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# DETECTION OF TERRESTRIAL IONOSPHERIC PERTURBATIONS CAUSED BY DIFFERENT ASTROPHYSICAL PHENOMENA

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**Abstract.** In this paper, we present our results of investigation of perturbations in the ionospheric D-region caused by different astrophysical phenomena. We considered induced time variations of electron density during solar X-flares, generation of gravity and acoustic waves by solar terminator, and possibility of gamma ray burst detection by very low frequency (VLF) radio signals. The studies are performed through analyses of data bases related to VLF radio signals recorded in real time by the receiver located in Belgrade that are being emitted by worldwide distributed transmitters.

## 1. INTRODUCTION

In addition to a purely scientific interest, studying the effects of specific ionospheric plasma perturbers finds practical applications, primarily in telecommunications. Namely, changes in the signal characteristics caused by varying ionospheric plasma conditions, require perutbation predictions in order to deal with disturbances in signal reception.

This dissertation presents results of studying the ionospheric D-region plasma based on continuous, simultaneous registration of very low frequency (VLF) electromagnetic waves being emitted by transmitters distributed worldwide and recorded by the AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) receiver located at the Institute of Physics in Belgrade from 2008.

The investigations are done in three different fields related to calculations of plasma parameters, detection of hydrodynamic (HD) waves and investigation of possibility to detect events that weakly perturb the considered plasmas by using VLF receivers. We developed theoretical and numerical procedures which are based on recorded experimental data and Long-Wave Propagation Capability (LWPC) numerical model for simulation of VLF signal propagation (Ferguson 1998).

## 2. MOTIVATION

The motives for making this study were:

1. The analysis of the obtained data base which enables perennial continuous monitoring of both periodical and non-periodical disturbances of the D-region plasma induced by numerous processes in space and in various parts of the Earth.

2. Investigation of possibility to detect events that weakly perturb the considered plasmas by means of the experimental setup used in the dissertation.

## 3. EXPERIMENTAL SETUP

In our investigations we monitor the low ionosphere by VLF AWESOME receiver which is located in Institute of Physics and has been operating since 2008. The performed study utilizes signals emitted at different fixed frequencies from transmitters in Germany, Italy, UK, Island, USA, and Australia. The relevant characteristics are given in Table 1.

Table 1: Transmitter characteristics and path length of analyzed VLF/LF signals. The data for transmitters are found in the file AWESOME Transmitters.pdf on `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 |

## 4. THEORETICAL PROCEDURES

As said in Introduction, the investigations presented in PhD thesis are done in three research fields related to plasma parameters, hydrodynamic waves and detections of weak ionospheric perturbations. In all cases we developed numerical and theoretical procedures which are later applied to particular influences of astrophysical events or to statistical analyses based on registration of perturbations during periods of radiation impacts from events occurring in outer space.

**Plasma parameters.** Space-time variations of the electron density are obtained by comparisons of recorded signal amplitudes and phases with those simulated by the LWPC numerical model (Ferguson 1998). They are further used in a theoretical model of plasma in the relaxation period that is developed in this study. The obtained final results for a given model yield space-time distributions of electron gain and loss rates, and the coefficient for the effective electron loss process. The resulting time-dependencies converge to values typical of the unperturbed plasma at considered locations which, consequently, reveals their spatial distribution in the unperturbed D-region plasma.

**HD waves.** One of the consequences of a large radiation impact in the ionosphere is induction of HD waves. The properties of these waves induced by astrophysical phenomena are studied in literature. However, all these studies deal with altitudes above the D-region which was the motivation for us to include the D-region medium into consideration.

The goal of this theoretical procedure is finding oscillation frequencies of waves which are excited in time intervals after the considered perturbation process took place and compare them with the situation during time periods before the occurrence of the perturbation. To extract the influence of the considered phenomenon we introduce two additional criteria: attenuations of excited waves in time, and repeating relevant excitations and attenuations in many cases, e.g. finding a statistical proof for the obtained wave periods. The developed procedures are based on Fourier analysis of signal amplitudes registered in real time. Visualizations of excitations and attenuations were obtained by calculations ratios of Fourier amplitudes related to the corresponding two domains.

**Detectability of weak perturbations.** The ionosphere is under permanent variable influences of different phenomena. Because of that detections of particular events which weakly ionize plasma are not reliable. In this PhD thesis, we developed a statistical procedure to examine the possibilities to detect the influence of phenomena based on analysis of many events.

## 5. RESULTS

The mentioned procedures are applied in calculations of plasma parameters in the case of solar X-flare as perturber, determination of HD waves induced by solar terminator (ST) and detectability of weak ionospheric perturbations induced by $\gamma$ ray bursts (GRBs) registered by the SWIFT satellite.

**Plasma parameters.** The investigations in this field are published in four papers in international journals: Nina et al. 2011,2012a,2012b and Nina & Čadež 2014. Here, we show a typical time evolutions of electron density $N$ which are calculated from the recorded signal amplitude and phase variations and the LWPC numerical program for

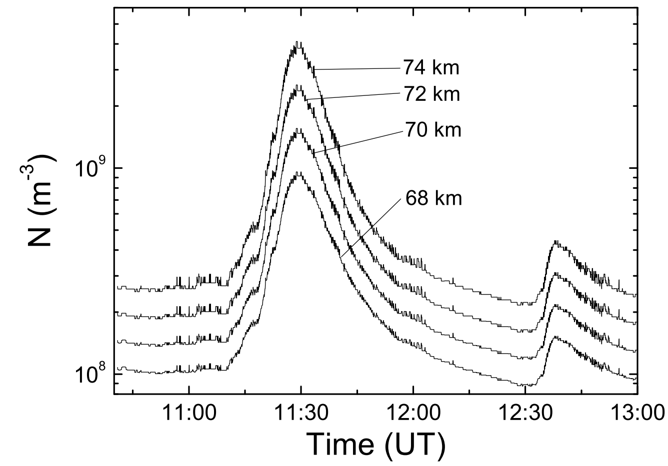


Figure 1: Time evolution of electron density during solar flares occurred on April 22nd, 2011 (Nina et al. 2011).

simulation of VLF signal propagation (Fig. 1). As an example of application of the developed theoretical procedure, we calculated the altitude distributions of electron gain rate $\mathcal{G}_{Ly\alpha}$ induced by Ly$\alpha$ radiation from the Sun (Fig. 2). All obtained results are in a good agreement with those in literature.

**HD waves.** The developed theoretical procedure for detection of HD waves are applied to events of sunrise and sunset during five days. The major conclusion of this study (Nina & Čadež 2013a) is that existence of such waves in the low ionosphere was proven for the first time. The obtained wave periods are within time domains 60 s - 100 s, 300 s - 400 s and 1000 s - 3000 s. The calculations of propagation characteristics of acoustic and gravity waves in conditions relevant to the low ionospheric medium show that the waves in the first time domain of waveperiods are acoustic waves, while the other two cases are related to gravity waves.

**Detectability of weak perturbations.** The obtained procedure for detection of weak low ionospheric perturbations is applied to the influence of $\gamma$-ray bursts. In addition to the observation of summary results for the entire sample of 54 registered events, this influence is considered to take into account the characteristics of the observed $\gamma$-ray bursts, characteristics of the ionosphere during the periods of their impacts and directions of rays impacts relative to the trajectory of the observed signal (Nina et al. 2013b, Nina et al. paper in preparation). The results prove the possibility of detection of low ionosphere perturbations induced by $\gamma$-ray bursts.

## 6. CONCLUSIONS

The main issues resulting from the dissertation are as follows:

1. Development of procedure for a continuous monitoring the electron density variations in the ionospheric D-region during a particular perturbation.

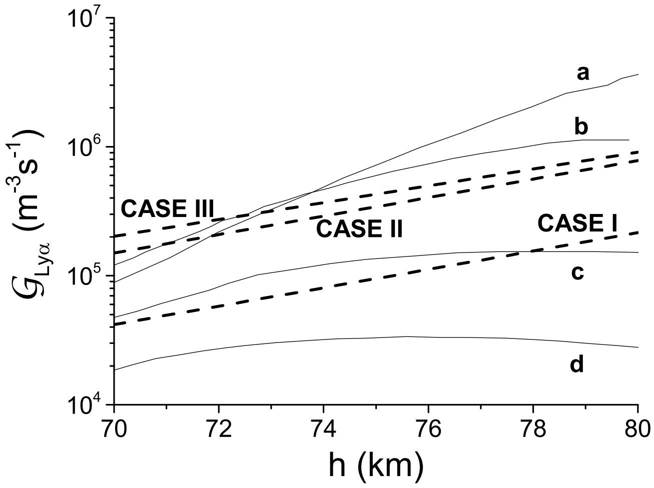


Figure 2: Altitude dependencies of the electron gain rate $\mathcal{G}_{Ly\alpha}$ for Case I, II and III related to flares occurred on May 5th, 2010, February 18th, 2011, and March 24th, 2011 analyzed in Nina and Čadež 2014, and their comparison with data presented in papers cited in Nina and Čadež 2014.

2. Development of procedure for determining the electron gain and loss rates, and the coefficient related to the electron effective loss in a unperturbed D-region from consequences of intense perturbations such as solar X-flares, for example.
3. Development of procedure for detection of hydrodynamic waves.
4. Detection of linear hydrodynamic waves in the D-region during the sunset and sunrise.
5. Development of procedure for detection of weak low ionospheric perturbations.
6. Proof of detectability of short living changes in electron density induced by $\gamma$-ray bursts.

All the developed procedures are universal in a sense that they are relevant to different perturbers and to different signals. Also, the procedures for detections of hydrodynamic waves and their detectability can be applied for studies in other fields.

In addition to the significance of these results it is important to emphasize that the registered data refer to specific parts of the D-region which are determined by locations of the considered transmitters and our receiver. For this reason, the corresponding data analysis provides an original contribution to the international studies of the ionosphere which, in addition to the scientific importance in astrophysics and geophysics, has also practical applications, for example in telecommunications.

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