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DIFFERENCES IN DETECTION OF D-REGION PERTURBATIONS INDUCED BY THE UV, X AND γ RADIATION FROM OUTER SPACE USING VLF SIGNALS

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Abstract. In this paper we present characteristics of detection of various events occurring in the outer space that perturb the D-region by emission of the UV, X, and γ radiation. The method of our analysis is based on monitoring variations of recorded VLF (very low frequency) radio signals in real time that are reflected from the D-region. We show examples of strong and weak perturbations and present a procedure for detection hydrodynamic waves.

1. INTRODUCTION

The ionosphere, having plasma characteristics, is very sensitive to electromagnetic disturbances whose intensity and variable influences coming from outer space as well as from the terrestrial atmosphere and lithosphere. The non-periodic and sudden events, such as solar flares (Nina et al. 2011, 2012a; Kolarski et al. 2011, 2014, Singh et al. 2014), coronal mass ejections (Bochev and Dimitrova 2003, Balan et al. 2008), solar eclipses (Singh et al. 2012), influences of processes in distant parts of the universe like supernova explosions followed by hard X and γ radiation (Inan et al. 2007), lightnings (Voss et al. 1998, Collier et al., 2011), and some processes in the terrestrial lithosphere like volcanic eruptions and earthquakes (Gousheva et al. 2008, Nenovski et al. 2010), induce temporal, space and time varying ionospheric perturbations. These disturbances cause numerous complex physical, chemical and dynamical phenomena in the ionosphere (Nina et al. 2012a, Nina and Čadež 2013, Jilani et al. 2013, Maurya et al. 2014) and may directly affect human activities, especially in the telecommunications. Besides a pure scientific interest to study the influence of solar activity to the terrestrial atmosphere, the understanding mechanisms and making predictions on resulting consequences in turbulent regions of the ionosphere has important applications in radio communications, planning networks of mobile communications satellites, high-precision applications of global navigation satellite systems, etc. (Bajčetić et al. submitted paper).

The atmospheric monitoring depends on altitude of considered medium. The location of the low ionosphere lies below the area being studied by satellite observations and above the region where balloon measurements find their application. The low ionospheric monitoring is based on rocket and radar measurements (Strelnikova and Rapp 2010, Chau et al. 2014), and on technology involving on propagation of very low frequency (VLF) radio waves. The advantages of the VLF method come from possibilities to observe a large part of the low ionosphere, to detect local perturbations, and to detect sudden events. All this is enabled by means of numerous transmitters and receivers forming a worldwide international network for continuous signal emission and reception.

The VLF radio signal propagation properties are determined by the wave attenuation and reflection. Changes in the received signal amplitude and phase are primarily consequences of variations in the low ionospheric electron density which enables investigation of this atmospheric layer by the VLF signal technology.

In this paper we show a possibility to detect different astrophysical phenomena by using the VLF method. We consider differences in ways of their detection and we present our procedure developed to detect hydrodynamic waves.

2. EXPERIMENTAL SETUP

The Belgrade VLF station consists of two receivers with one electrical (AbsPAL - Absolute Phase and Amplitude Logger) and two magnetic loop (AWESOME - Atmospheric Weather Electromagnetic System for Observation Modeling and Education) antennas, respectively. They can simultaneously register 6 and 15 signals emitted by different transmitters at fixed frequencies, respectively. The first of them has been operating since 2004, while the second one since 2008. During this period we have collected a large data base containing a written information about numerous low ionospheric responses to different natural and human-induced events. This allows for making statistical analyses of considered phenomena and to detect differences within a long-term period. In our investigations we considered signals whose characteristics are given in Table 1.

3. OBSERVATIONS AND RESULTS

3. 1. DETECTABILITY

As a part of atmosphere, the low ionosphere is under permanent influences of events coming from outer space, and Earth's layers. Here, we consider detections of low ionospheric plasma perturbations due to the radiation coming from outer space. The intensity of plasma reactions in the low ionosphere depends on the incoming radiation flux in atmosphere, absorption in higher layers, and total ionization cross section in the ionospheric D-region. During perturbations, variations in the D-region electron density can be large, but they can also be very small which, consequently, causes large and small changes in VLF signal characteristics.

Table 1: Transmitters characteristics and path length of analyzed VLF/LF signals. The data for transmitters are found in file AWESOME Transmitters.pdf in website `http://nova.stanford.edu/~vlf/IHY_Test/TechDocs/`.

SIGN	LOCATION	FREQUENCY (kHz)	POWER (kW)	LENGTH (km)
DHO	Rhauderfehn Germany	23.4	800	1304
GQD	Anthorn UK	22.1	200	1935
ICV	Isola di Tavolara Italy	20.27	20	976
NRK	Grindavik Island	37.5	800	3230
NAA	Cutler Maine, USA	24.0	1000	6548
NWC	North West Cape Australia	19.8	1000	11974

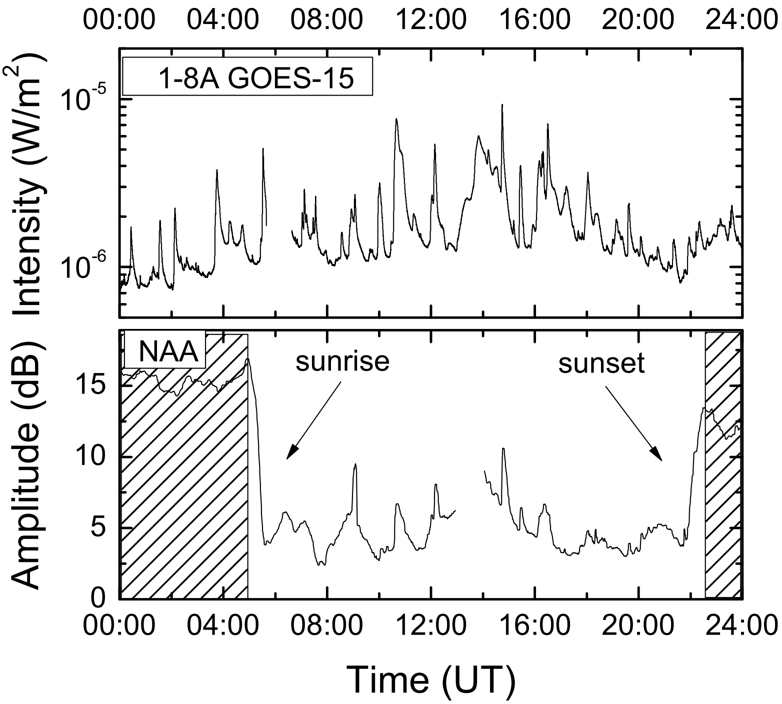

Figure 1: Amplitude variation of the NAA signal emitted from the USA (bottom panel). The shaded domains are related to the signal propagation during the night-time. The large variations during the daytime are due to the increased radiation induced by the solar X-flare (upper panel).

As investigations showed, dominant roles in the quite D-region plasma ionization have the Lyα radiation coming from the Sun, and cosmic radiation (Swamy 1991). The most important perturber of this area is the X-radiation emitted from the Sun during solar X-flares.

In Fig. 1, we show differences in the NAA signal amplitude at the nighttime and daytime, and its increases as reactions to the rising of the incoming X-radiation in the atmosphere, registered by the GOES-15 satellite during solar X-flares.

The variations shown in Fig. 1 are the evident consequences of considered phenomena. But, in some cases, the reactions to a particular phenomenon are weak and changes in the recorded signal cannot be related to them with certainty. The inability to pinpoint particular weak influences is consequence of numerous events which affect ionospheric plasma. They have time and space dependent intensity at the considered location and cause a signal noise that can be very large during unstable conditions. As illustration, the NAA signal during the period around the time of registration the γ ray burst GRB090726 is given in Fig. 2.

A more quiet state was in the period around the γ ray burst GRB110412A that can be visible from the time evolution of amplitude of five VLF signals as shown in Fig. 3. Here we can see signal changes after starting the GRB detection, but more cases must be considered for a certain confirmation of possibility to detect a ionospheric response to a similar high energy radiation impact (Nina et al. 2013, Nina et al. paper in preparation).

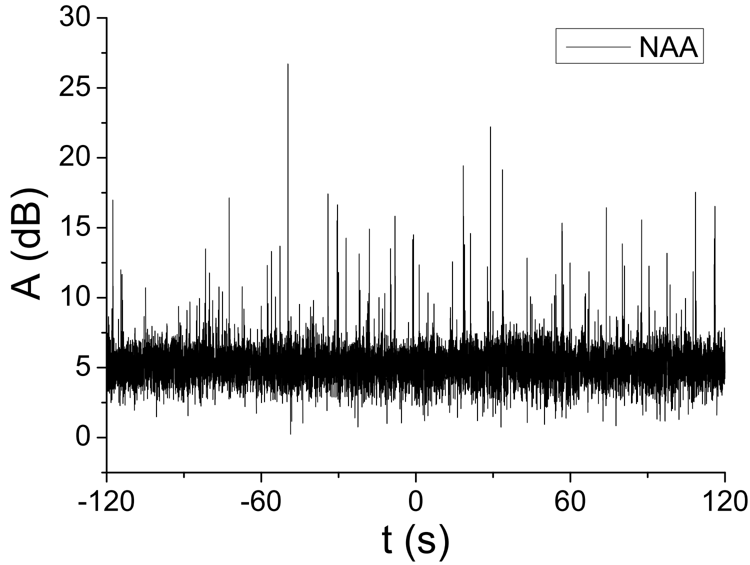

Figure 2: Display of frequent amplitude disturbances of the VLF signal emitted by NAA transmitter located in the United States on July 26, 2009 during the period around the time of registration the γ ray burst GRB090726 whose starting time corresponds to 0 in the graph.

3. 2. DETECTION OF HYDRODYNAMIC WAVES

Hydrodynamic waves in the ionosphere can be induced by different events that relatively strongly perturb a part of the atmosphere. They can be both sudden like sprite and periodical like a solar terminator (ST). In literature, the study of the latter case is related only to altitudes above the D-region. Our intention was to develop a procedure for detection acoustic and gravity waves in the low ionosphere (Nina and Čadež 2013).

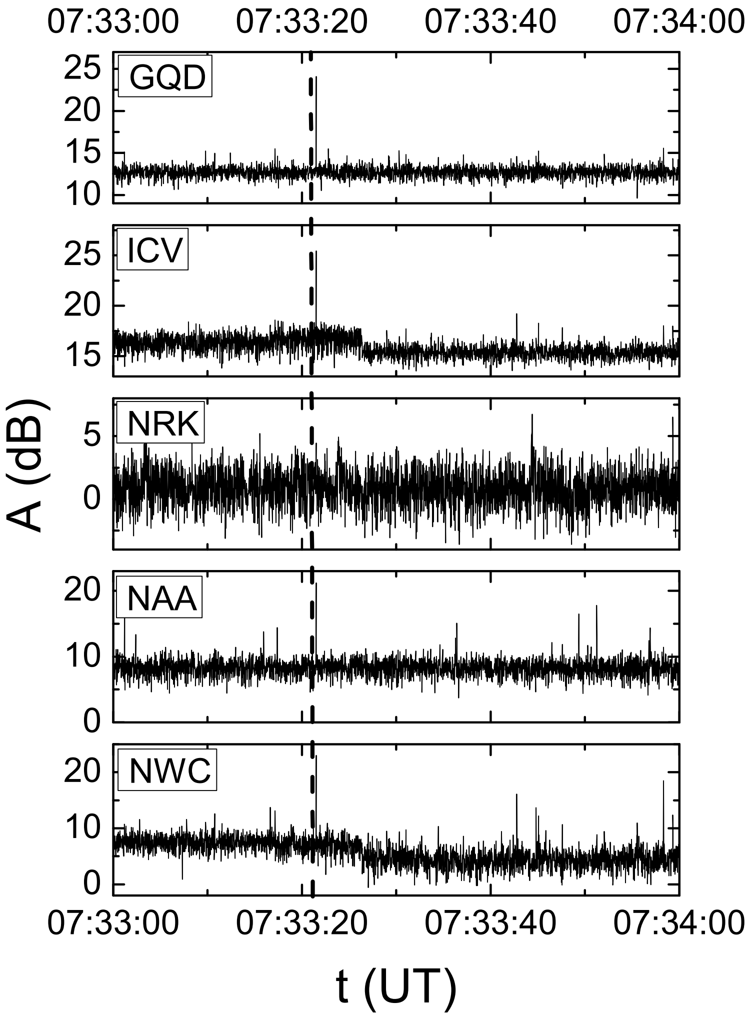

Figure 3: Amplitude variations of signals emitted from different locations (from the top panel: the UK, Italy, Iceland, the USA and Australia) and recorded in Belgrade after the γ ray burst GRB110412A registered on April 12, 2011, with start at 7:33:21.15 UT indicated by vertical line.

In this paper we show our investigation of the sunrise effect on the low ionosphere using the signal registered within the time interval 5:00 UT - 7:00 UT, emitted by the DHO transmitter located in Germany (Fig. 4). Here, the three distinct time sections of 30 min are shaded and labeled by **n**, **sr** and **d**, respectively. They cover periods before (the entire signal path is at the nighttime), during, and after (the entire signal path is at the daytime) the sunrise, respectively.

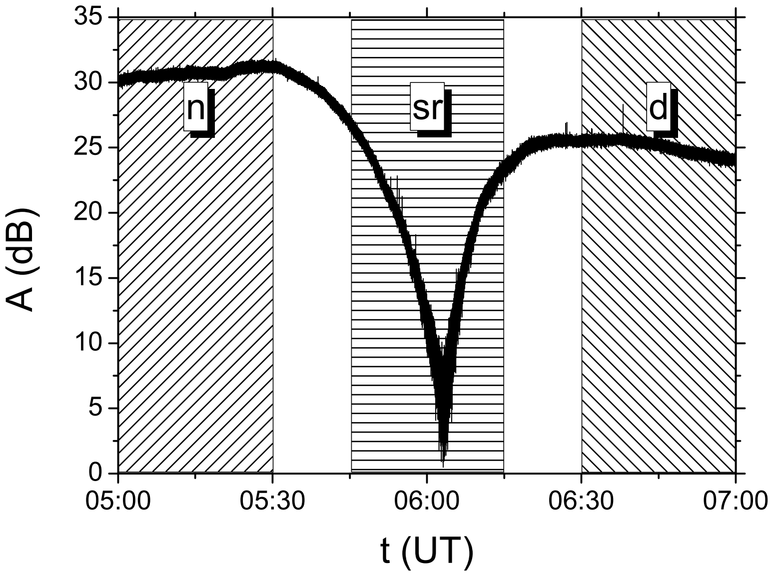

Figure 4: The time evolution of the VLF signal amplitude emitted by the DHO transmitter in Germany and recorded by the AWESOME VLF receiver in Serbia. The shaded domains designate the 30 min time intervals before, during and after the sunrise.

Details of the applied procedure of signal analysis are explained in Nina and Čadež (2013). The procedure consists of two steps. First, the Fourier transform is applied to the recorded amplitudes A(t) during each of the considered time domains. The corresponding oscillation spectrum $A_{\rm F}(\omega)$ follows from the Fourier transform:

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

where $\omega \equiv 2\pi/\tau$ and τ are the oscillation frequency and oscillation period, respectively. The obtained values are shown in the Fig. 5 (left panels) for $\tau > 1$ min. Second, Fourier amplitudes $A_{\rm F}$ for relevant domains (as labeled in Fig. 4) are compared by scaling as follows:

$$\alpha_n^{sr}(\tau) \equiv \frac{A_{\rm F}(\tau; sr)}{A_{\rm F}(\tau; n)},\ \alpha_d^{sr}(\tau) \equiv \frac{A_{\rm F}(\tau; sr)}{A_{\rm F}(\tau; d)},\ \alpha_{dn}(\tau) \equiv \frac{A_{\rm F}(\tau; d)}{A_{\rm F}(\tau; n)}.$$

Resulting values are shown in Fig. 5 (right panels).

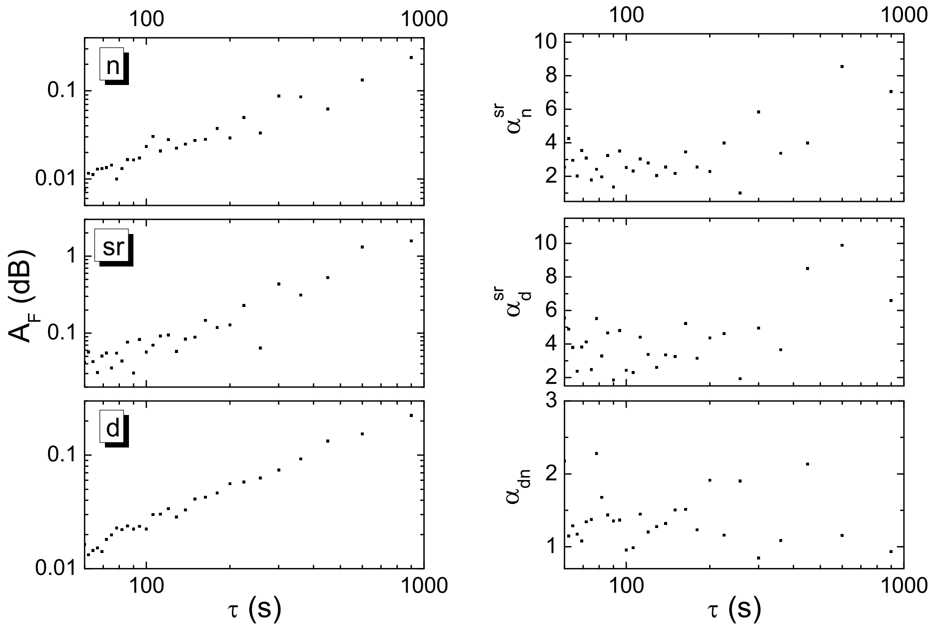

Figure 5: Fourier amplitudes of the VLF signal for domains **n**, **sr** and **d** (upper, middle and bottom left panels, respectively). The right panels show ratios of Fourier amplitudes related to domains **sr** and **n**, **sr** and **d**, and **d** and **n**, respectively.

For investigations of physical conditions in the low ionosphere, the most important information is the relation between signal properties in the **d** and **n** domains with quasi-stationary conditions which allows for detections of AGWs. In Nina and Čadež (2013) the extraction of waves excited by the ST was carried out by considering the following three typical characteristics of the phenomenon:

1. AGW waves are excited during the ST and become attenuated to a certain degree afterwards.

2. These two processes occur both at the sunrise and sunset in spite of different daytime/nighttime conditions of the medium.

3. This repeats itself daily.

The peaks in the bottom right panel show the excitation of the Fourier amplitude of the VLF signal after the sunrise. The obtained peak values at 60 s and 400 s for τ are in a good agreement with results in Nina and Čadež (2013) for the low ionosphere showing an enhanced induction of AGWs by the ST for oscillation periods τ within intervals 60 s - 100 s, 300 s - 400 s, and over 1000 s. Our results for the low ionosphere are very similar to those obtained for higher altitudes (De Keyser and Čadež 2001a, 2001b, Hernandez-Pajares et al. 2006, Afraimovich 2008).

3. 3. VARIATIONS IN PLASMA CHARACTERISTICS

As we said in Introduction, the recorded signal characteristics can be used for diagnostic of the low ionosphere. This can be done by using some numerical models for simulation of VLF signal propagations. In our investigations the Long-Wave Propagation Capability (LWPC) numerical model (Ferguson, 1998) was used. Here, we point out that the signal characteristics cannot be monotonous functions of electron density. For this reason, the quantitative descriptions in some cases, especially within the periods of solar terminator, cannot be obtained directly from the observed data and it is necessary some additional modeling of the low ionosphere.

To calculate the altitude and time dependencies of the electron density $N(h,t)$, we usually perform the ground based low ionosphere monitoring using the VLF radio signal emitted by the DHO transmitter (Germany). The reason for this is the best quality of the recorded signal owing to the high emission power of 800 kW and a suitable signal frequency for the location of the receiver, and a relatively short signal propagation path. The latter property is significant as it excludes significant variations in the vertical stratification of parameters in the ambient ionospheric plasma. This is important because the low ionospheric characteristics are time and space dependent, variations can be both periodically and sudden, and can be caused by events that induced both global and local perturbations.

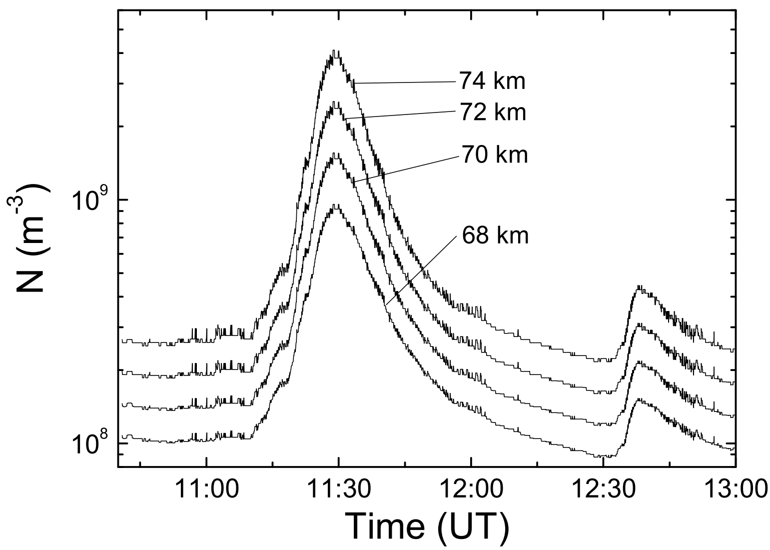

Figure 6: Time evolution of electron density during solar flares occurred on 24. 03. 2011.

The reactions of considered plasma on astrophysical events depend on the state of physical and chemical conditions in the medium. For example, the study published in Nina et all. (2011), has shown that increasing of the Lyα radiation, the most important origin of the quiet D-region plasma photo-ionization, does not have an important influence during presence of the solar X-flare influence. Also, the different geophysical conditions (for example in polar and equatorial zones) and periodical time variations in external influences (for example during the solar cycle, year, and day) make ionospheric variations space and time dependent. This points to the limited use of data from the literature in specific calculations related to a specific location and in a specified time period. For this reason, the main goal of our investigations of D-region plasma properties is the development of procedures for modeling plasma parameters from experimental data related to the considered time and space defined by transmitter and receiver locations. Thus, in studies of Nina et al. (2012a,b) we have calculated the electron density time and altitude distributions during the influence of two flares. In Fig. 6 we have shown one typical reaction of the D-region plasma to solar X-flares.

In Fig. 7, obtained in Nina and Čadež (2014), we can see variations in the Lyα photo-ionization rate in quiet low ionosphere calculated in periods after large perturbations and their comparison with corresponding results from literature.

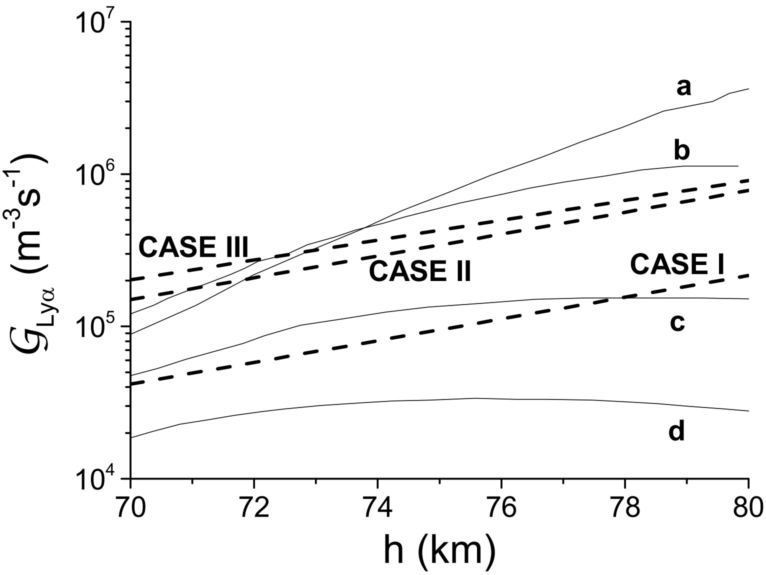

Figure 7: Altitude dependencies of the electron gain rate $\mathcal{G}_{Ly\alpha}$ for Case I, II and III (Nina and Čadež, 2014), and their comparison with data presented in Mitra (1977) (a), Rowe (1972) (b), Aikin et al. (1969) (c) and Bourdeau et al. (1965) (d). Case I, II and III relate to flares occurred on May 5th, 2010, February 18th, 2011, and March 24th, 2011 analyzed in Nina and Čadež, 2014.

4. SUMMARY

In this paper we present analyses and differences in detection of D-region perturbations induced by the UV, X and γ radiation from outer space using VLF signals. We overview our procedures related to detection of hydrodynamic waves and calculations of plasma parameters, which have a universal character in sense that they can be applied to any relatively small part of the D-region during its reactions to different events.

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References

Afraimovich, E. L: 2008, First GPS-TEC evidence for the wave structure excited by the solar terminator, *Earth, Planets and Space*, **60**, 895.

Aikin, A. C.: 1969, The ion pair production function of the lower ionosphere, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Md.

Bajčetić, J., Kolarski, A., Nina, A, Čadež, V. M., Todorović, B. M.: Solar X-flares and HF radio signal propagation in ionospheric D-region, *Geoscience and Remote Sensing Letters, IEEE*, submitted paper

Balan, N., Alleyne, H., Walker, S., Reme, H., McCrea, I., Aylward, A.: 2008, Magnetosphere-ionosphere coupling during the CME events of 07-12 November 2004, *Journal of Atmospheric and Solar-Terrestrial Physics*, **70**, 2101.

Bochev, A. Z., Dimitrova, I. I. A.: 2003. Magnetic cloud and magnetosphere - ionosphere response to the 6 November 1997 CME, *Advances in Space Research*, **32**, 1981.

Bourdeau, R. E., Aiken, A. C., Donley, J. L.: 1965, The lower ionosphere at solar minimum, Goddard Space Flight Center, NASA, Greenbelt, Md.

Chau, J. L., Röttger, J., Rapp, M.: 2011, PMSE strength during enhanced D region electron densities: Faraday rotation and absorption effects at VHF frequencies, *Journal of Atmospheric and Solar-Terrestrial Physics*, **118**, Part A, 113.

Collier, A. B., Lichtenberger, J., Clilverd, M. A., Rodger, C. J., Steinbach, P.: 2011, Source region for whistlers detected at Rothera, Antarctic, *Journal of Geophysical Research*, **116**, 3219.

De Keyser, J., Čadež, V. M.: 2001a, Excitation of low-frequency fluctuations at the magnetopause by intermittent broadband magnetosheath waves, *Journal of Geophysical Research*, **106**, 29467.

De Keyser, J., Čadež, V. M.: 2001b, Transient development of magnetohydrodynamic wave mode conversion layers, *Journal of Geophysical Research*, **106**, 15609,

Ferguson, J. A.: 1998, Computer programs for assessment of long wavelength radio communications, Version 2.0, Technical document 3030, Space and Naval Warfare Systems Center, San Diego CA.

Gousheva, M. N., Glavcheva, R. P., Danov, D. L., Hristov, P. L., Kirov, B. B., Georgieva K. Y.: 2008, Electric field and ion density anomalies in the mid latitude ionosphere: Possible connection with earthquakes?, *Advances in Space Research*, **42**, 1, 206.

Hernandez-Pajares, M., Juan, J. M., Sanz, J.: 2006, Medium scale traveling ionospheric disturbances affecting GPS measurements: Spatial and temporal analysis, *Journal of Geophysical Research*, **111**, A07S11.

Inan, U. S., Lehtinen, N. G., Moore, R. C., Hurley, K., Boggs, S., Smith, D. M., Fishman, G. J.: 2007. Massive disturbance of the daytime lower ionosphere by the giant γ-ray flare from magnetar SGR 1806-20, *Geophysical Research Letters*, **34**, 8103.

Jilani, K., Mirza A. M., Khan, T. A.: 2013, Ion-acoustic solitons in pair-ion plasma with non-thermal electrons, *Astrophysics and Space Science*, **344**, 135.

Kolarski, A., Grubor, D.,Šulić, D.: 2011, Diagnostics of the solar X-Flare impact on lower ionosphere through seasons based on VLF-NAA signal recordings, *Baltic Astronomy*, **20**, 591.

Kolarski, A., Grubor, D.: 2014, Sensing the earths low ionosphere during solar flares using VLF signals and goes solar X-ray data, *Advances in Space Research*, **53**, 11, 1595.

Maurya, A. K., Phanikumar, D. V., Singh, R., Kumar, S., Veenadhari, B., Kwak, Y. S., Kumar, A., Singh, A. K., Kumar, N. K.: 2014, Low-mid latitude D region ionospheric perturbations associated with 22 july 2009 total solar eclipse: Wave-like signatures inferred from VLF observations, *Journal of Geophysical Research: Space Physics*, **119**, 10, 8512.

Mitra, A. P.: 1977, Ionospheric Effects of Solar Flares, Mir, Moscow.

Nenovski, P., Spassov, C., Pezzopane, M. Villante, U., Vellante, M., Serafimova, M.: 2010, Ionospheric transients observed at mid-latitudes prior to earthquake activity in Central Italy, *Natural Hazards and Earth System Sciences*, **10**, 1197.

Nina, A., Čadež, V. M.: 2013, Detection of acoustic-gravity waves in lower ionosphere by VLF radio waves, *Geophysical Research Letters*, **40**, 18, 4803.

Nina, A., Čadež, V. M.: 2014, Electron production by solar Lyα line radiation in the ionospheric D-region, *Advances in Space Research*, **54**, 7, 1276.

Nina, A., Čadež, V. M., Srećković, V. A., Šulić, D.: 2011, The Influence of solar spectral lines on electron concentration in terrestrial ionosphere, *Baltic Astronomy*, **20**, 609.

Nina, A., Čadež, V. M., Srećković, V. A., Šulić, D.: 2012a, Altitude distribution of electron concentration in ionospheric D-region in presence of time varying solar radiation flux, *Nuclear Instruments and Methods in Physics Research B*, **279**, 110.

Nina, A., Čadež, V. M., Šulić, D., Srećković, V. A., Žigman, V.: 2012b, Effective electron recombination coefficient in ionospheric D-region during the relaxation regime after solar flare from February 18, 2011, *Nuclear Instruments and Methods in Physics Research B*, **279**, 106.

Nina, A., Popović, L. Č., Srećković, V. A., Simić, S.: 2013b, Book of Abstracts of IX SCSLSA, eds L. Č. Popović, M. S. Dimitrijević, Z. Simić and M. Stalevski, 70.

Nina, A., Popović, L. Č., Srećković, V. A., Simić, S.: paper in preparation.

Rowe, J. N.: 1972, Model studies of the lower ionosphere, Sci. Rep.No. 406, Pennsylvania State Univ., Univ. Park, USA.

Singh, Ashutosh K., Singh, Rajesh, Veenadhari, B., Singh, A. K.: 2012, Response of low latitude D-region ionosphere to the total solar eclipse of 22 July 2009 deduced from ELF/VLF analysis, *Advances in Space Research*, **50**, 10, 1352.

Singh, Ashutosh K, Singh, Ashutosh K, Singh, Rajesh, Singh, R. P.: 2014, Solar flare induced D-region ionospheric perturbations evaluated from VLF measurements, *Astrophysics and Space Science*, **350**, 1, 1.

Strelnikova, I., Rapp, M.: 2010, Studies of polar mesosphere summer echoes with the EISCAT VHF and UHF radars: Information contained in the spectral shape, *Advances in Space Research*, **45**, 247.

Swamy, A. C. B.: 1991, A new technique for estimating D-region effective recombination coefficients under different solar flare conditions, *Astrophysics and Space Science*, **185**, 153.

Voss, H. D., Walt, M., Imhof, W. L., Mobilia, J., Inan, U. S.: 1998, Satellite observations of lightning-induced electron precipitation, *Journal of Geophysical Research*, **103**, 11725.