Diagnostics of plasma in the ionospheric D-region: detection and study of different ionospheric disturbance types

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Abstract. Here we discuss our recent investigations of the ionospheric plasma by using very low and low frequency (VLF/LF) radio waves. We give a review of how to detect different low ionospheric reactions (sudden ionospheric disturbances) to various terrestrial and extra-terrestrial events, show their classification according to intensity and time duration, and present some methods for their detections in time and frequency domains. Investigations of detection in time domain are carried out for intensive long-lasting perturbations induced by solar X-ray flares and for short-lasting perturbations caused by gamma ray bursts. We also analyze time variations of signals used in the low ionospheric monitoring after earthquake events. In addition, we describe a procedure for the detection of acoustic and gravity waves from the VLF/LF signal analysis in frequency domain. The research of the low ionospheric plasma is based on data collected by the VLF/LF receivers located in Belgrade, Serbia.

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1 Introduction

The ionosphere is the part of the atmosphere located between about 50 km and 1000 km where the charged particles significantly influence its physical and chemical properties [1,2]. For this reason the study of plasma properties and all processes with a focus on charged particle production plays a crucial role in its understanding. In addition to scientific importance [3,4,5], studies of the ionospheric plasma and the dynamics of perturbations induced therein can, for example, be of great practical significance in fields related to telecommunications [6] and may also contribute to a better insight into features related to elementary disasters like earthquakes [7].

The ionosphere being a part of the terrestrial outer layer is constantly exposed to many influences coming from the outer space in addition to those occurring in the Earth’s layers which all affect its dynamics [8,9,10]. Consequently, the physical properties of the atmosphere (density, temperature etc.) are time and space dependent [11,12] which justifies the use of monitoring variations of atmospheric parameters for indirect detection of different phenomena both of cosmic and terrestrial origin [13-15].

Generally, the phenomena that affect the local environment cause different reactions of its constituents. These responses vary in intensity, duration and location of the perturbation, which requires application of various observational setups and techniques for their detection. Some of the most important measurement characteristics are the distance between the experimental setup and observed area, observed altitude range, time resolution and sensitivity. Based on this, one can divide the observation methods in various ways:

- Based on distance between the experimental setup and observed area. There are two types of atmospheric monitoring: in situ (by rockets and satellites/space probes) and remote sensing (by satellites, radars, ionosondes, very low and low frequency (VLF/LF) emitters and receivers). In the first case, the instruments are placed at the location that is being observed while the remote sensing observations are based on detection of signals emitted by transmitters located at some distance away from the receivers and the area which is being monitored. Data obtained by remote sensing techniques are less precise than those by in situ measurements but they cover a significantly broader observational area.

- Based on the observed altitude range. Thus, LIDAR (Light Detection and Ranging) [16] is used for observations of the atmosphere at altitudes of a few kilometers, balloons are enforceable for measurements at
about 30 km while radar, rocket, and measurements by radio signals can be used for observations of the ionosphere.

- Based on time resolution, taking advantage from the fact that the duration times of phenomena can be very different. For example, some disturbances, such as those caused by lightnings, gamma ray bursts (GRBs) and meteor passings through the atmosphere can last up to several ms while phenomena like solar X-ray flares, coronal mass ejections, and hurricane events can perturb part of the atmosphere for periods lasting tens of minutes, hours, or days. For this reason the time resolution of the received data must be adapted to the duration time of the observed phenomenon.
- Based on sensitivity, which is particularly important in the case of weak perturbations. In addition to instrument characteristics it depends on the area where signals propagate (length of the signal propagation path and plasma medium properties).

In this paper we focus our research on the lower ionosphere located between 50 km and 90 km where the dominant source of ionization under unperturbed conditions comes from the solar Lyα radiation (above about 70 km at daytime) which induces formation of the D-region, and cosmic rays (at nighttime and below about 70 km at daytime). Variations in intensity of these radiations as well as the increase of incoming X and gamma radiation fluxes in the atmosphere, induction of different types of waves, and changes in the atmospheric electric conductivity cause sudden changes in the ionospheric plasma properties. The sources of these sudden ionospheric disturbances (SIDs) have extraterrestrial and terrestrial origins. The most important SIDs result from solar X-ray flares and lightnings while influence of other noticed phenomena like GRBs rarely induce very significant SIDs. These perturbations have various properties reflected in their duration and intensity which can further be used for their classification.

The aim of the paper is to present methods of SID detection and their differences depending on causing events (terrestrial and extra-terrestrial) based on time and frequency domain analysis. We point out the importance of certain characteristics of the low ionosphere monitoring in study of its non-periodic, local, short-term, and weak reactions. Keeping in mind that SIDs can be classified according to their duration time as short-term (like in the case of lightning occurrence) and long-term (like in the case of some solar influences), and based on intensity to strong (e.g. induced by solar X-ray flares) and weak (e.g. due to GRBs), we classify the relevant procedures for extraction of SIDs. This kind of investigation is important for further analyses of characteristics of plasma parameters such as electron density, electron gain and loss rates, recombination coefficients and temperature under perturbed conditions. In these researches it is necessary to implement a numerical program package like the Long-Wave Propagation Capability (LWPC) and use analytical procedures like those given in

Here we analyze the indirect detection of non-periodic phenomena and solar terminator (ST) by monitoring VLF/LF radio waves whose propagation depends on the low ionosphere properties and, consequently, varies with induced disturbances in this atmospheric part. The presented examples of given procedures are obtained in analyses of data collected by the AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) and AbsPAL (Absolute Phase and Amplitude Logger) VLF/LF receivers in Belgrade, Serbia for signals emitted by the DHO, ICV, and NAA transmitters located in Germany, Italy and the USA, respectively.

Here we limit our study to ionospheric variations after and during occurrences of considered events. We point out that there are some studies which analyze prediction of particular events using ionospheric perturbation detections, but this task requires a more detailed analysis which is out of the scope of this paper but will be in focus of our upcoming investigations.

The paper is organized as follows: In Sec. 2 we describe our observations and experimental setup, in Sec. 3 we present time domain analysis, and in Sec. 4 we give a model for detection of SIDs using the frequency analysis. Results of our research concerning detections of SIDs using VLF signal analyses in time and frequency domain are presented in Sec. 5 and, finally, a short summary of this study is given in Sec. 6.

2 Observations and experimental setup

As said in Introduction, this study is focused on ground based measurements of the VLF/LF radio waves (3 kHz - 30 kHz and 30 kHz - 300 kHz frequency domains) which are reflected in the Earth-ionosphere waveguide. This method is based on the fact that the considered signals propagate through the low ionosphere which affects characteristics of their propagation and, consequently, the shapes of registered VLF/LF wave variations in real time, indicating the presence of non-stationary physical and chemical conditions in the perturbed medium along the VLF/LF wave trajectories (for details see, for example [25,26]). Namely, perturbations make the local electron density and, consequently, the height of the wave reflection, time dependent [27] which further alters the VLF/LF wave trajectory and causes the registered wave amplitude and phase to be time dependent.

The global experimental setup for the VLF/LF monitoring technique consists of numerous transmitters and receivers distributed worldwide that enable observations of a large part of the low ionosphere and detections of local plasma perturbation patterns in the D-region. A number of receivers are incorporated in some international networks like AWESOME, SAVNET, and AARD-DVARK. A very important characteristic of this technique for ionospheric monitoring is a continuous emission and reception of radio signals with a very good time resolution (it can be 10 µs) allowing detections of sudden, and, consequently, non precisely predicted, events, as well as detection of short-term ionospheric reactions.

In this work we present data recorded by the VLF/LF AWESOME and AbsPAL receivers located in the Institute...
of Physics in Belgrade, Serbia. These receivers operate since 2004 and 2010, respectively. Here we study connections of SIDs with three specific events for time-domain: GRBs (2009-2012), solar X-flare in 2010 and earthquake in Serbia in 2010, as well as connections with ST in 2010 for the frequency domain analysis.

We consider the 23.4 kHz, 20.27 kHz and 24 kHz signals emitted by the DHO (Germany), ICV (Italy) and NAA (USA) transmitters, respectively, with time resolutions of 0.02 s (for the analysis of short-term SIDs, such as those induced by GRBs), 1 s (for the analysis of perturbations induced by solar X-ray flares) and 1 min (for the analysis of long-term SIDs, possibly induced by earthquakes). The emission power of these signals is 800 kW, 20 kW and 1000 kW, respectively, and they are transmitted as can be seen in Fig. 1 showing the amplitudes recorded by the Belgrade AWESOME receiver on December 21, 2010. The detection breaks occurring in time intervals 7-8 UT and 13-14 UT are of a pure technical nature related to the DHO transmitter being off-air, and the procedure of how the collected data are preprocessed and archived respectively.

3 Time domain analysis

Characteristics of a detected signal by a particular device for the VLF/LF radio wave acquisition are time dependent and connections of their signatures with ionospheric perturbers are very hard to track. There are two main reasons for that:

- First, as it was anticipated in Sect 1, the plasma located in the low ionosphere is simultaneously exposed to influences of numerous natural and artificial events. Consequently, the recorded signal characteristics which indirectly reflect ionospheric plasma properties are subject to noise and different tendencies which become of prime importance in detection of particularly weak perturbations.
- Second, in addition to periodical and sudden variations of ionospheric plasma conditions, characteristics of signals like mutual locations of the transmitter and receiver, power of transmitted signal, and the geographical area through which the signal propagates affect the recorded signal properties. Namely, the intensity of the received signal amplitude depends on the emission power and on the distance between the transmitter and receiver. In the case of emission power, a more intense emission induces a larger amplitude of the received signal than emitted signal with lower power. On the other hand, the influence of the transmitter-receiver distance on the considered relationship is not so simple. This can be visualized using simulations of signal propagation within the Earth-ionosphere waveguide by the LWPC numerical model developed by the Naval Ocean Systems Center (NOSC), San Diego, USA [29]. In Fig. 2, upper panels, we show simulated amplitude of signals emitted by the DHO transmitter (Germany) with the emission power of 800 kW and by the ICV transmitter (Italy) with the emission power of 20 kW at the ground in directions toward the Belgrade VLF/LF receiver. We analyze three moments in period before and during the solar X-ray flare occurred on May 5, 2010. We take the quiet period before the flare, denoted as period "0" in the panels, as the reference dependency, while the periods "1" and "2" correspond to perturbed stages where we estimated the ionospheric conditions, before the perturbation maximum and at the peak of the perturbation, respectively.

In this figure we can see that the amplitude intensity is weaker for the ICV signal than for the stronger DHO signal at all distances from the transmitters. Also, the dependencies between the ionospheric changes of electron density induced by the X-ray radiation increase and the VLF/LF signal amplitudes are not monotonous, e.g. a growth of the electron density \(N_e(0) < N_e(1) < N_e(2)\) does not necessarily imply an increase of the recorded signal amplitudes. This is visible in the bottom panels showing that the amplitude changes can be both positive and negative when the electron density is larger (cases "1" and "2") than in the case of quiet conditions "0". One can see that these changes in amplitude depend on the distance from the transmitter. As an experimentally recorded example of different reaction on electron density increase/decrease we present amplitude variations of signals emitted by the NAA, ICV and DHO transmitters located in the USA, Italy.
Fig. 2. Simulated amplitudes (upper panels) and their changes (bottom panels) relative to the initial quiet ionospheric state of the VLF signals versus distance from the DHO (left panels) and ICV (right panels) transmitters that emit them during the quiet condition "0" and in two perturbed stages "1" and "2" induced by the solar X-ray flare occurred on May 5, 2010.

and Germany, respectively, which were induced by the electron density increase due to the solar X-ray flare occurred on March 25, 2011 (see Fig. 3). It is noticeable that more intensive ionization processes result in the increase of the NAA signal amplitude (upper panel), decrease of the ICV signal amplitude (middle panel) and the combined tendency of the DHO signal amplitude (bottom panel).

Despite of numerous impacts on the ionospheric plasma, individual events can cause dominant influence on local plasma properties. In that case the relationship between a particular event and the corresponding SIDs (here classified as strong SIDs) can be analyzed. However, in some cases we can not extract the low ionospheric reaction induced by some considered events. There are three main reasons for that:

– The intensity of the SID is weak and it cannot be extracted from the noise in one particular case;
– The shape of signal variation caused by the considered event is the same or very similar to those induced by some other phenomena occurring in the same time period;
– The reaction does not induce clearly visible changes in recorded signal properties

Here, we take these reactions as weak SIDs. The study of the relationship between the considered events and relevant local plasma reactions is primarily based on statistical analyses. For these procedures it is very important that no other processes, inducing reactions similar to those expected in the considered case, are present. For example, the statistical analysis of the short term SIDs induced by GRBs is not relevant in the case when numerous amplitude peaks exist before the satellite detection of the GRB (Fig. 3 bottom panel).

There are different procedures for detection of weak SIDs. Here we explain the following methods:

– **Extraction of amplitude peaks.** This technique is used and described in [22] where the short duration low ionospheric reaction on a GRB is confirmed. This is based on determination of times when the peaks of the signal amplitude $A(t)$ deviate from the base curve $A_{\text{base}}(t)$ by more than $r$ times the amplitude of noise $A_{\text{noise}}(t)$:

$$\frac{A(t) - A_{\text{base}}(t)}{A_{\text{noise}}} \geq r,$$

and their occurrence in time bins before or after the registration of the considered events.
Fig. 3. Differences in the amplitude time evolutions of the signal emitted in the USA (upper panel), Italy (middle panel), and Germany (bottom panel) and received by the AWESOME VLF/LF receiver in Serbia during the influence of the solar X-ray flare occurred on March 25, 2011.

- **Comparison with relevant quiet period.** Information about the existence of SIDs can be obtained using a comparison of signal characteristics from time periods with practically the same conditions, but in absence of SIDs. This procedure is very useful in the case when there are no sudden strong variations in the signal characteristics time evolutions.

- **Superposed epoch technique.** This technique is applicable when we have a weak perturbation which is not clearly visible in one particular case because of the low signal intensity but which is repeated under the same influence. For example, this method is used to detect the transmitter-induced precipitation of the inner radiation belt electrons in the low ionosphere which is practically very small [30]. It is based on the averaged sum of time series of the signal amplitude. Here it is important to say that perturbations are of the same duration. Namely, in the case when the amplitude variations are short-term with respect to the considered time interval, and are not frequent, this method can not confirm them although their occurrences are in the same time period after the influence of perturber. This conclusion is obtained for a short term response of the low ionosphere on GRBs [22] whose detection is confirmed using the procedure for extraction of amplitude peaks.

For both types of SIDs, strong and weak, analyses of the ionospheric plasma require independent data related to detection of processes which perturb it like data collected by satellite-borne detectors for radiation coming from the outer space or ground-based optical meteor detectors.

In addition to the SID detection using the analysis of signal characteristics in time domain, SID can be discovered as intensification of waves at some frequency in the considered medium. In diagnostic of the low ionospheric plasma by radio waves, this method can be applied to electron density variations in periods when we can assume a monotonous relationship between the recorded signal characteristic and electron density.

4 Frequency domain analysis

In addition to the SID detection based on the signals analysis in the time domain, the recorded data can be processed by appropriate techniques and further analyzed in the frequency domain in order to extract waves existing in the considered medium. These waves can be excited by natural [31,32] and artificial [33] events and, depending on their frequency and medium properties, they can be divided into several types like acoustic, gravity and planetary waves.
Here, our attention is focused on explanation of the theoretical procedure for determination of possible acoustic and gravity waves (AGWs) in the lower ionosphere and on presentation of processing for determination of the excited wave frequency from the VLF/LF signal amplitude analysis.

4.1 Theory

Keeping in mind that typical atmosphere models give $n_0 \sim 10^{24} \text{m}^{-3}$ for the neutral particle density and only $n_p \sim 10^8 \text{m}^{-3}$ for charged particles at heights $H \sim 90$ km where VLF/LF radio waves are being deflected, we can assume that the electric and magnetic effects play a negligible role in local dynamics. Consequently, standard hydrodynamic rather than magneto-hydrodynamic (MHD) equations can be applied in analysis of the low ionospheric waves. For this reason in our study we start therefore from the general set of hydrodynamic equations for adiabatic processes in ideal neutral gas:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad \rho = \rho_R a T, \tag{2}
\]

\[
\frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \rho \mathbf{g}, \tag{3}
\]

\[
\frac{\partial p}{\partial t} + (\mathbf{v} \cdot \nabla) p = \gamma \rho \left[ \frac{\partial \rho}{\partial t} + (\mathbf{v} \cdot \nabla) \rho \right]. \tag{4}
\]

Here $\gamma = c_p/c_v = (i + 2)/i$ is the ratio of specific heats for gas particle with $i$ degrees of freedom. For a mono atomic and two atom molecules, respectively, $R_a = k/m_a = R/M_a$ is the individual gas constant for molecules with particle mass $m_a$ or molar mass $M_a$, $k = 1.3807 \times 10^{-23} [\text{J/K}]$ is Boltzmann’s constant, and $R = 8.3145 [\text{J/K/mol}]$ is the universal gas constant. Other quantities in Eq. (2) have their usual meanings.

In what follows, we consider waves whose spatial dimensions are sufficiently small in comparison with both the radius of the Earth $R_E = 6371$ km and any temperature inhomogeneity length $L_T$ that can be defined on the basis of existing temperature profiles. Consequently, the plane parallel geometry can be applied with gravitational acceleration $\mathbf{g} = -g \hat{e}_z$ (with $g=9.81 \text{ m/s}^2$) in a locally isothermal medium. Under these assumptions the atmosphere is taken to be vertically stratified, initially in hydrostatic equilibrium, and then perturbed by harmonic waves of small amplitude. This means that Eqs (2)-(4) can be linearized by taking each variable $\Psi(x, y, z, t)$ as a sum of its basic unperturbed value $\Psi_0(z)$ and a small first order perturbation $\Psi_1(x, y, z, t)$ arising from waves, i.e.:

\[
\Psi(x, y, z, t) = \Psi_0(z) + \Psi_1(x, y, z, t), \tag{5}
\]

where:

\[
|\Psi_1(x, y, z, t)| \ll |\Psi_0(x, y, z, t)| \tag{6}
\]

and

\[
\Psi_1(x, y, z, t) = \tilde{\Psi}_1(z) e^{-i(k_z z + k_y y) t}. \tag{7}
\]

Expressed in terms of the wavelength $\lambda \equiv 2\pi/(k_x, k_y, k_z)$, our modal analysis is restricted to atmospheric waves obeying the conditions:

\[
\lambda_x, \lambda_y \ll R_E, \quad \lambda_z \ll L_T \tag{8}
\]

which is equivalent to studying plane waves in a horizontally stratified isothermal atmosphere.

Eqs. (2) - (4), linearized with perturbations given by Eqs. (5) - (7) and Eq. (5), reduce to two equations: one for the basic unperturbed state and one for small perturbations.

The basic unperturbed state is thus described by:

\[
\frac{dp_0}{dz} + \rho_0 g = 0, \tag{9}
\]

\[
p_0 = \rho_0 R_a T_0, \quad T_0 = \text{const}, \tag{10}
\]

whose solution is:

\[
\rho_0(z) = \rho_0(0) e^{-z/H} \quad \text{or} \quad p_0(z) = p_0(0) e^{-z/H} \tag{11}
\]

with $H$ being the characteristic scale-height of the isothermal atmosphere given by:

\[
H = \frac{p_0(0)}{\rho_0(0) g} = \frac{v_s^2}{\gamma g}, \tag{12}
\]

while the small perturbations are governed by:

\[
v_s^2 \omega^2 \frac{d^2 \hat{v}_{1z}}{dz^2} - \gamma g \omega^2 \frac{d \hat{v}_{1z}}{dz} + (\omega^4 - k_0^2 \omega^2 + k_0^2 v_s^2 N_{BV}^2) \hat{v}_{1z} = 0. \tag{13}
\]

Here $\omega$ is angular frequency, $k_0^2 \equiv k_x^2 + k_y^2$ is the total horizontal wavenumber, $v_s$ is the adiabatic speed of sound defined as:

\[
v_s^2 \equiv \frac{p_0}{\rho_0} = \gamma R_a T_0 = \text{const}, \tag{14}
\]

and $N_{BV}$ is the Brunt-Väisälä frequency given as:

\[
N_{BV}^2 = (\gamma - 1) \frac{g^2}{v_s^2}. \tag{15}
\]

Taking Eq. (11) into account, Eq. (13) has solutions of the following form:

\[
\hat{v}_{1z} = C \times e^{(1/2 H \pm ik_z z)} \tag{16}
\]

which finally yields the dispersion relation:

\[
\omega^4 - \left( k_0^2 + k^2 + \frac{1}{4 H^2} \right) v_s^2 \omega^2 + k_0^2 v_s^2 N_{BV}^2 = 0 \tag{17}
\]

that has to be satisfied for solutions like Eq. (15) to exist with a non-zero integration constant $C$.

The dispersion relation Eq. (17) is quadratic in $\omega^2$ which indicates the existence of two wave-modes in the considered medium: AGW modes, also known as p- and g-modes in stellar seismology.
where $\omega$.

Due to the boundary conditions of Eq. (8), it is convenient to express the dispersion relation Eq. (16) in terms of wavelengths and wave frequencies in the following way:

$$\lambda_0(f) = D_0(f) \left[ 1 + \frac{D_2(f)}{\lambda_0^2 - D_2(f)} \right]$$

(17)

with:

$$D_0(f) = \frac{v^2(f^2 - f_{BV}^2)}{f^2(f^2 - f_0^2)}$$

$$D_2(f) = \frac{v^2}{f^2 - f_0^2}$$

(18)

and:

$$f_0 = \frac{\gamma g}{4\pi v_s}$$

$$f_{BV} = \frac{N_{BV}}{2\pi}$$

$$\lambda_{0,z} = \frac{2\pi}{k_{0,z}}$$

(19)

where $f_0$ and $f_{BV}$ correspond to the acoustic cut-off and Brunt-Väisälä frequencies, respectively.

A family of hyperbolae obtained from Eq. (17) in a $(\lambda_0, \lambda_z)$-plot with $f$ being a parameter is shown in Fig. 5. In calculations we take $T_0 = 200$ K as typical temperature of the considered medium. The dispersion relation Eq. (17) has two separate domains describing:

- acoustic modes if $\infty > f \geq f_0 = 0.00606$ Hz, and
- gravity modes for $f \leq f_{BV} = 0.00594$ Hz.

There are no propagating waves with $f_{BV} \leq f \leq f_0$.

4.2 Signal processing

One of the procedures for frequency determination of the excited waves is based on the Fast Fourier Transform (FFT) applied on collected data for VLF/LF amplitude using equation:

$$A_F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-i\omega t} A(t) dt,$$

(20)

where $A_F(\omega)$ represents the Fourier amplitude at frequency $\omega$.

To find excitation of waves, model described in details in [32], requires applying the FFT on time periods of the same duration before and after the considered perturbation. The first step of this procedure is calculation of ratios of the Fourier amplitude in the time periods "$2"$ $A_F(f;2)$ and "$1" $A_F(f;1)$:

$$\alpha_{21}(f) \equiv \frac{A_F(f;2)}{A_F(f;1)}$$

(21)

As in the case of analysis in time domain, the detected variations by this equation can be consequences of different events. For this reason, to extract waves induced by one considered phenomenon, two additional criteria are introduced:

- Attenuation of the excited waves in time. This property can be analyzed in the same way as in the procedure for determination of the excited wave frequencies but for the time periods immediately after perturbation (period "$2"$) and a subsequent period lasting the same amount of time (period "$3"$). Relevant frequency dependent coefficient is:

$$\alpha_{23}(f) \equiv \frac{A_F(f;2)}{A_F(f;3)}$$

(22)

- Statistic confirmation of wave excitation by considered phenomenon taking more examples into consideration.

5 Results and discussions

Here, we present detections of SIDs using VLF signal analyses in time and frequency domain. The resulting detections are further connected with our recent research of the solar X-ray flare and GRB events influences on the low ionosphere as well as with an investigation of the possible relationship between earthquakes and the ionospheric perturbations, for which detailed analyses will be the focus of our upcoming studies.

5.1 Signal evolution in time domain

As we said in Sect. 2 the method for SID detections depends on their characteristics, especially on their intensity, duration, and repetition. Here we give examples for detections of strong and weak SIDs.

5.1.1 Detection of strong SIDs

As noted above, when SID is strong enough, we can use a comparison with independent detections of different processes and link it to some event. One of the most important sudden perturbers of the ionospheric D-region plasma is the solar X-ray flare [33, 34, 35, 36, 37], and here we will explain the main characteristics of SID on the example of this phenomenon occurred on March 24, 2011. In Fig. 6
there are presented time evolutions of the X-radiation flux \( I \) recorded by the GOES-15 satellite in wavelength range between 0.1 nm and 0.8 nm (upper panel) and amplitude \( \Delta A \) (middle panel) and phase \( \Delta P \) (bottom panel) changes of the DHO signal recorded by the AWESOME receiver in Serbia in considered period. For comparison of satellite and VLF receiver recorded variations considering characteristic time periods, we can divide SID period in three specific time domains (TDs):

- **TD 1.** In this period denoted as time interval (TI) I the intensity of the X-radiation is too small to induce an increase in the electron production which can noticeably change receiving radio signal characteristics. For this reason the electron density increase is not detected and we can say that the start of the SID detection has a time delay with respect to the solar X-ray flare detection by satellite.

- **TD 2.** As we presented at the beginning of this section related to the explanation of Fig. 3 the signal variations are different during the period of increased radiation after the SID beginning. Because of that modeling of the D-region plasma is necessary for comparison of variations in the radiation and ionospheric plasma characteristics. In the considered case, there are three TDs in this TD: TI II where both the radiation intensity as well as the signal amplitude and phase increase, TI III where \( \Delta A \) and \( \Delta P \) still grow in spite of start of solar radiation attenuation, and TI IV where signal characteristics also decrease. The last one is the simplest example where the signal has a similar time evolution as the X-radiation flux with time delay in relevant maximum values. However, other events may have different signal variations (see Fig. 3): decrease, complex shape, saturation in the extreme values etc. For these parameters the division of TD 2 is different than in this case.

- **TD 3.** When intensity of the X-radiation decreases to the values which do not produce enough electrons that noticeably affect ionization processes we can assume that the influence of a solar X-ray flare ends. Here we take that this happens when the intensity of the flare falls back to the level where the VLF signal started to increase (borderline between TD 1 and TD 2). Although there are no perturber influences in this TI V, signal characteristics reach values similar to those before the disturbance only at the end of TI V. So we can conclude that there are some relaxation periods to balance the processes of production and loss of electrons.

The explained properties related to Fig. 3 are also noticed in several other events (solar X-ray flares occurred on May 5, 2010, February 18, 2011, April 22, 2011 (two flares)) which we studied in [11,12,19,25,26,27,38]. In these studies we analyzed different space and time dependent plasma parameters in the D-region (the electron density, effective recombination coefficient, electron temperature, electron plasma frequency, contribution of Lyα line in ionization processes, electron content in the D-region and its contribution in changes of the total electron content during solar X-ray flares) using:

- The equation for electron density dynamics:
  \[
  \frac{dN(r, t)}{dt} = G(r, t) - L(r, t),
  \]
  where \( G(r, t) \) and \( L(r, t) \) are the electron gain and electron loss rate respectively that are related to the location \( r \) and time \( t \).

- The electron density \( N_e \) calculations [39] from the Wait’s parameters \( H' \) and \( \beta \) obtained using the LWPC numerical model:
  \[
  N_e(h, t) = 1.43 \cdot 10^{13} e^{-\beta(t)H'(t)} e^{(\beta(t) - \beta_0)h},
  \]
  where \( N_e \) is in m\(^{-3}\), \( H'(t) \) and \( h \) are in km, \( \beta \) is in km\(^{-1}\) and \( \beta_0 = 0.15 \) km\(^{-1}\).

- Procedure for numerical determination of the best combination of Wait’s parameters which satisfied condi-
VLF/LF data and they are developed for calculations of: (25) The electron density, electron plasma frequency and electron content \( N_e = N_e/N_0^0 \), and \( N_e^0 = 1 \text{ m}^{-3} \). (19).

\[
\Delta A_{\text{sim}}(\beta, H') \approx \Delta A_{\text{rec}}(t),
\]

where \( \Delta A_{\text{sim}} \) and \( \Delta P_{\text{sim}} \) are simulated amplitude and phase changes, while \( \Delta A_{\text{rec}} \) and \( \Delta P_{\text{rec}} \) are registered ones. This procedure explained in [41] shows how we can use VLF/LF recorded data in diagnostic of the D-region plasma.

The calculated electron density values (see Fig. 7) show that these examples represent the group of events for which the electron density and signal characteristics have very similar time evolution shapes. For this reason the time intervals and time domains given in Fig. 6 are relevant for the electron density, too. The analytical and numerical procedures given in these studies are based on recorded VLF/LF data and they are developed for calculations of:

1. The electron density, electron plasma frequency and index of refractivity during perturbation time period [12,27].
2. The photo-ionization rate in the upper part of the ionospheric D-region induced by the Lyo line radiation coming from the Sun in unperturbed conditions [11].
3. The effective recombination coefficient during relaxation period [26].
4. The Lyo line contribution in the ionization rate in the maximum of X-radiation flux [38].
5. The electron temperature during relaxation period [12].
6. The D-region electron content contribution in the total electron content [19].

The main results of presented studies are:

- The existence of a time delay between the onset and the maximum of the electron density perturbation with respect to the corresponding phases of the X-ray flux time evolution and the existence of a relaxation period for the D-region plasma [11].
- The dominant influence of the increased intensity of radiation lines in the X-ray spectrum on the enhancement of the electron density in the D-region during the solar flares [25,38].
- Increase of the electron density more than one order of magnitude at the top of the D-region [11].
- Increase of the effective recombination coefficient at the end of the relaxation and its decrease with altitude [26].
- Increase in contribution of the D-region electron content in the total electron content with X-radiation intensity maximum [10].
- Decrease of the electron temperature at the end of the relaxation and its increase with altitude [12].
- Increase of the electron temperature changes with altitude at the end of the relaxation [12].

5.1.2 Detection of weak SIDs

Detection of a weak SID depends on its characteristics: the intensity, duration and repetition. In these cases statistical analysis is needed to establish a potential link between some phenomenon and the considered type of SID. Here we present the methods for examination of the weak VLF/LF signal changes. We analyze periods around GRBs and earthquake.

Extraction of amplitude peaks. Fig. 8 presents the increase in number of amplitude peaks \( r = 2, 3, 4 \) and 5 times larger than noise amplitude for a sample of 54 GRBs lasting less than 1 min which are observed by the SWIFT satellite in the period 2009-2012. In this sample we took in consideration the 24 kHz VLF signal emitted by NAA transmitter located in the USA and received in Serbia with time resolution of 20 ms within the periods from 2 min before to 2 min after satellite detection which is not significantly affected by other perturbers. These relatively quiet conditions are required for the shown procedure because of numerous peaks induced by other events which can significantly change statistics, as it is shown in Fig. 4. As one can see, the increase of number of relevant amplitude peaks is larger in periods of 2 min after GRB detections than in the same duration period before which confirms detectability of a short term reaction of the low ionosphere to GRBs.

Here we point out that this method is based on the statistical analysis of one type event data set and it gives information about detectability of SIDs that can be connected with the considered phenomenon.

Comparison with the relevant quiet period. As an example for this method we present the comparison of amplitude of the 20.27 kHz VLF signal emitted by the transmitter IVC in Isola di Tavolara, Italy, and received by the AbsPAL receiver located in the Institute
of Physics in Belgrade, Serbia for three days in sunset period: the day of the earthquake that struck near Kraljevo, Serbia, on November 3, 2010 (00:57 UT) and one day before and after it. As we can see in Fig. 9 in the day of the earthquake the inverse peaks after 15 h UT, A_{01} and A_{02} start earlier than in the other two days (A_{-1} for day before and A_{1} for day after). It is important to point out that two minima are recorded although the two reference days indicate the existence of just one. Here we can not certainly claim that the signal changes are induced by the earthquake. However it is important to emphasize that similar correlation of the earthquake occurrence with such a signal perturbation is analyzed also in [42] and processing of the sample of the signal amplitudes in periods around particular earthquake events can be used for examination of the considered relationship.

5.2 Signal evolution in frequency domain

As illustrative example of method based on frequency analysis, we apply the procedure described in Sect. 4 on ST induced waves in the low ionosphere. We consider the 90 min time intervals at the beginning and end of the daytime and night sections when quasi-stationary conditions of the basic state (needed for analysis of the linear waves) are achieved. These intervals are noted as "a" (before sunrise), "b" (after sunrise), "c" (before sunset) and "d" (after sunset). The relevant coefficients related to sunrise \( r_{sr, exc} \) and \( r_{sr, att} \), and sunset \( r_{ss, exc} \) and \( r_{ss, att} \) on May 9, 2010 are calculated by Eqs. (21) and (22), and plotted in Fig. 10. Here we can indicate three common peak domains in all plots. They correspond to perturbations that produce much larger Fourier amplitudes after
perturbations and much smaller ones at the end than at
the beginning of the related time section. These domains
lie between $3 \cdot 10^{-4}$ Hz and $10^{-3}$ Hz, $3 \cdot 10^{-4}$ Hz and $4 \cdot 10^{-3}$ Hz and $10^{-2}$ Hz and $2 \cdot 10^{-2}$ Hz. According to
the analysis given in Sect. 4.1 the first two oscillation fre-
quency domains correspond to the gravity modes and the third
one to the acoustic modes. The detailed analysis of five
days given in [52] confirms that corresponding wave
time periods are a result of the ST induced perturbation
which is in agreement with those for higher altitudes of
the E- and F-regions from literature [43,44]. Also, similar
fluctuations in the form of magnetohydrodynamic waves
were also found in high magnetospheric regions as exter-
nally driven modes with typical periods ranging from few
seconds to more than 1000 s [45,46].

6 Summary

To conclude this research we point out the existence of
different SIDs which required different methods for their
detections by VLF/LF radio signals monitoring. Here we give the classification of the
SIDs and suggest several methods for their detections us-
ing time domain analyses:

- Strong SIDs. These plasma perturbations are sufficiently
  large to cause detectable changes in signal character-
  istics and in these cases we can analyze relationship
  between one particular event properties, and the iono-
  sphere and, consequently, VLF/LF signals reactions.
  Here we point out time delays in the ionospheric re-
  sponse and its relaxation period after perturbation.
  Also, we point out and explain differences in the signal
  reactions to some phenomena.

- Weak SIDs. The uncertainty in detections of these par-
  ticular events is induced by:
  - Weak intensity of SIDs;
  - The occurrence of other nearly simultaneous phe-
    nomena that induce very similar variations to the
    ones sought for;
  - No clearly visible changes in recorded signal prop-
    erties.

Here, statistical analysis is needed to establish a po-
tential link between a phenomenon and the considered
type of SID. The suggested methods which can be used
for possible confirmation of the low ionospheric reac-
tions to the considered phenomenon are:
- Extraction of amplitude peaks.
- Comparison with the relevant quiet period.
- Superposed epoch technique.

In addition to the explained procedure for signal analy-
zes in the time domain, we present a method for detection
of AGWs. It is based on implementation of the FFT on
recorded signal amplitude within periods before, immedi-
aply and some time after several events of the same type
in order to determine the excited wave frequencies, their
attenuation and repetition, which, consequently, confirm
induction of AGWs by the considered phenomenon.

All these procedures have been described with some
relevant examples for better clarity.

In addition to the application of various experiment-
mental settings to monitor different height domains, there are
several types of measurements of the same area. Each of
them has its own advantages and disadvantages. The pre-
sent study shows that our experimental equipment is
completely suitable for the monitoring of different SIDs:
periodical and unperiodical, long-lasting and short-lasting,
global and local, strong and weak. This is possible since
there is a continuous emission and reception of radio sig-
als, very good time resolutions of collected data and nu-
merous worldwide located transmitters and receivers. The
main disadvantage of this technique is the absence of in-
formation on local plasma medium which can be obtained
using in site measurements by the rockets. However, that
kind of measurement is not continuous and usually it can
not be used for detection of unpredicted SIDs like those
induced by e.g. GRBs.

Finally, we want to point out the importance of large
databases in different statistical analyses and their combi-
nation in statistical analyses of the relatively rare events,
like earthquakes, and comparative analyses of the different
signals or geographical areas reactions.

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