flare, calculation of the sequence of events should give an increasing error for each subsequent flare.

Basing on the analysis above, we determined acceptable ranges for the heliogeophysical conditions for the selected geographical points and moments of time. The values for $T$, $\left[N_2\right]$, $\left[O_2\right]$, $\left[H_2O\right]$, $\left[O_3\right]$, and $\left[CO_2\right]$ that fell within the above ranges, were used to construct the probability density functions with an altitude step of $\Delta h = 5$ km. These functions were used for calculation of the most likely values, which we applied to solve the system of differential equations for the ionization-recombination cycle. The ionization rate $q$ was determined as a function of time with a step size of $\Delta t = 1$ min. The system of Equation 1 was solved for each set of the obtained vertical profiles for the input parameters. At the output, we obtained the electron concentrations under calm conditions and during solar flares of different classes.

Figure 4 features the X-ray flux registered by the GOES satellite and the vertical profile of the ionization rate and electron concentration observed above the Mikhnevo geophysical observatory during $X$- and $M$-class flares on October 25, 2013. The electron concentration registered during X-ray flares increased by more than two orders of magnitude at some altitudes of the $D$-region.

Figure 5 features the $Ne$ concentration dynamics at an altitude of $h = 75$ km during the time interval of October 25, 2013, as calculated by using the temperature $T$ and concentration of neutrals $M$ obtained from the AURA satellite and the MSIS model (Hedin, 1991). The blue error bars represent the standard deviation of the AURA data selected for the calculation.

The curves obtained show a difference between the $T$ and $M$ values obtained from the MSIS model and the most likely values obtained from the satellite. In addition, in Figure 5, one can see a significant contribution to the accuracy of the $Ne$ concentration calculation made by not only the ionization rate but also by the temperature and concentration of the neutral components. Therefore, we assume that the statistical analysis of the input parameters based on the satellite data should fundamentally improve the $D$-region simulation quality at least for calm conditions and $C$- and $M$-class flares when the concentration of $Ne$ is the most sensitive to the considered variations.
4. **Model Verification Based on the Experimental Data Obtained for VLF Radio Wave Propagation during X-Ray Flares and Discussion of the Results**

As mentioned above, we used the amplitude characteristics of the VLF transmitter signals (Table 1) received at the Mikhnevo geophysical observatory for verification of the results obtained for modeling of the lower ionosphere at the flares listed in Table 2.

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**Figure 5.** Electron concentration during X- and M-class flares on October 25, 2013 above the geophysical observatory Mikhnevo calculated by using the MSIS model and the data received from the AURA satellite.

**Figure 6.** The theoretical and experimental time variation of the amplitude of a radio wave due to C-, M- and X-class X-ray flares on October 24 and 25, 2013 and June 9 and 10, 2014, as received from the GBZ transmitter.
Figure 6 presents the results obtained from comparison of theoretical and experimental curves for 10 considered flares of different classes that occurred on October 24 and 25, 2013 and June 9 and 10, 2014. The diagrams show the time variation of the signal from the GBZ transmitter.

It is found out that the constructed plasma-chemical model allows us to predict the amplitude response to weak ionospheric disturbances with sufficiently high accuracy, which is evident in the bottom panels of Figure 6. Moreover, three recurrent C-class flares that occurred on June 10, 2014 are correctly simulated, which indicates a minor influence of the dynamics of small neutral components.

As for the M-class flares, verification of the lower ionosphere model built according to the radiophysical data showed that the model allows describing quantitative variation of the experimental value of the amplitude received from the GBZ transmitter. The difference between the experimental and calculated values reaches a maximum during the highest ionization rate, with values lying within a range of 1.5 dB.

The top right panel of Figure 6 presents the results obtained by simulating the ionospheric response to a X-class flare that occurred on October 25, 2013. The amplitude dynamics simulation is not correct in the part following the flare start at 08:00 UT. The current heuristic model of the radiation spectrum and ionization of the lower ionosphere (Korsunskaja, 2019) does not describe ultrahard X-radiation, which could be the reason for the difference between the theoretical and experimental results. Analysis of the Sun’s radiation spectrum based on RHESSI observatory data (http://sprg.ssl.berkeley.edu/~tohban/browser/) has proven the presence of ultrahard X-radiation in this flare.

It is obvious that X-class flares have the greatest influence on the amplitude variations, which can lead to a loss of signal at these frequencies. Therefore, the ability of the model to predict the qualitative and quantitative behavior of experimental values for the amplitude \( A_{\exp} \) during high energy flares is of great interest in this work.

Figure 7 presents the results obtained from the modeling of three X-class flares that occurred on October 25, 2013 (08:01 X1.7) and June 10, 2014 (11:42 X2.2, 12:52 X1.5) on six European VLF paths. The top panels show the GOES flux in the XL (0.1–0.8 nm) and XS (0.05–0.4 nm) channels during the considered flares.

As shown in Figure 7, the constructed model describes quite well the response of the VLF signal amplitude to the initial sharp increase of the solar X-radiation flux. It should be noted that the starting amplitude response to the flare that occurred on October 25, 2013 was described qualitatively and quantitatively quite correctly on 5 paths out of 6, but, as follows from the behavior of the radio wave amplitude, the subsequent relaxation of the medium differed markedly from the real one. At the same time, within 2 h after the disturbance, the theoretical value of the amplitude reaches the experimental value.

As for the right panels in Figure 7, the X1.5 flare (12:36 UT), which occurred on June 10, 2014, is described worse than the X2.2 flare (11:36 UT) on all paths. It is most likely that this behavior is associated with incorrect accounting for the relaxation processes of the medium after the first perturbation. Thus, as a consequence, the D-region ionization during the second flare is calculated with inaccurate initial conditions.

The following work will include further development of the ionization model aimed at determining the correct account of ultrahard X-radiation, rectification of the relaxation processes and rate constants and advanced verification for all available paths and transmitter frequencies.

In addition to qualitative evaluation of the results obtained, we analyzed the quantitative difference in [dB] between the simulated and experimental values for the radio wave amplitude during the flares considered. For this purpose, a function \( D(t) = A_{\text{theor}}(t) - A_{\exp}(t) \) was analyzed for 4 days including the days with solar flares listed in Table 2.

As quality criteria for the obtained results, we selected two parameters: the root mean square error (RMSE) and the \( D(t) \) module integral rationed by the integration time interval (from start to end of the particular flare), as given in formulas 10, 11:

\[
\text{RMSE} = \sqrt{\frac{n}{\sum_{i=1}^{n}(D_i(t))^2}}
\]
Figure 7. X-ray flux from the GOES satellite (top panels) and theoretical and experimental time variation of the amplitudes of the radio waves received from the GBZ, ICV, FTA, GQD, DHO, TBB transmitters. The left panels present the results during the X1.7 flare on October 25, 2013 and the right panels show the results for the X2.2 and X1.5 flares on June 10, 2014.
It is obvious that the smaller the value for these parameters, the better the model describes the measured values for the signal amplitude.

Figure 8 shows the obtained normalized values of RMSE (%) and $I$ averaged for each class of flares. Both diagrams are provided with indication of the transmitters from Table 1 and the frequencies at which they operate. The red, yellow, and green colors show the lines corresponding to the X-, M-, and C-class flares, respectively. RMSE, root mean square error.

The obtained criteria provided in Figure 8 confirm the conclusion made for qualitative evaluation of the agreement between the theoretical and experimental results; generally, the smaller the class of simulated flare, the better it is described with use of the constructed model. There are some exceptions. For example, the values for the lowest criteria correspond to M-class flares on the DHO–Mikhnevo path.

In addition to the dependence on flare energy, one can notice some correlation of the results with the transmitter frequency. For example, simulated data for the paths from lower frequency transmitters: GBZ, ICV, FTA, and GQD have a better agreement with the experimental data for the X-class flares. At the same time, there is a significant difference in the path lengths for the transmitters: GBZ, ICV, FTA, GQD and those for DHO and TBB. The latter two show the worse agreement with the experiment. Thus, in terms of modeling high-energy flares, the issue of correct calculation of the electron concentration profile defining the geometry of the waveguide remains undecided.

As a result of the verification using data from ground-based radiophysical measurements taken at the Mikhnevo geophysical observatory, it is found that the average normalized RMSE is $\sim 7\%$, $14\%$, and $18\%$ for C-, M-, and X-class flares, respectively. Qualitative and quantitative analysis of the verification results for the VLF signal amplitude shows good predictive capability for the model built for describing weak and moderate ionospheric disturbances generated by solar flares.

5. Conclusions

The verification results obtained for a model simulating the ionospheric D-region carried out according to ground-based radiophysical measurements taken at the Mikhnevo geophysical observatory prove that application of satellite data obtained for the neutral atmosphere and ionization rates calculated on the
basis of actual radiation flux values within the X-ray and ultraviolet ranges allows one to describe the lower ionosphere during solar flares with adequate accuracy. Additionally, it should be emphasized that a year of high solar activity is characterized by a C-class flare level for the background X-ray flux. This means that additional ionization of the lower ionosphere by X-ray radiation must be taken into account at all times rather than only at the time of an actual large flare.

When simulating the ionosphere under the condition of X-class flares, we obtained contradicting results. In our opinion, the main reason for errors occurring for modeling of the D-region during a high-level of ionization is the unaccounted for ultrahard X-radiation. This leads to inaccurate calculation of the electron concentration profile, and, consequently, errors in determining the absolute value of the amplitude response to a sharp growth in ionization. Consequently, this affects the accuracy in describing environmental relaxation after the disturbance. At the same time, we note that the model recovers the background amplitude, varying by ~0.5 dB from the experimental value within 1–2 h after a X-class flare event.

Data Availability Statement

The VLF data set used in the present work was collected by the Mikhnevo observatory of Sadovsky Institute of Geospheres Dynamics of Russian Academy of Sciences (http://geospheres-dynamics.com/). The experimental atmospheric data obtained by the AURA satellite are available at https://disc.gsfc.nasa.gov/. The satellite data for the radiation flux obtained by the GOES and SDO satellites are available at http://satdat.ngdc.noaa.gov/sem/goes/data/ and http://lasp.colorado.edu/eva/data_access/evewebdataproducts/. The MSIS model profiles can be obtained under https://ccmc.gsfc.nasa.gov/modelweb/models/msis_vitmo.php. All the other data necessary to reproduce the reported findings are available at https://doi.org/10.5281/zenodo.4055274.

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